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DAYLIGHTING TECHNOLOGY ASSESSMENT:

FINAL REPORT

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ABSTRACT AND ACKNOWLEDGEMENTS

This report was undertaken to provide NYSERDA with information from which to initiate a research program in daylighting. The intent was to review the state of the art in this broad field, identify current trends and directions in both design/practice and research, develop a quantitative basis from which to estimate the magnitude of potential benefits, and then to identify actions that might be helpful to accelerating implementation and utilization of daylighting strategies.

Our report draws heavily from past and ongoing daylighting research at Lawrence Berkeley Laboratory, from contacts with other research and professional groups, from extensive contacts with building designers and engineers, and from technical and design-oriented publications. Additional support for this study was provided by the U.S. Department of Energy as part of our ongoing research program; portions of this work were then expanded and appear elsewhere as technical publications.

Our initial directions and final conclusions were reviewed and commented on by an ad-hoc advisory group that included a cross section of building design and operation interests in New York State. Members of this group and their affiliations were:

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The comments provided by individuals in this group were valuable and useful; however, the report does not necessarily represent the beliefs or opinions of any single member or the group as a whole.

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CONTENTS

TABLES

ILLUSTRATIONS

ILLUSTRATIONS

Section 1

INTRODUCTION

This report provides a broad overview and summary of the status of daylight utilization in nonresidential buildings as of the early 1980s. Since the oil embargo of 1973 and subsequent changes in energy policy and costs in the U.S., daylighting has been increasingly viewed as an important energy-conservation option. As with many other aspects of energy use in buildings, the design community's perspective on daylight utilization has changed dramatically in the past 12 years and has moved through three distinct stages. For the first three to five years after 1973, there was little recognition of the potential role of daylighting as an energy strategy on the part of all but the leading edge of the profession and researchers. However, by the late 1970s, daylighting began to be more enthusiastically embraced by a larger fraction of practitioners, to the extent that by the early 80s "daylighting" was almost a cliche associated with any building described as "energy efficient".

As we move into the middle of this decade, we see a reduced emphasis overall on the energy crisis, a more critical examination of energy-saving claims, and at the same time an increased concern for occupant satisfaction and productivity. Daylighting fits well in this context, for there are still substantial real savings to be generated in daylighted buildings, although we recognize that greater care must be taken to properly integrate daylighting strategies with efficient electric lighting strategies and to control cooling loads and electrical demand. Building occupants desire the views associated with daylighting and generally appreciate the color rendition, modeling effects, and hourly variability that fenestration provides, although these desires may not always be forcefully expressed. During the coming decade, successfully daylighted buildings that meet energy, cost, and occupant response criteria will require increasing attention to design integration issues, to technical detail in several fields, and to lighting quality in our indoor environments. Key decision makers throughout the building design process will be asked to make cost-conscious evaluations and critical performance tradeoffs.

This Daylighting Technology Assessment was written to describe the state of the art in daylight utilization; identify gaps in our knowledge, tools, or techniques for applying daylighting strategies effectively; and recommend activities that could be undertaken to provide the information, data, products, tools, etc., to fill these gaps. The focus is on identifying specific research tasks that would advance the state of the art. No attempt is made here to assign priorities to the many research tasks identified. After a summary of our key recommendations (Section 2) and a brief historical perspective (Section 3), Section 4 presents quantitative estimates of daylighting's potential savings. Sections 5 through 11 assess a number of key performance-related issues that determine the effects of daylighting strategies. Section 12 discusses constraints and incentives in the building community that might inhibit or accelerate effective daylighting utilization. Additional supporting data collected in the course of this study are provided in several appendices. Each of sections 4 through 12 closes with a set of recommendations in addition to the overall summary given in Section 2.

Section 2

SUMMARY AND RECOMMENDATIONS

SUMMARY

Increased utilization of daylighting to reduce electric lighting requirements can have beneficial impacts on utility costs (energy and peak demand) and can enhance the visual quality of indoor environments. At this time however, these benefits exist largely as potentials. Our review of the state of daylighting applications suggests the following generalizations:

- General interest in daylight utilization as an energy-saving and load management strategy is high and increasing.
- Potential benefits include not only energy savings but also reductions in peak demand, load shaping, and reductions in HVAC size and cost.
- Unlike some conservation strategies that have unknown or undesired side effects, daylight utilization is linked in most peoples' minds to other positive attributes: view, health, increased productivity, etc.
- Although interest may be high, the general level of understanding of the design and technical issues and solutions is low. This is due in part to the almost complete lack of successfully daylighted buildings that can be examined.
- The technical and design skills needed to optimize daylighted building designs and to maximize energy and load savings (while maintaining or improving visual quality and comfort) are virtually non-existent. The designers and consultants who venture beyond the simplest of proven solutions find themselves in unexplored territory.
- The real cost to a building owner of an unsuccessful daylighting solution (reduced productivity) can be very high.
- Continued improvements in lighting design strategies and lighting hardware will reduce the dollar impact of daylighting savings. Strategies for an economically optimal combination of electric lighting hardware and daylighting are not well understood.

These observations can be best summed up by noting that the potentials are high, but that the risks and uncertainties remain high as well. Extensive computer simulations discussed in Section 4.0 allow us to estimate potential savings. In a daylighted perimeter zone of a building, 70 percent of lighting energy consumption can be saved. In an office occupancy with typical installed power levels of 2.3 watts per square foot (W/ft^2) lighting will require 5.8 kilowatt-hours per year (kWh/yr). Daylighting could thus displace approximately 4 kWh/ft^2-yr. An effective lighting control system might provide 2.4 W/ft^2 savings under peak conditions for 8 months per year (this includes lighting savings and associated cooling load reductions). At $0.10/kWh for energy and $20/kW-month for peak demand, the annual savings come to $0.80/ft^2-yr. This provides a powerful incentive to examine the potential savings in more detail.

RECOMMENDATIONS

Our review of the current state of the art in daylighting utilization in buildings and the potential energy savings and peak load reductions suggests several critical and promising areas for research activities. In developing our list of recommendations we use the following general criteria:

1. The activity would initiate or accelerate the technical solution to a problem that obstructs widespread daylight utilization.

2. The activity would provide information and/or design tools to educate or facilitate decision-making that would lead to greater daylight utilization.

3. The activity complements or accelerates high priority daylighting research underway elsewhere.

Major project themes are identified below. More detailed recommendations in some areas are found in individual sections of the report.

<u>Education and Technology Transfer</u>

There is a need for two types of activities in this area: transfer of emerging research results to designers and decision-makers; and collection, packaging, and dissemination of existing information to the appropriate audiences. The projects are clustered into two major areas:

<u>Development and implementation of educational programs on daylighting potentials, issues, and design techniques, should emphasize existing educational channels and organizations</u>. This includes continuing education programs, university-level programs in architecture, engineering and lighting design, professional society

activities, trade shows, utility programs, etc. Material for these programs can come from many sources including activities such as demonstrations in New York State. In many cases, it should be possible to co-fund activities with these other organizations. Utilities and the Illuminating Engineering Society are organizations that have existing commitments in this area and thus may be more likely than others to participate in joint programs. We suggest developing a state-wide infrastructure of expertise on daylighting based on existing educational institutions that already have a demonstrated commitment to working closely with design professionals. One would start development of the infrastructure with the goal of having the participants financially self-supporting in 2 to 4 years based on user fees and local utility/industry support. This network would provide the average designer with access to specialized tools (e.g., computer models, photometric instrumentation) they would otherwise be unable to use. The network would also provide the design community with seminars, data bases, and other reference materials and expertise.

Design tools and other design data for daylighting are in short supply. Efforts to develop, evaluate, and promote use of appropriate daylighting design tools should be supported. Some examples are mentioned in the text. In the area of design tools, emphasis should be placed on techniques to compare and evaluate tools since we expect many new tools to emerge from the public and private sector over the next few years. There are DOE-supported projects in this area that might be accelerated. Data on product performance, measured building performance, test criteria, etc., are universally required to assist designers and are rarely available in up-to-date and usable formats. Appropriate data bases on many of the subjects discussed in this report should be developed and updated. An institution or organization that is viewed as both competent and objective is required to collect, filter, and disseminate these data. After initial implementation it is likely that these activities could be financially self-supporting. In some subject areas they can build on work started elsewhere and might continue as joint efforts.

Daylight Resource Availability

Data on daylight availability are essential for design purposes and to make accurate estimates of the potential savings in daylighted buildings. A two-fold effort is suggested. In the short term the applicability of existing data bases and calculation techniques to New York climates should be investigated and available information should be expanded or modified to ensure that adequate interim data are available for all design and analysis purposes. This could be accomplished at modest cost if the end use of data was well defined. This work might also define the level of technical data and detail required for the longer term, effort outlined below. For the longer term, one or more data collection projects should be undertaken to ensure that accurate data are available for key New York population centers. This might be done in conjunction with existing university and/or utility studies of solar energy availability. Another way to reduce costs is to piggyback photometric instrumentation on other demonstration or data collection projects. Carefully conceived collection, calibration, and analysis protocols must be developed prior to collecting data. There is now sufficient (painful) experience with solar data collection to assemble an advisory group to ensure that old mistakes are not repeated. Specialized studies should also be undertaken to explore subjects such as daylight available in built-up urban areas, ground cover (e.g., snow) effects on daylight, and other unique microclimate influences.

New Technologies

Detailed examinations of the performance of existing buildings and computer simulation studies of energy use in daylighted buildings will suggest areas where new fenestration and lighting control technologies might be useful. A number of specific topics are suggested in the body of the report. We suggest support of new technology development but urge caution at the same time. The product development cycle is expensive if followed from concept to marketplace, and the funding required to make a substantial positive impact is often large. Products uniquely suited for New York applications might be candidates, although there are probably few in this category. Products in which New York-based industry has a substantial stake might also be candidates for special consideration. Otherwise, one should look for situations in which novel, high-risk concepts can be advanced to the stage where normal market development processes take over, emphasizing co-funding situations that provide high leverage for the new funds invested. New DOE solicitations for advanced glazing developments will be initiated in the future and might present possibilities for co-funding. Most product research and development occurs at a national level so it will be important to ensure that local or state funds do not duplicate private or publicly supported projects elsewhere. Because of the high cost and long development time for most new products, we believe that development of performance data from laboratory testing or field measurements in demonstration buildings is probably a more cost-effective way to accelerate market introduction and acceptance of new technologies unless co-funding agreements are possible or unless the available support can critically leverage a promising product concept.

Energy and Peak Load Simulation Studies

This report discusses results of energy and peak load simulation studies in several building modules for different daylighting approaches in different climates. This type of study provides basic guidance for the design community and manufacturers who are concerned that their products meet real performance needs. However, simulation of daylighted building performance is still in its infancy.

Additional studies are required to quantify more precisely the impact of daylighting on additional building types and design strategies, and to determine the potentials for load management and peak load savings. This may involve some new algorithm development, although much of what is required is under development with support from other sources. Since designers do often lack the luxury of detailed analysis of daylighting impacts due to fee limitations, it might be useful to subsidize additional analysis efforts in exchange for access to the building after it is built to determine the effectiveness of the additional design data. Candidate simulation results should be examined to determine if they can be readily converted into simplified calculations procedures that might be added to the design tool section. Results of simulation studies should also be converted into more extensive economics studies that identify the range of cost-effective savings from the perspective of different owners and investors. Finally, simulation studies are in desperate need of validation and verification--this is discussed in the next section.

Building Monitoring Program

Performance data for daylighted buildings are virtually nonexistent. A review of over 40 "daylighted" buildings described in the architectural and engineering press provided little useful data on the magnitude of daylight savings. A few buildings have been monitored with DOE support under the auspices of the Passive Solar Commercial Buildings Program. These data are necessary, not only to validate computer models that provide guidance to designers, but also to convince hard-nosed decision-makers that these approaches are viable and cost-effective. We propose a series of major interrelated activities in this area.

Data Base. Develop and maintain a data base on daylighted building performance, including both new and retrofitted buildings of all types. This should contain not only buildings in New York State but in similar climates in the U.S. The emphasis should be on measured performance data although, it is recognized that only a small number of buildings will have such data available initially. The ideal data base would contain a relatively fine level of detail on the best solutions.

Monitoring Program. Since few performance data are currently available for daylighted buildings, we suggest a major but carefully conceived and focused effort to collect such data. Monitoring should be done at several levels (daylighting impact only, daylighting/cooling impact, total energy impact, peak load impact, etc.) and on several time frames-- e.g., walk-through, short-term, and long-term. The buildings to be monitored should include a range of daylighting strategies as utilized in appropriate building types. Prior to implementation of a monitoring program, every effort should be made to identify sources of existing measured data from utilities, building/owner associations, etc. A properly executed building monitoring program will be a major and expensive program. However, we believe the benefits of such a program justify this undertaking from the perspective of (1) increasing our technical understanding of how to design effectively daylighted spaces; (2) identifying future research needs; and (3) convincing building owners and decision-makers of the value of daylighted buildings. A monitoring program should include some investigations of occupant response and issues related to the quality of the daylighted spaces. Building monitoring is both complex and expensive, so we suggest that improved monitoring techniques be developed (discussed below) and that efforts be made to involve other interested parties such as utilities and building owners. The needs and interests of the groups that might be influenced by the results of the monitoring program should be considered throughout program development and implementation.

Measurement Techniques. Existing experience with monitoring nonresidential buildings suggests that the cost of traditional monitoring is very high. We believe it will be possible to develop new instrumentation and monitoring procedures that would reduce costs while improving the usefulness of data collected. Some work in this area is now underway and the status of this work should be investigated prior to undertaking new efforts in this area.

Section 3
HISTORICAL PERSPECTIVE

Unlike some of the newer and more exotic strategies to reduce building energy consumption, daylighting has a long and varied history. Prior to the invention of the electric light, buildings and their fenestration systems were routinely designed to admit daylight and utilize natural ventilation. Candles and oil or gas lamps could not compete with the quantity and quality of light provided by the sun and sky. Even after the invention of the electric light and through the first three decades of the twentieth century, daylight as a light source compared favorably with incandescent sources. Recommended illuminance levels were sufficiently low that moderate-sized windows could provide adequate illuminance throughout much of the year. Large floor-to-ceiling dimensions accommodated good daylight penetration and natural ventilation. The patent literature from 1880 to 1930 is filled with practical and fanciful solutions for admitting light from the sun and sky to building interiors.

From 1930 to 1950 profound changes occurred in building technology and design that combined to reduce the value of daylight. The introduction of the fluorescent lamp and the continued decline in the relative cost of electricity made it cheaper and more convenient to maintain higher interior illuminance levels with electric lighting. Mechanical ventilation systems and mechanical cooling systems replaced natural ventilation as the mechanism for controlling thermal comfort. To minimize the volume of air exchanged and to reduce heat gains, floor-to-ceiling heights dropped and window size was reduced. As land and building costs increased, the economic pressures for reduced building height, greater net usable space, and more compact buildings increased. All of these actions tended to reduce the opportunities for effective daylight utilization.

From the 1940s to the 1970s these technical and economic trends accelerated. In addition, the building design profession was guided by the assumption that appearance was the primary objective because our technological prowess (and cheap energy) made it possible to build any design in any climate and ensure that it could be heated, cooled, and lighted. The design profession had the ability to overwhelm any natural energy flow in buildings with a brute-force approach to providing climate control and desired illuminance. Daylight is rarely discussed as a determinant of building designs in this period, and, when it is, its relationship to view and aesthetics is the primary focus. The use of daylight as an energy and load management strategy is rarely mentioned.

Following the recent period of rapidly rising energy costs (and rising building costs), the varied potentials of daylight have been rediscovered. However, there has been a painful and awkward growth in interest and activity, since most of the infrastructure for evaluating daylight (e.g., professional education) has long since disappeared in architectural curricula. Furthermore, the past decade was a time of great turmoil in the lighting design profession, as designers struggled to adjust their long-standing concerns for lighting quality to newly imposed requirements for energy efficiency. It is probably fair to comment that architects quickly rekindled their interest in daylight, but have lacked the skills to translate that interest into workable buildings; lighting designers traditionally saw daylight as a minor and peripheral adjunct to their fundamental business of lighting buildings, and engineers generally lacked the interest and skills to address the problems. Building owners and other decision-makers were not convinced that daylight as a design and energy strategy was a safe, low-risk, cost-effective investment. The existing data base of buildings that could serve as models of good daylighting design was (and still is) largely non-existent.

The next 10 years should see substantial change in this situation. New and more efficient fenestration systems and lighting controls will become available. Design tools, skills, and confidence have increased to the point where daylighting strategies are more frequently incorporated into new buildings. During the next 10 years, results from these buildings and advances in other areas should accelerate identification and more widespread use of successful approaches. It is our hope that this report will help identify some of the actions that might advance effective daylight utilization.

Section 4

POTENTIAL ENERGY SAVINGS

INTRODUCTION

Fenestration's influence on total building energy performance involves a complex interaction among the fenestration's thermal and optical characteristics and other building parameters, set within the context of climate and orientation.

Defining the benefits of daylighting is difficult for several reasons. First, it is a complex problem that is linked to many aspects of commercial building performance. Second, until recently the large computer models used for energy analysis were unable to model daylighting effects accurately. There is little or no operating experience and few measured performance data on the thermal performance of fenestration, and even less information on the effects of daylighting. In order to understand fully the energy-conservation and economic benefits of daylighting, it is necessary to consider lighting energy consumption, thermal performance, and peak electrical demand.

Detailed data on peak electrical demands are necessary to completely analyze the costs/benefits of daylight-responsive electric lighting systems and to accurately determine total electrical costs. Reducing both consumption charges and demand should provide substantial operating savings.

The studies discussed here focus on improving our understanding of the relationship between fenestration parameters and 1) electric lighting reductions due to daylighting, 2) thermal loads both with and without daylighting, and 3) the impact of daylighting strategies on building electrical demand.

We analyzed daylighted building performance using two approaches based on ongoing fenestration research at LBL. In the first phase of these studies, we developed methodologies for conducting parametric studies and assessing their results. These results provided the basis for a second phase in which the methodologies were further developed, the parametric range was expanded, and newly available advanced analysis tools were used.

Results indicate that for a typical daylighted perimeter zone in a commercial office building in New York State, annual electric lighting savings can be as high as 80%. Peak electric demand reductions were also substantial. In many instances, during peak demand hours no electric lighting was required in daylighted zones. For the building studied, with 62% core area and 38% perimeter area, peak demand reductions for the entire building reached 15%. Greater percentages of daylighted floor space could yield even greater reductions in peak demand.

Peak demand as a summer phenomenon is composed primarily of electric lighting and cooling. The large window areas necessary for maximum daylighting savings also admit solar gain, which may cause cooling load increases that exceed daylighting benefits. Furthermore, daylighting benefits begin to saturate and level off with window areas much smaller than necessary for maximum benefits, while cooling load continues to rise monotonically even after daylighting benefits begin to level off. Optimum design solutions, which are suggested in this report, will require further research that accounts in detail for energy consumption economics and various building energy interactions (e.g., HVAC system design and thermal storage systems) as well as fenestration parameters.

Daylighting from skylights offers savings potentials that can be even greater than those from windows. Once again, however, the energy benefits of skylights can be negated by the less favorable orientation for solar gain and the corresponding cooling loads. Design optimization involves critical sizing issues that require further research.

The results, while clearly pointing up the energy-conserving potential of daylighting, demonstrate the need for more detailed performance data and design guidelines to allow daylighting's potential to be realized.

PHASE-ONE STUDIES

Methodology

In order to study the effects of fenestration on building energy performance, representative five-zone commercial office modules were designed. A module configuration was evolved through a series of sensitivity studies that provided the basis for a building-block approach for calculations. The building module is square in plan and 60.96 meters (200 ft) on a side. It contains four identical perimeter zones each 9.14 meters (30 ft) deep, surrounding a core zone. Ceiling height is 3.05 meters (10 ft). The module can be considered as a single floor in a multistory building. No net heat transfer occurs through the floor or ceiling, or between perimeter zones.

Glazing is flush with the exterior surface and no exterior shading elements or obstructions exist. The windows are furnished with drapes having a shading coefficient multiplier of 0.6. There is an 80% probability that the drapes are closed when direct solar transmission exceeds 63 W/m^2 (20 $Btu/hr \cdot ft^2$)

A ceiling-mounted fluorescent lighting system provides 538 lux (50 footcandles) and requires 21.5 W/m^2 (2 W/ft^2). The electric lighting in the outer 4.57 meters (15 ft) of each perimeter zone can be reduced in response to daylight. Daylight does not influence electric lighting usage in the inner portion of the 30-ft-deep zone. The lighting controls are assumed to dim linearly to a minimum 30% power, thus providing a maximum savings of 70% of the electric lighting energy.

For this phase of the studies the conductance of the opaque wall was held constant and that of the glass was varied. The conductance of single glazing and quadruple glazing were taken as limiting values. Intermediate cases of single glazing with a low-emissivity surface and conventional double and triple glazing were also studied.

Shading coefficient of the glass was varied in increments of 0.2 from 0 to 1.0. A constant value of 0.8 was taken for visible transmittance within a shading coefficient range of 0.4 to 0.8. Results for other visible transmittance values can be estimated as described later. Window-to-wall ratios of 0.9, 0.6, 0.3, 0.15, and 0.0 were used to provide a full range of glazing areas.

Annual energy consumption was modeled with a development version of DOE-2.1, which was modified to improve the analysis of fenestration performance. These improvements were incorporated into DOE-2.1B, which was used in the next phase of the studies. Since the DOE-2.1 development version lacked a daylighting algorithm, a simplified daylighting algorithm was added as a preprocessor and annual energy performance was calculated both with and without the utilization of daylight in the perimeter zones.

Results

For the case of moderate to large windows with high U-values, (e.g., single glazing), thermal performance is dominated by heating load and total energy consumption generally falls with increased shading coefficient (SC) since the solar gain usefully offsets heating loads. To make significant reductions in total energy consumption, the U-value and/or window area must be reduced. As the U-value is reduced, the thermal balance point in the perimeter zone shifts, resulting in a proportionally higher cooling load. In the north zone, Fig. 4.1, an increase in shading coefficient adds slightly to the cooling load; on east, south, and west orientations, the cooling load increase is significant. The results for the south zone presented in Fig. 4.2 show total energy consumption rising at high SC with an optimum performance at an intermediate value of SC. The optimum value for SC decreases as U-value is decreased. Thus with large single-glazed windows, the primary conservation strategy is to reduce conductance. This in turn requires a reduced shading coefficient to avoid negating the heating load savings by increased cooling loads. However, as window size is reduced the optimum SC increases. Solar gain per unit glass area is then limited to that which can be utilized in the heating season, and the negative cooling impact is controlled by the smaller window size. These results suggested use of several lumped parameters, primarily (SC x area) and (visible transmittance x area), which were subsequently used to characterize window performance in the next phase of this work.

All daylighting calculations in the Phase-One Study were performed using a visible transmittance of 0.8. Using this value as an upper limit for daylighting savings and taking the nondaylighted case as a lower limit, it is possible to interpolate to estimate savings for any intermediate transmittance value. Daylighting savings vary with latitude, climate, orientation, hours of occupancy, lighting control system, glazing transmittance, and glazing area. The primary variables of interest in this phase of the study are glazing transmittance and area. Although for a given hourly climatic condition, daylight illumination in an interior space is a nearly linear function of glazing area and transmittance, the relationship between annual savings and these glazing parameters is more complex. For example, daylight illumination above the desired lighting level produces no additional energy savings. Thus, as window area and/or transmittance increase, savings do not increase proportionally, and for a given window area, interpolation between the nondaylighted case and the 0.8 transmittance case is highly non-linear.

Table 4-1 provides sample data for New York City from the simplified daylighting model which allows daylight savings to be estimated for any glazing area and glazing transmittance (T_v). The values in the matrix are the percent of total electric lighting energy consumption averaged over all four perimeter zones. The highest value in the table, 100 (T_v = 0.1, WWR = 0.1), represents 100% electric lighting. The lowest value, 69.4 (T_v = 1.0, WWR = 1.0), represents a 30% reduction in electric lighting energy. The lowest value representative of parameters used in this study corresponds to T_v = 0.8, WWR = 0.9, about a 30% reduction. This is close to the theoretical maximum savings (35%) since only the outer half of the perimeter zone is daylighted and the dimmable lighting control system never reduces lighting energy by more than 70%. Note that for a given shading coefficient the full range of visible transmittance may not be realizable since it will not be possible to have a visible transmittance more than about twice the value of the shading coefficient.

These results with daylighting utilization are predicated on an electric lighting load of 21.5 W/m^2 (2 W/ft^2), which is representative of current energy-efficient lighting design practice. If daylighting is utilized to offset the higher electrical lighting loads found in many existing buildings, it can provide far more dramatic benefits. Conversely, with more efficient electric lighting, the impact of daylighting diminishes, as will be seen in the next section.

PHASE-TWO STUDIES

Methodology

Completion of the early phase of work raised many additional questions regarding the relative importance of the visible transmittance of the glass, the installed lighting power, and the lighting control strategy. A new series of parametric studies was developed using an expanded range of variables and DOE-2.1B, an upgraded version of the program with an integral daylighting model. In order to facilitate daylighting calculations in this improved version of DOE-2, the building module was revised.

This new module consists of four identical perimeter zones, each 4.8 m (15 ft) deep, surrounding a square common core zone. As before the ceiling and floor were modeled as having no net heat transfer. The overall envelope thermal conductance was held constant in order to isolate solar gain and daylighting effects. Thus when glazing area or glazing U-value was changed, the wall U-value was adjusted to maintain a constant overall envelope conductance. After basic performance patterns were established, the overall conductance was varied over a representative range. Fenestration characteristics were varied by changing the number of panes of glazing, glazing area, visible transmittance, and shading coefficient. As base-case conditions, we assumed that occupant requirements for thermal and visual comfort would result in the use of drapes or shades for any hour in which transmitted direct solar radiation exceeded 63 W/m^2 (20 $Btu/hr{\cdot}ft^2$), or any hour in which window luminance produced a glare index greater than 20. The interior shading device reduces solar heat gain by 40% and visible transmittance by 65%, values typical of conventional interior drapes or blinds.

Electric lighting power density was varied from 12.9 to 34.5 W/m^2 (1.2 to 3.2 W/ft^2) based on a design illuminance of 538 lux (50 fc). We examined the effects of stepped switching and continuous dimming in response to daylight. The continuous dimming system modeled dims from 100% light output with 100% power to 0% light output with 10% residual power.

The DOE-2.1B building energy analysis program used as the modeling tool incorporates a daylighting model that calculates hourly interior daylight illuminance for each zone of a building based on architectural design and hourly weather data. Our initial intent was to complete analysis for two climates in New York State, New York City and Albany, using WYEC weather tapes. However, as part of another study, we examined the performance of daylighted buildings in Madison, Wisconsin. Madison weather data was available on WYEC tapes and approximates that of Albany both monthly and annually within a few percentage points. Weather summary comparisons are presented in Tables 4-2 and 4-3. We have thus chosen to analyze simulation results from Madison to characterize the impact of daylighting in Albany. These two climates, exemplary of the climate range of populous areas in New York State, provide satisfactory bounds to this study.

Total plant energy consumption was calculated for the entire five-zone module; however, in order to examine the effects of orientation, we also studied zone-by-zone requirements based on zone-level coil loads. The interactions among various HVAC systems and building envelope characteristics can be important, but were not a primary issue in this study. In another part of this report we examine the impact of daylighting in a typical high-rise building with several different HVAC options.

Results

Energy Use--Windows. The numerous parametric runs provided a data base that demonstrates the complexity of daylighting energy analysis relative to our primary concerns--climate, orientation, and fenestration--along with other physical and operational building parameters. To simplify interpretation of results, we define a new term, effective aperture, which is the product of the ratio of glass area to floor-to-ceiling wall area (WWR) times visible transmittance (or, when appropriate, shading coefficient). The value of visible transmittance is taken as two thirds that of the shading coefficient, a generally conservative assumption.

The dimming system is continuously responsive to variations in daylight level and maximizes the benefit from low daylight levels. The simple stepped system reduces electric lighting power only when daylight exceeds the design criteria and provides all required lighting; at zero electric light output there is zero power consumption. Thus the step-switching system is most effective at high interior daylight levels, where it outperforms the continuous dimming system with low-level losses; step switching is least effective in situations in which low daylight levels provide only a fraction of desired illuminance.

The principal effect of daylighting is to reduce electric lighting use. Sample DOE-2 reports for north and south perimeter offices in New York City are presented in Tables 4-4 through 4-9 for a small aperture (WWR = 0.21) with moderate transmissivity (0.40). Even with this small aperture, annual percent lighting reductions are 20% for the north zone (Table 4-4) and 28% for the south zone (Table 4-5). Maximum monthly savings of 37% in the north zone and 44% in the south zone occur during July when maximum cooling loads are contributing to annual peak electrical demand. The daylighting illuminance range is indicated for each month in Tables 4-6 and 4-7. The average hourly percent lighting reduction on a monthly basis is shown in Tables 4-8 and 4-9. In the south zone (Table 4-9), mid-day daylighting levels in summer months have not yet saturated, as indicated by the 40-65% lighting energy reductions during occupied hours. More daylight introduced at these hours would be useful and the effective aperture could be increased somewhat before it would increase cooling loads without adding lighting benefits. North zone lighting energy reductions (Table 4-8) reach a maximum of 48% at noon in July, indicating that substantially more daylight could be effectively utilized.

As the effective aperture increases from 0, lighting energy savings first rise rapidly but electrical consumption for lighting then levels off. For a given effective aperture, the fractional savings depend on the design illuminance level, lighting power density, and the lighting control strategy. Figure 4.3 illustrates the change in fractional lighting energy savings as a function of effective aperture for three design illuminance values with a stepped system and for a continuously dimmed system. These results for "Albany" (Madison, Wisc.) are representative of savings potential with daylighting in the northern tier in the U.S. For small apertures the savings are not linear with respect to design illuminance level. For larger apertures the shape of the curves indicates that daylighting becomes saturated and further savings are minimal. Results for New York City are similar.

The choice of lighting control strategy has several consequences. Figure 4.4 illustrates lighting energy consumption with a dimming control and a stepped control both set to 538 lux (50 fc). For small apertures, the dimming control always outperforms the stepped system because for many hours the available daylight is below the control setpoint, allowing partial savings with the dimming system but none with the switched control. As aperture size increases, the difference between the two is reduced. Eventually the switched system outperforms the dimming system because of the dimming system's low-end operating characteristics. This pattern appears on all orientations in both climates.

Total electric lighting energy savings can be substantial. Approximately 50 to 80% of electric lighting in the perimeter can readily be saved. Note, however, that the savings saturate at moderate effective apertures of 0.2 to 0.3, similar to the results shown in Table 4-1. This suggests that for a 538-lux (50-fc) setpoint, a 50% glazed wall with 50% transmittance or a 30% glazed wall with 80% transmittance will provide most of the possible daylighting savings in a typical 15-foot-deep perimeter zone. Walls that are fully glazed from a 0.8-m-high (30-in.) sill to ceiling have 71% glazing and would provide most of the potential savings with a transmittance as low as 30%. These moderately transmitting products may also reduce discomfort from glare. However, the highly reflective architectural glasses in common use, which have 8 to 14% daylight transmittance, provide substantially lower daylighting savings. These glazings emphasize sun and glare control at the expense of daylight transmittance. Note that if the design illuminance level was lowered to 323 lux (30 fc), a level that might be used for ambient lighting only, the fractional savings in all the above cases would increase, notably with the very low transmittance glazings.

During winter months, the balance point of a zone shifts when the electric lighting is reduced and additional heating energy is consumed. The magnitude of the heating-load increase depends on orientation. The worst case occurs in a north zone, which can show a 25% increase for large effective apertures. However, for the south zones the increase can be much smaller, about 5%. This is because the solar gain that was unusable when the electric lights were on is now being used to offset part of the increased heating load. In the summer, reduced electric lighting diminishes cooling loads.

An overall picture of total zone plant energy requirements for a south zone as a function of glazing parameters and lighting load is shown in Figure 4.5, which presents total plant energy results for "Albany" for two different lighting loads:

12.9 and 23.7 W/m^2 (1.2 and 2.2 W/ft^2). The curves initially decrease to a minimum and then rise monotonically as effective aperture increases. We show curves for a nondaylighted case (solid line) and for two daylighted cases, one for continuous dimming, and one for step switching. The continuous dimming system outperforms step switching for small effective apertures, but the curves cross and change relative positions for larger apertures.

For this south orientation, after an optimum effective aperture is reached, total energy consumption increases, dominated by the rising cooling load. In this case there is an obvious tradeoff between cooling and daylighting, and the optimum solution is somewhat sensitive to installed lighting power. For 23.7 W/m^2 (2.2 W/ft^2) installed lighting load, the optimum effective aperture is approximately 0.30. However, the optimum is not sharply defined and even at the largest value studied (approximately 0.4), the energy requirement with daylighting is only slightly higher than at the optimum, and is well below that of an insulated wall. If we drop to an installed lighting load of 12.9 W/m^2 (1.2 W/ft^2) on the south zone, the optimum shifts to a smaller effective aperture of approximately 0.25. For either lighting power density, the energy requirement in the daylighted case is always less than that of an opaque wall for the range of effective aperture studied.

A comparison between north and south zone performance shows that the relative differences are small (Figs. 4.5 and 4.6). In the south zone, total energy requirements decrease to an effective aperture of 0.20 - 0.25 for the nondaylighted case, after which the south zone's total energy requirement rises. This rise occurs even though heating requirements are reduced in the south zone as effective aperture increases, resulting entirely from the large increase in cooling requirements. In the north zone, for the entire effective aperture range studied, total energy requirements for both the daylighted and nondaylighted cases monotonically decrease with increasing effective aperture. Solar gain is primarily diffuse and has a greater influence on heating load reductions than on cooling load increases. These results are a consequence of the fact that we have adjusted the wall conductance to hold the overall U-value constant as glazing area changes. The specific influence of effective aperture on lighting, and cooling requirements is shown in Figures 4.7 and 4.8.

Although a daylighted building will clearly have a lower cooling load than an identical nondaylighted building, the effective efficacy of daylight as a light source has been the subject of much discussion and some misconceptions. It has been often stated that since the efficacy of daylight of 90-130 lumens per Watt (lm/W) is higher than that of electric lighting systems (60-90 lm/W), daylighting always produces a lower cooling load impact than electric lighting. We believe this is an incorrect generalization, although there are circumstances in which it will be true.

If we plot cooling load vs. effective aperture for different values of installed lighting power density we find that the curves rise monotonically for very low lighting power densities, indicating that the net impact of each increment of glass is to increase cooling load. For cases with high installed lighting power densities, the cooling load first drops as effective aperture increases, and then rises through the rest of the aperture size range. This indicates that there are conditions under which the cooling load impact of daylight is less than that of electric light.

The fallacy of the comparative efficacies of daylight and electric light is based on a misuse of the term efficacy. The cooling load impact of any source of radiant energy is dependent not only on the intrinsic special distribution of the source but also on how that source contributes to heat gain and lighting requirements in the building. In the case of electric lighting, we can define an "effective efficacy" as the ratio of useful illuminance (in this case, the design illuminance), 538 lux (50 fc), to the input power density, which varies. This results in an effective efficacy of 19 lm/W, 29 lm/W, and 72 lm/W, corresponding to lighting power densities of 29.2 W/m^2, 18.3 W/m^2, and 7.5 W/m^2, respectively. The reason that these values differ from the typically quoted fluorescent system values is that the effective efficacy accounts for light that never contributes to useful workplane illuminance.

Direct calculation of an effective efficacy for daylight is much harder because the illuminance distribution varies in time and space. Two primary effects reduce the effective efficacy of daylight: the nonuniform distribution of daylight and the design of simple lighting control systems. Our lighting control system adjusts the electric light in response to the illuminance at a point two-thirds of the distance from the window to the back wall of the room. Under typical sky conditions in a small perimeter room, the illuminance falls off sharply from the window to the back wall. The average illuminance throughout the space is approximately twice the illuminance at the control point. Since the electric lighting power is set based on the control point value at any given time, there is approximately twice the average luminous flux (and thus twice the radiant gain) at the workplane that is accounted for by the value measured at the lighting control point. This reduces the effective efficacy by a factor of two. In addition, just as in the case of electric lighting, a fraction of the admitted luminous flux is absorbed by room surfaces and never provides useful illuminance. In a sidelighted space this fraction will normally be greater than with ceiling-mounted electric light since the flux is admitted from the side. There are additional losses in the window system and other factors that further reduce effective efficacy. When we account for all these factors, using the perimeter office we have modeled, we find the nominal efficacy of daylight has been reduced to an effective efficacy of 30 lm/W. This suggests that of the three electric lighting power densities we considered, the daylight strategy reduces cooling loads only in the case of the least efficient electric lighting system and then only for small apertures. This approximate analytical result is confirmed by simulation results. As aperture size increases, the effective efficacy of daylight will always be further reduced.

Daylight can reduce cooling loads relative to many electric lighting designs if we alter the parameters of this study. For example, in our studies of a skylighted space with properly distributed skylights, the illuminance distribution is more uniform and the room optical losses are lower so the effective efficacy is much higher than in the sidelit perimeter office. Furthermore, the nature of this problem suggests that advanced glazing systems having better spectral and directional control properties;improved lighting controls would also greatly improve the cooling load impacts. Until these interrelated effects are better understood, claims regarding the impacts of daylighting on cooling loads should be examined carefully on a case-by-case basis.

Energy Use--Skylights. As with vertical fenestration systems, energy savings from horizontal skylights vary as a function of the lighting level (fc) and the lighting control system. Figures 4.9, 4.10, and 4.11 show lighting, cooling, and total energy savings as a function of effective aperture for four different lighting systems: continuous dimming at lighting levels of 30, 50, and 70 fc, and stepped switching at 50 fc. As might be expected, the three continuous dimming systems have similar savings curves, with downward shifts in energy savings with daylighting as the required maintained lighting level increases. Stepped systems provide somewhat smaller savings except at very large effective apertures, where the minimum power requirement of the continuous dimming system results in better performance from the stepped switching system for the same lighting level (50 fc).

Figure 4.12 shows annual energy use vs. effective aperture for an extended range of effective aperture (up to 0.08). Note that daylighting savings approach their maximum value at very small effective apertures, approximately 0.02. This is also the aperture size by which cooling and total energy consumption have reached and passed their minimum values. Increasing effective aperture beyond this point provides additional hours in which daylighting exceeds lighting level design requirements and imposes an increasing cooling energy penalty. This crossover is typically reached at a much smaller effective aperture in flat skylights than in vertical fenestration as a consequence of the greater daylight availability and the less favorable orientation to solar geometry. Flat skylights receive maximum direct solar radiation in the summer when it imposes a cooling load, and minimum direct solar during the winter when it can be used to offset heating requirements. The use of properly designed exterior shading elements on flat skylights or otner skylight or roof monitor configurations can change this relationship to yield improved net annual energy performance.

Peak Demand Analysis. Unless electricity is the primary heat source in a cold climate, electrical consumption in office buildings typically peaks during summer months when cooling requirements are at a maximum. In this study we modeled heating being supplied with a gas-fired boiler and cooling being provided with an open centrifugal chiller. Therefore, the peak electric demand conclusions of this study are limited to summer peaking. Results might change with electric heat sources such as heat pumps.

Using the same prototypical building module as above (including the core), we extended our analysis to examine peak demand impacts of fenestration on the whole module. Figure 4.13 shows that daylight from moderate-to-large effective apertures can reduce total building peak demand by 14-15% in "Albany", compared to a nondaylighted building with identical glazing when the electric lighting is 18.3 W/m^2 (1.7 W/ft^2) (compare curves B and D). In this case the daylighted perimeter floor space is only 37% of the total. The fraction of total building peak demand saved will vary with the ratio of perimeter area to core area.

A plot of required chiller size as a function of effective aperture is included in Fig. 4.13. Chiller size increases continuously with effective aperture even in the daylighted cases. This pattern contrasts with the peak load patterns, which show an intermediate value of effective aperture for the minimum peak loads. The data for "Albany" indicate that the incremental chiller savings due to reduced lighting loads occur at low effective aperture values and remain constant, while the incremental adverse impact of solar gain continues to increase as effective aperture increases. These results emphasize the importance of control of solar gain if daylighting is to be successfully utilized to control peak demand.

The results described above also depend on installed lighting power density. When the installed electric lighting is very efficient, daylighting without window management requires a larger chiller than window management without daylighting. ("Window management" refers to operation of simple internal shading devices to reduce solar gain.) When installed electric lighting power density is above 21.5 W/m^2 (2.0 W/ft^2), daylighting is generally beneficial in terms of chiller size. Chiller size is approximately linearly dependent on electric lighting level regardless of daylighting and window management, although the rate of increase will vary with the conservation strategies utilized.

Peak electrical demand as a function of installed electric lighting power density for "Albany" is shown in Fig. 4.14. Changes in installed lighting power are assumed to represent hardware changes that increase or decrease luminous efficacy. In all cases the illuminance design criterion remains 538 lux (50 fc). For the nondaylighted cases, including a building having no windows, the relationship between peak demand and electric lighting power is linear and the plots for different values of window area or shading coefficient are parallel. However, for daylighted cases, the relationship between peak electric load and lighting power density becomes more complex.

In "Albany" the three nondaylighted cases represent glazing areas of 0%, 21%, and 71%. These have essentially the same slope (see Fig. 4.14). The value includes the cooling impact of lighting as well as the effect of operating schedules. These schedules assume that 90% of the installed lighting power is operating during most daytime hours. These values represent results for core and perimeter zones combined. If we examine results from the perimeter zone alone, we find that, at peak conditions with small windows (August 31, 3 pm), the electric lighting is operating at about 30% power. For large windows, the lighting is operating at its lowest limit, 10% power. All the peak demands plotted in Fig. 4.14 (both daylighted and nondaylighted) occurred between 3 and 5 pm on August 31. The figure shows that the daylighted case will always have a lower peak electric demand than the equivalent nondaylighted case. However, if we compare the case of the large window with daylighting to the small window without daylight, we find that the large window/daylighted case has a lower peak electric demand only for lighting power densities above 1.5 W/ft^2. As the electric lighting becomes more efficient, peak demand is minimized by using smaller fenestration with good sun control to minimize cooling load. Once again we find there are potential benefits with daylighting but generalizations are dangerous without considering the effects of all of the relevant building design parameters.

Monthly distribution of peak demand in New York City is shown in Fig. 4.15. Monthly total electrical consumption is also indicated. In this case of small glass area (WWR = 0.21) and high transmittance (effective aperture = 0.20), peak demand rises dramatically during summer months when daylighting produces very significant peak load-shaving benefits. With a much larger effective aperture of 0.55 (WWR = 0.71), as shown in Fig. 4.16, this summer peak pattern is repeated to an even greater degree. Note, however, that while the effective aperture more than doubles, the peak load savings with daylighting are only slightly improved, indicating the rate of rise in cooling load due to increased solar gain exceeds the rate of increase in daylighting benefits. This is consistent with results in Fig. 4.13, which shows essentially no incremental improvement in peak savings for effective apertures greater than 0.25. While total cost optimization constitutes a complex issue requiring detailed study, daylighting as a design strategy offers the potential for important peak load reductions to utility systems and to building owners.

SIMPLIFIED PERFORMANCE ANALYSIS

Analysis of data in the preceding figures provides insight into key performance trends but makes evaluation of the impact of individual parameters difficult. We therefore developed a simple set of predictive equations that incorporate key fenestration variables. A large integrated data base was created from results of DOE-2 runs, then a series of multiple regressions was undertaken to define coefficients for selected configuration variables that could accurately predict relative energy use. Multiple regression is a statistical analysis procedure in which relationships between different variables are established mathematically using a least-squares approach. Generally, sets of independent variables are defined from which a dependent variable is predicted.

In this analysis, distinct expressions were generated for cooling peak, cooling energy, heating energy, and total electric requirements. Heating peak was not considered in the study after initial results indicated that its value was a function of the startup load and thus could not be related to configuration parameters in a meaningful way. The analysis of daylighting resulted in correction factors to the lighting terms. The resulting regression expression for the perimeter zone was of the form:

$$b_1U_oA_T + b_2A_gSC + b_3k_dA_fL + b_4A_f \qquad (1)$$

where:

- b's = solved for regression coefficients, for each zone
- U_o = exterior envelope overall U-value (Btu/hr·ft-°F)
- A_T = exterior wall area (ft²)
- A_g = window area (ft²)
- SC = shading coefficient
- A_f = floor area (ft²)
- L = lighting wattage (W/ft²)
- k_d = correction factor due to daylighting.

This form of the equation was used for each orientation for each of the energy quantities studied. Its compact form and conveniently segregated terms permit a qualitative as well as quantitative analysis of individual components contributing ot zone energy use. Tables 4-10 and 4-11 present the regression coefficients and certain relevant statistical variables to indicate the reliability of the fit for New York and "Albany". Figures 4.17 to 4.22 present some of the data in graphic form. Generally, the r^2 (square of the correlation between the predicted value and actual value) values are on the order of 0.97 and above (an r^2 value of 1.0 represents a perfect correlation), with the exception of the heating energy in the perimeter zones, which is usually below this value. However, when heating approaches the magnitude of cooling (this can be seen by observing the mean value of the data), the r^2 increases correspondingly. The skylight or rooftop envelope portion of the analysis yielded a regression expression similar to Eq. (1), the only difference being the lack of an orientation variation.

The daylighting correction to the lighting term of the basic equation was obtained as a function of effective aperture. The effective aperture, which is a dimensionless parameter, is defined as the product of window/wall ratio and visible transmittance. For skylights this product is multiplied by the skylight well factor. The following expression was derived:

$$k_d = 1. - b_5(E_a) - b_6(E_a)^2 \quad (2)$$

where:

k_d = correction factor to the lighting wattage due to daylighting

b's = regression coefficients

E_a = effective aperture.

This equation can be used for each of the energy quantities analyzed. The coefficients are presented in Tables 4-10 and 4-11.

Whole-building energy performance is necessary in determining building coincident peak electrical load and peak load reductions due to daylighting. In order to assess the energy performance for a whole building, Eq. (1) was rewritten in the following form:

$$b_i U_o A_T + b_2 A_g SC + b_3(k_d A_p + A_c)L + b_4(A_p + A_c) \quad (3)$$

where:

A_p = total perimeter floor area (ft^2)

A_c = core floor area (ft^2).

The appropriate coefficients can also be found in Tables 4-10 and 4-11.

The statistical correlations presented in Tables 4-10 and 4-11 for the various multiple regressions indicate that good predictions of DOE-2 results are obtained by using Eq. (1). The form could be made more accurate by considering quadratic and cross-coupled independent variables of the input heat gain/loss components. Generally, the more detailed the regression model, the better the predictive quality of the final equation. However, although large numbers of independent variables may be more accurate in a mathematical sense, their use is limited in a practical sense. It should be kept in mind that the results of this study are valid only within the range of variables parameterized. One should not expect to be able to define a building's actual energy use from these results, but rather should use them to estimate relative performance among alternative designs.

COST IMPACTS

While energy savings from daylighting can be presented in many forms, the bottom line to most building owners and managers is operating cost savings. Because utility rate structures and energy costs vary as a function of source, season, and demand, detailed analysis of cost savings is complex.

Using large commercial Consolidated Edison rate structures for October 1983 (see Table 4-12) for Manhattan, both annual electricity and natural gas costs were calculated for the prototypical floor considered in this analysis, as well as for a building consisting of 30 of these floors. Because of decreasing energy costs with rising consumption, the energy costs of the multi-floor configuration are less than 30 times that of the single floor. Thirty floors were analyzed as a case where the bottom (cheapest) energy step dominates. The typical cost savings are about 27% or $\$0.40/ft^2$ of daylighted space or about 10% or $\$0.15/ft^2$ averaged over the entire building. Figures 4.23 and 4.24 present total annual fuel and electricity costs for a single floor and for the 30-story building. A typical U_o value (0.205 $Btu/hr \cdot ft^2\text{-}^oF$) and a median electric lighting power density (1.7 W/ft^2) are held constant. Note that over 60% of the total building floor area is located in the core of the building and is thus not influenced by daylighting strategies.

BUILDING APPLICATIONS

Background

As an example of daylighting's effects in a real building, the PSEG/Tishman building in Newark, NJ was modeled with DOE-2.1B using New York City WYEC weather data. Three perimeter systems were compared: a constant-volume, variable-temperature (CVVT) system as used in the generalized module case, a variable air volume (VAV) system typical of those currently used, and a four-pipe induction unit (FPIU) representative of systems installed in the mid-1960s. The formulation of regression correlations for the latter two systems is discussed. The significant difference between results for the different system types leads to the conclusion that system types greatly affect the energy impact of daylighting and that more work is needed in this area.

Building Description

The PSEG building is a 35-story, high-rise office building with its four sides facing the four cardinal directions. There was no heat transfer assumed between floors. Anomolies in the building, such as the building's computer room and accompanying double-bundle chiller, were deleted. The interior ceiling height was kept at 9 ft, the exterior wall height at 10.6 ft, and the perimeter zone depth at 11.5 ft. The north and south perimeter zones consist of 10 modules 11.5 ft wide; the east and west of 10 modules 21.3 ft wide. The total perimeter area per floor is 10,380 ft^2 and the core area per floor is 14,145 ft^2.

Daylighting control points were placed in the perimeter zones 2.5 ft off the floor midway between side walls, one-third and two-thirds of the way from the window to the back wall. The daylighting control point farthest from the glazing governed the electric lighting system modeled (continuous dimming). Continuous dimming and no daylighting controls were compared. The lighting level was set at 50 fc, and window management was not included in the analysis.

Parametric variations on window area, shading coefficient, and visible transmission were treated in the same way as in the previous work. Fluorescent lights were also assumed to be evenly distributed. The electric lighting power density varied between 0.7 and 2.7 W/ft^2 for the VAV system and between 1.7 and 3.7 W/ft^2 for the FPIU system.

HVAC Systems

Initial sensitivity runs revealed a significant difference in energy consumption between different HVAC system types. To compare this building against results from the prototypical module previously discussed, it was first modeled with a constant-volume, variable-temperature system for each of the four perimeter zones as used in the module parametric study. (Note that the other system types use one system to serve all four perimeter zones.) The cooling and heating extraction loads and peak cooling rates, as a function of effective aperture, were compared to the previous regression results for spaces with both no daylighting and continuous dimming lighting controls. An electric power lighting density of 1.7 W/ft^2 and an exterior wall U-value of 0.205, based on ASHRAE criteria, were held constant throughout these runs (i.e., a full parametric series of runs was not made with this system type). These results for annual heating and cooling loads and for peak cooling extraction rates are detailed in Figs. 4.25 to 4.48. Agreement between the DOE-2.1B results and the regression-predicted cooling energy and cooling peak is quite good. The slight difference is due mainly to differences in space geometry. Heating energy differences are significant, yet differ only by a constant. This was traced to a difference in infiltration losses resulting from different building geometry.

Current (VAV) and 1965 (FPIU) System Results

The building was next modeled parametrically with two different system types. In both these cases, heating and cooling schedules and set points, night cycle control, humidity control, and outside air requirements are consistent with the previous runs. VAV systems were used as an example of current building practice. One system served the core and another served all four perimeter zones. A configuration using a constant-volume reheat fancoil system to serve the core zone and a four-pipe induction unit to serve the perimeter zone was modeled to represent the building's system as it would have been designed in 1965. Unlike the previous system, the VAV system has an enthalpy control on the economiser and thus a higher economiser limit of 70^{o}F. Variable parameters included exterior U-values (0.154, 0.205, 0.308 Btu/hr·ft^{2}-^{o}F), electric power lighting density (0.7, 1.7, and 2.7 W/ft^{2} for the current systems, and 1.7, 2.7, and 3.7 W/ft^{2} for the 1965 systems), and lighting control type (none or continuous dimming).

The VAV system would normally include a perimeter baseboard heating system which would increase in capacity with window area, assuming the exterior overall heat transfer coefficient also increased with window area. In our analysis, overall U-values are kept constant with area changes, and thus increasing window area does not warrant perimeter heating. However, because the overall U-value was varied as one of the regression variables, the effects of different U-values for the walls and windows can be modeled using the regression equations.

Because the VAV system is intended to represent buildings in which daylighting controls are not retrofit measures but were included in the design of the initial building, the difference between daylighted and nondaylighted cases will include a difference in plant equipment sizes. Thus, for the VAV system, for both daylighted and nondaylighted cases, fan sizes, heating and cooling coil capacities, and plant equipment can be sized by DOE-2. However, in the case of the buildings with 1965 systems, daylighting controls would be added as a retrofit. While supply air quantities can be changed, it would be impractical to change fans, coils, and plant equipment. Thus, the daylighting cases of the 1965 building are modeled on DOE-2 with system fan and coil sizes and plant equipment sizes as would have been installed in a 1965 nondaylighted building.

Figures 4.29 and 4.30 show the perimeter heating and cooling extraction loads for the constant-volume, variable-temperature (CVVT) system, the VAV (current) and the FPIU (1965) system. Electric lighting power density and the overall exterior wall heat transfer coefficient were held constant at 1.7 W/ft^2 and 0.205 Btu/hr·ft^2-^{o}F, respectively. Cases without and with continuous dimming lighting controls were considered.

Results for the FPIU system are substantially higher for both heating and cooling over the full range of effective aperture for both daylighted and nondaylighted cases. The CVVT and VAV results track each other well for cooling but show large differences for heating, particularly at large values of effective aperture. These results can be explained partly by the different design and operating characteristics of each system. Based on these simulation results, it is clear that currently designed HVAC systems have the potential to operate much more efficiently than systems routinely specified 20 years ago. However, it is also important to note that the details of HVAC system design, sizing, and operation can greatly influence building energy performance and must be carefully considered as part of any envelope design package.

Regression Coefficients

As with the module study, the results from many DOE-2 runs were compressed into a more usable form through a regression procedure. The regression equation for annual system cooling load, system hourly cooling peak, annual system heating load, and annual total system load is of the same form as Eq. (1). Regression coefficients for the PSEG building with VAV and FPIU systems are presented in Table 4-13. These can be used to easily calculate the energy and cost impacts of a range of envelope and fenestration alternatives.

SUMMARY AND RECOMMENDATIONS

Daylighting is a potentially important design and conservation strategy in nonresidential buildings. Results from an hour-by-hour simulation model that accounts for daylighting impacts helps refine our understanding of this complex subject. An extensive set of parametric analyses for a simple office module in several climates suggests the following generalizations:

- Increasing window area and/or transmittance to increase daylighting savings reaches an optimum point beyond which total energy consumption increases due to greater cooling loads.

- Control of solar gain is vital if daylighting strategies are to provide maximum net energy benefits.
- Managed windows without daylighting controls may require less energy than unmanaged windows with daylighting.
- Daylighting may not always be a "cooler" light source than fluorescent lighting--the conditions under which this statement holds true depend on the details of window management and installed lighting power.
- Daylighting strategies provide peak demand management opportunities, but the results depend on design and operating details.
- Daylighted buildings may have lower total peak electrical demand, but may require larger cooling systems than nondaylighted buildings with smaller windows.
- Installed lighting power and lighting control system characteristics are major factors in determining the real value of daylighting strategies.
- Most of the conclusions above are sensitive to climate, orientation, and other building modeling assumptions.
- Strategies that minimize annual energy consumption may not minimize annual operating costs, because operating costs often consist of two energy sources (fuel, electricity) and may include demand charges. In general, the difference between fuel costs and electricity/demand costs will tend to emphasize lighting and cooling effects and de-emphasize heating.

While we believe that these results provide a useful perspective on this subject, we remind the reader that there are still very few measured building data to verify simulation results. Changes in base-case conditions and operating assumptions may also modify some conclusions.

TABLE 4-1

ANNUAL PERCENTAGE OF TOTAL ELECTRIC LIGHTING ENERGY REQUIRED FOR 9.1-METER-DEEP OFFICE SPACE IN NEW YORK CITY AS A FUNCTION OF GLAZING PROPERTIES (VISIBLE TRANSMITTANCE AND WINDOW/WALL GLAZING RATIO).

Visible Transmittance, T_V

T_v / Window/Wall Ratio (WWR)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
.1	100	97.9	96.5	94.4	92.3	90.8	89.4	88.0	86.6	85.2
.2	97.9	94.4	90.8	88.0	85.2	83.1	81.7	79.6	78.2	76.8
3	96.5	90.8	86.6	83.1	81.0	78.2	76.1	74.6	73.2	72.5
4	94.4	88.0	83.1	79.6	76.8	74.6	73.2	72.5	71.8	71.1
5	93.0	85.2	81.0	76.8	74.6	72.5	71.8	71.1	70.4	70.1
6	90.8	83.1	78.2	74.6	72.5	71.8	71.1	70.3	69.9	69.7
.7	89.4	81.0	76.1	73.2	71.8	71.1	70.2	69.9	69.6	69.4
.8	88.7	81.0	75.3	72.5	71.1	70.4	70.0	69.7	69.5	69.4
9	88.7	81.0	75.3	72.5	71.1	70.4	70.0	69.7	69.5	69.4
1.0	[illegible].7	81.0	75.3	72.5	71.1	70.4	70.0	69.7	69.5	69.4

TABLE 4-2
MONTHLY WEATHER DATA SUMMARY FOR ALBANY, NY.

YEAR 1969 TRY ALBANY, NEW YORK — MONTHLY WEATHER DATA SUMMARY

LATITUDE = 42.75 LONGITUDE = 73.80 TIME ZONE = 5

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YE
AVG. TEMP. (F) (DRYBULB)	21.3	25.0	31.1	48.3	56.4	66.3	69.6	70.2	61.0	49.1	39.7	22.6	46
AVG. TEMP. (F) (WETBULB)	20.1	23.5	27.8	42.5	50.3	61.0	64.0	64.1	56.1	43.8	37.1	21.5	42
AVG. DAILY MAX. TEMP.	29.2	31.9	39.2	59.9	68.1	76.9	79.4	82.0	72.9	60.8	45.7	28.9	56
AVG. DAILY MIN. TEMP.	13.0	17.5	23.1	36.0	44.4	54.8	59.4	59.0	51.2	37.0	33.1	15.2	37
HEATING DEG. DAYS (BASE 65)	1353.8	1118.7	1C51.5	518.4	304.0	100.3	49.5	56.6	196.5	506.6	759.4	1313.0	7328
(BASE 60)	1198.8	978.7	896.5	386.0	194.5	43.4	21.5	24.5	120.3	373.9	609.4	1158.0	6005
(BASE 55)	1043.8	838.7	742.1	268.9	112.3	16.3	6.8	9.3	65.8	259.9	460.3	1003.0	4827
COOLING DEG. DAYS (BASE 70)	0.	0.	0.	7.8	15.0	69.4	93.6	121.7	32.1	3.3	0.	0.	342
(BASE 75)	0.	0.	0.	2.8	4.5	30.4	35.6	57.6	12.3	.3	0.	0.	143
(BASE 80)	0.	0.	0.	.5	1.5	11.3	11.7	19.1	3.9	0.	0.	0.	47
MAXIMUM TEMP.	41	43	60	83	87	91	92	91	88	79	60	54	
MINIMUM TEMP.	-7	1	6	14	29	42	44	43	36	17	11	-19	-
NO. DAYS MAX. 90.AND ABOVE	0	0	0	0	0	2	2	1	0	0	0	0	
NO. DAYS MAX. 32 AND BELOW	20	15	5	0	0	0	0	0	0	0	2	23	
NO. DAYS MIN. 32 AND BELOW	29	28	27	12	5	0	0	0	0	8	14	28	1
NO. DAYS MIN. 0 AND BELOW	5	0	0	0	0	0	0	0	0	0	0	3	
AVG. WIND SPEED (MPH)	9.6	10.4	11.6	10.4	9.0	7.8	6.7	5.7	5.4	6.6	8.1	9.7	8
AVG. WIND SPEED (DAY)	11.7	11.4	13.0	11.0	10.2	8.6	7.5	6.9	7.0	8.2	8.8	10.3	9
AVG. WIND SPEED (NIGHT)	8.4	9.7	10.2	9.6	7.1	6.4	5.5	4.1	3.6	5.2	7.5	9.3	7
AVG. TEMP. (DAY)	23.2	27.2	33.9	51.9	59.8	69.3	72.7	74.6	65.4	53.7	41.8	25.0	52
AVG. TEMP. (NIGHT)	20.2	23.5	28.5	43.9	51.2	61.2	64.6	64.4	56.1	44.9	38.1	21.2	40
AVG. SKY COVER (DAY)	7.3	7.1	7.3	6.6	6.8	6.7	7.9	5.8	7.2	6.5	8.5	7.6	7
AVG. REL. HUM. AT 4AM	91.3	90.6	78.9	80.8	84.5	91.6	90.7	90.8	86.8	77.6	82.9	93.6	86
10AM	88.7	84.9	71.2	65.0	65.3	72.8	75.6	71.7	76.8	67.8	81.3	90.7	75
4PM	71.3	70.0	55.0	50.5	50.5	61.7	61.1	53.7	56.3	50.4	70.4	76.9	60
10PM	85.6	84.9	71.5	67.5	72.7	80.7	79.5	80.5	80.9	71.6	82.8	87.0	78

YEAR 1969 TRY ALBANY, NEW YOR — MONTHLY WEATHER DATA SUMMARY

DESIGN TEMPERATURES -- SUMMER ---------- WINTER

PER CENT	SUMMER T(DRY)	SUMMER T(WET)	WINTER T(DRY)
1.0	88	76	-1
2.5	86	74	2
5.0	83	73	

MONTHLY AVERAGE TEMPERATURES AS A FUNCTION OF HOUR OF THE DAY

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
0	19.7	23.1	28.9	42.7	50.1	60.6	63.5	63.7	56.2	45.0	38.4	20.9	42.8
1	19.6	23.5	27.9	41.8	49.1	59.6	62.5	62.7	55.1	43.8	38.0	20.3	42.1
2	19.2	22.6	27.2	40.6	48.2	58.7	61.8	62.1	54.6	43.0	37.8	20.0	41.4
3	19.0	21.8	26.7	40.0	48.0	57.6	61.8	61.2	54.3	42.4	37.6	19.5	40.9
4	17.8	21.3	26.3	39.5	47.7	56.8	61.8	60.7	54.2	41.7	36.9	19.6	40.4
5	17.6	20.4	25.8	38.7	47.3	56.7	62.1	60.3	53.6	40.9	36.5	19.4	40.0
6	17.0	20.5	24.8	39.3	50.0	60.2	63.8	61.6	54.2	40.5	36.3	19.8	40.8
7	16.5	20.0	25.9	42.6	52.1	62.7	66.1	65.7	56.3	41.6	36.5	19.2	42.2
8	16.6	20.4	28.3	45.4	54.4	65.2	68.1	69.3	58.9	46.0	37.2	19.8	44.2
9	18.4	23.1	30.5	48.0	56.7	68.2	70.4	72.2	61.6	49.4	38.9	21.7	46.7
10	21.0	25.0	32.3	50.9	59.2	70.4	73.1	74.5	64.5	52.4	40.8	23.8	49.1
11	22.9	27.1	34.5	53.7	61.2	72.4	75.1	76.8	66.7	54.9	42.3	25.6	51.2
12	24.4	28.6	35.9	55.1	62.7	73.1	76.6	78.5	69.2	57.3	43.3	26.4	52.7
13	25.7	29.8	36.7	56.6	64.0	74.3	77.4	80.1	70.9	58.9	44.1	27.3	53.9
14	26.9	30.9	37.8	57.6	65.3	74.6	77.8	80.7	71.4	59.2	44.0	27.4	54.6
15	26.8	31.1	37.9	57.8	66.5	74.6	77.9	81.1	71.5	59.5	43.7	27.1	54.7
16	26.3	30.8	37.5	57.5	66.2	74.2	78.2	80.4	69.6	58.3	43.1	25.9	54.1
17	24.9	29.5	36.2	56.5	65.5	73.7	76.8	78.6	67.7	55.4	41.3	24.5	52.7
18	23.4	27.8	34.0	54.5	63.2	71.6	74.9	76.0	63.4	51.8	40.6	23.8	50.5
19	22.6	26.8	32.0	51.3	60.0	69.7	72.2	71.6	60.4	50.2	39.9	23.5	48.5
20	22.0	25.3	30.8	49.3	57.0	66.7	69.4	69.1	58.8	48.3	39.5	23.0	46.7
21	21.9	24.6	30.0	47.9	54.9	64.6	67.7	67.5	57.5	47.0	39.2	22.4	45.5
22	21.2	23.8	29.6	46.7	53.0	63.3	66.5	65.9	56.9	46.2	38.3	21.9	44.5
23	20.5	23.3	28.5	45.2	52.1	61.9	64.8	65.1	56.3	45.5	38.3	20.8	43.6

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
GROUND TEMPERATURES	500.0	498.0	499.0	503.0	508.0	513.0	517.0	519.0	518.0	515.0	510.0	504.0
CLEARNESS NUMBERS	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01

TABLE 4-3
MONTHLY WEATHER DATA SUMMARY FOR MADISON, WI.

YEAR 1974 TRY MADISON,WI MONTHLY WEATHER DATA SUMMARY

LATITUDE = 43.10 LONGITUDE = 89.30 TIME ZONE = 6

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Y
AVG. TEMP. (F) (DRYBULB)	19.8	20.0	32.9	48.6	54.2	64.4	73.0	66.9	57.6	50.9	37.3	27.2	4
AVG. TEMP. (F) (WETBULB)	18.3	18.5	30.8	42.8	49.2	57.5	64.6	61.3	51.4	45.2	34.7	26.1	4
AVG. DAILY MAX. TEMP.	25.9	28.4	40.9	60.3	63.3	75.5	84.4	78.2	70.0	62.1	44.9	32.8	5
AVG. DAILY MIN. TEMP.	13.1	9.2	25.5	37.3	44.6	52.4	59.9	55.3	45.2	39.2	29.9	21.2	3
HEATING DEG. DAYS (BASE 65)	1402.0	1260.1	993.8	514.9	359.1	128.5	37.3	88.5	278.3	450.8	831.3	1172.9	751
(BASE 60)	1247.0	1120.1	839.6	391.3	241.8	65.8	12.9	38.5	184.1	324.0	684.2	1017.9	61
(BASE 55)	1092.0	980.1	686.6	280.3	145.6	26.3	2.8	12.5	109.9	217.6	539.5	862.9	49
COOLING DEG. DAYS (BASE 70)	0.	0.	0.	8.2	8.9	54.0	178.5	70.1	24.0	3.3	0.	0.	3
(BASE 75)	0.	0.	0.	2.7	3.8	21.3	98.8	27.3	9.6	.4	0.	0.	1
(BASE 80)	0.	0.	0.	.2	1.3	4.5	44.2	8.1	2.5	0.	0.	0.	
MAXIMUM TEMP.	48	44	67	83	88	89	96	90	85	79	70	41	
MINIMUM TEMP.	-17	-14	-3	22	27	43	48	43	26	22	17	7	
NO. DAYS MAX. 90 AND ABOVE	0	0	0	0	0	0	8	2	0	0	0	0	
NO. DAYS MAX. 32 AND BELOW	15	16	3	0	0	0	0	0	0	0	4	13	
NO. DAYS MIN. 32 AND BELOW	28	27	25	13	4	0	0	0	2	8	20	27	
NO. DAYS MIN. 0 AND BELOW	9	6	1	0	0	0	0	0	0	0	0	0	
AVG. WIND SPEED (MPH)	8.8	9.6	10.7	11.5	10.3	9.0	8.4	7.7	8.6	8.5	8.8	7.8	
AVG. WIND SPEED (DAY)	9.3	11.1	11.9	13.5	11.6	10.7	9.7	9.4	10.0	10.3	10.1	8.4	
AVG. WIND SPEED (NIGHT)	8.5	8.6	9.6	9.0	8.3	6.1	6.4	5.5	7.1	6.8	7.9	7.4	
AVG. TEMP. (DAY)	21.8	23.3	35.2	52.1	57.1	68.0	76.9	71.0	62.5	55.3	40.2	28.9	
AVG. TEMP. (NIGHT)	18.6	17.7	30.9	44.2	49.5	58.2	66.9	61.5	52.3	47.0	35.1	26.1	
AVG. SKY COVER (DAY)	6.8	6.6	8.0	7.2	8.0	6.3	5.8	7.3	5.0	6.7	7.1	8.0	
AVG. REL. HUM. AT 4AM	85.2	91.5	89.4	78.2	86.6	86.7	84.2	93.4	85.0	80.1	87.7	91.5	
10AM	85.0	84.9	82.0	64.9	70.7	64.3	61.4	71.0	64.0	64.4	83.3	91.2	
4PM	71.0	71.7	69.7	52.5	57.2	51.8	49.9	56.6	48.1	48.6	64.8	79.8	
10PM	85.4	83.0	81.0	69.5	76.8	74.1	70.6	82.9	76.9	72.4	82.7	89.6	

YEAR 1974 TRY MADISON,WI MONTHLY WEATHER DATA SUMMARY

DESIGN TEMPERATURES ---------------------------------- SUMMER ---------- WINTER

PER CENT	T(DRY)	T(WET)	T(DRY)
1.0	91	74	-10
2.5	87	73	-6
5.0	84	71	

MONTHLY AVERAGE TEMPERATURES AS A FUNCTION OF HOUR OF THE DAY

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
0	17.9	16.8	29.9	44.0	49.2	57.3	66.5	61.5	52.4	46.1	35.7	26.2	42.1
1	18.0	16.9	29.8	43.0	48.6	55.9	65.2	60.3	51.5	45.2	34.9	25.9	41.4
2	18.3	16.0	29.4	42.1	48.0	55.8	64.1	59.0	50.6	44.8	34.3	25.5	40.8
3	18.3	15.1	28.6	41.7	47.5	55.2	63.1	57.7	49.3	44.7	34.1	25.0	40.2
4	18.2	14.8	28.5	41.5	47.1	54.4	62.5	57.4	48.8	44.3	33.5	24.5	39.8
5	17.6	14.6	28.3	41.1	46.9	54.6	62.2	56.9	48.6	43.6	33.0	24.1	39.4
6	17.3	14.2	27.9	41.2	48.7	58.0	65.8	58.2	48.0	43.5	33.3	24.0	40.2
7	17.2	14.5	28.6	43.9	51.3	62.2	69.6	62.9	51.5	44.3	33.0	24.3	42.1
8	17.0	16.0	30.4	46.6	53.0	65.2	72.6	66.6	56.3	48.2	34.5	24.4	44.4
9	18.5	19.0	32.0	49.0	55.1	67.4	75.5	69.5	59.9	52.0	36.8	25.9	46.9
10	20.0	21.8	33.9	51.4	57.4	69.2	78.1	72.1	62.8	54.2	38.8	27.5	49.1
11	21.4	23.9	36.2	53.1	59.1	71.0	79.7	73.4	64.5	56.6	40.6	28.9	50.8
12	22.6	25.4	37.6	54.8	60.6	72.1	81.2	74.3	66.1	58.8	41.9	30.1	52.3
13	23.5	26.4	38.7	56.0	61.3	72.7	81.9	75.7	67.5	60.3	43.2	30.8	53.3
14	24.3	26.9	39.2	56.7	62.0	73.7	82.8	76.5	68.4	60.8	43.7	31.4	54.0
15	24.3	26.6	39.0	56.9	62.3	73.9	83.0	76.3	68.4	60.7	43.5	31.4	54.0
16	23.5	26.0	38.7	57.1	60.8	73.0	82.5	75.8	67.5	59.5	42.0	30.5	53.2
17	21.7	24.5	37.1	56.1	60.4	72.0	81.1	75.0	65.8	57.0	39.7	28.8	51.8
18	20.5	22.3	35.4	53.9	58.9	70.3	79.5	72.7	62.0	52.9	38.6	28.0	49.7
19	19.6	21.2	34.0	50.3	56.2	67.8	76.1	69.2	57.5	51.2	37.5	27.7	47.5
20	19.2	20.2	33.3	47.9	53.4	64.0	72.9	66.0	55.3	49.3	36.4	27.2	45.6
21	18.6	19.7	32.3	46.7	52.0	61.3	70.5	64.4	54.2	48.8	35.8	26.8	44.4
22	18.6	19.1	31.3	45.9	50.5	60.1	69.1	62.9	53.3	47.8	35.5	26.6	43.5
23	18.6	18.3	30.9	44.8	49.7	58.8	67.7	61.7	52.3	47.6	35.5	26.3	42.8

GROUND TEMPERATURES	501.0	498.0	499.0	503.0	509.0	516.0	521.0	523.0	522.0	519.0	512.0	506.0
CLEARNESS NUMBERS	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE 4-4

DAYLIGHTING SUMMARY REPORT, NORTH ZONE OFFICE MODULE, NEW YORK. VISIBLE TRANSMITTANCE = 0.4, SHADING COEFFICIENT = 0.6, WINDOW/WALL RATIO (WWR) = 0.21. LIGHTING CONTROL IS LOCATED AT REFERENCE POINT #1, TEN FEET FROM THE WINDOW.

SPACE NORTH-ZONE

	PERCENT LIGHTING ENERGY REDUCTION BY DAYLIGHTING (ALL HOURS)			PERCENT LIGHTING ENERGY REDUCTION BY DAYLIGHTING (REPORT SCHEDULE HOURS)			REPORT SCHEDULE HOURS WITH SUN UP: AVERAGE DAYLIGHT ILLUMINANCE (FOOTCANDLES)		PERCENT HOURS DAYLIGHT ILLUMINANCE ABOVE SETPOINT		AVERAGE GLARE INDEX		PERCENT HOURS GLARE TOO HIGH	
MONTH	TOTAL ZONE	REF PT 1	REF PT 2	TOTAL ZONE	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2
JAN	8.8	8.8	20.9	8.8	8.8	20.9	5.9	14.6	0.	1.9	.2	1.8	0.	0.
FEB	10.9	10.9	25.3	10.9	10.9	25.3	6.6	15.5	0.	2.1	.3	2.0	0.	0.
MAR	17.2	17.2	39.0	17.2	17.2	39.0	9.0	20.9	0.	6.4	.5	2.6	0.	0.
APR	21.2	21.2	46.2	21.2	21.2	46.2	12.1	28.0	0.	18.6	1.1	3.8	0.	0.
MAY	26.9	26.9	54.9	26.9	26.9	54.9	13.8	31.4	0.	24.6	1.4	4.1	0.	0.
JUN	31.3	31.3	62.0	31.3	31.3	62.0	15.4	34.3	0.	32.7	1.7	4.6	0.	0.
JUL	36.6	36.6	68.4	36.6	36.6	68.4	17.2	38.1	0.	41.5	2.2	5.1	0.	0.
AUG	29.2	29.2	57.1	29.2	29.2	57.1	15.0	33.1	0.	24.0	1.6	4.6	0.	0.
SEP	21.9	21.9	45.5	21.9	21.9	45.5	12.3	27.1	0.	13.9	1.2	3.7	0.	0.
OCT	17.2	17.2	37.9	17.2	17.2	37.9	10.0	22.1	0.	6.0	.8	2.9	0.	0.
NOV	11.5	11.5	26.9	11.5	11.5	26.9	7.0	16.5	0.	.9	.4	2.2	0.	0.
DEC	8.0	8.0	18.5	8.0	8.0	18.5	5.1	11.8	0.	0.	.1	1.3	0.	0.
ANNUAL	20.2	20.2	42.2	20.2	20.2	42.2	11.4	25.7	0.	16.4	1.1	3.4	0.	0.

TABLE 4-5

DAYLIGHTING SUMMARY REPORT, SOUTH ZONE OFFICE MODULE, NEW YORK. VISIBLE TRANSMITTANCE = 0.4, SHADING COEFFICIENT = 0.6, WINDOW/WALL RATIO (WWR) = 0.21. LIGHTING CONTROL IS LOCATED AT REFERENCE POINT #1, TEN FEET FROM THE WINDOW.

SPACE SOUTHZONE

	PERCENT LIGHTING ENERGY REDUCTION BY DAYLIGHTING (ALL HOURS)			PERCENT LIGHTING ENERGY REDUCTION BY DAYLIGHTING (REPORT SCHEDULE HOURS)			REPORT SCHEDULE HOURS WITH SUN UP: AVERAGE DAYLIGHT ILLUMINANCE (FOOTCANDLES)		PERCENT HOURS DAYLIGHT ILLUMINANCE ABOVE SETPOINT		AVERAGE GLARE INDEX		PERCENT HOURS GLARE TOO HIGH	
MONTH	TOTAL ZONE	REF PT 1	REF PT 2	TOTAL ZONE	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2
JAN	18.7	18.7	37.3	18.7	18.7	37.3	11.6	25.7	0.	18.4	.8	3.4	0.	0.
FEB	21.6	21.6	43.8	21.6	21.6	43.8	12.4	27.7	0.	19.7	1.0	3.7	0.	0.
MAR	26.8	26.8	56.2	26.8	26.8	56.2	14.3	32.3	0.	25.5	1.2	4.3	0.	0.
APR	24.3	24.3	50.4	24.3	24.3	50.4	13.9	31.8	0.	16.4	1.1	4.3	0.	0.
MAY	32.2	32.2	59.7	32.2	32.2	59.7	15.9	36.2	0.	26.8	1.5	4.7	0.	0.
JUN	37.4	37.4	63.7	37.4	37.4	63.7	17.8	39.7	.4	36.2	1.9	4.9	0.	0.
JUL	44.4	44.4	67.8	44.4	44.4	67.8	20.4	45.8	4.4	43.1	2.5	5.4	0.	0.
AUG	34.0	34.0	61.6	34.0	34.0	61.6	17.1	38.3	.7	25.3	1.7	5.0	0.	0.
SEP	27.3	27.3	55.6	27.3	27.3	55.6	14.7	32.1	0.	18.7	1.3	4.4	0.	0.
OCT	27.1	27.1	51.4	27.1	27.1	51.4	15.8	33.9	0.	29.8	1.4	4.4	0.	0.
NOV	21.0	21.0	40.7	21.0	21.0	40.7	12.1	26.2	0.	16.1	.9	3.4	0.	0.
DEC	17.9	17.9	33.7	17.9	17.9	33.7	11.5	24.8	0.	18.7	.9	3.0	0.	0.
ANNUAL	27.9	27.9	52.0	27.9	27.9	52.0	15.2	33.8	.6	25.5	1.4	4.3	0.	0.

TABLE 4-6

DAYLIGHT ILLUMINANCE FREQUENCY OF OCCURRENCE, NORTH ZONE. VISIBLE TRANSMITTANCE = 0.4, SHADING COEFFICIENT = 0.6, WINDOW/WALL RATIO (WWR) = 0.21. LIGHTING CONTROL IS LOCATED AT REFERENCE POINT #1, TEN FEET FROM THE WINDOW.

SPACE NORTHZONE

PERCENT OF HOURS IN ILLUMINANCE RANGE

ILLUMINANCE RANGE (FOOTCANDLES)

MONTH	REF PT	0 -- 10	-- 20	-- 30	-- 40	-- 50	-- 60	-- 70	-- 80	-ABOVE
JAN	-1-	79	21	1	0	0	0	0	0	0
	-2-	45	22	22	7	2	1	0	1	0
FEB	-1-	73	26	0	0	0	0	0	0	0
	-2-	49	17	14	13	5	2	0	0	0
MAR	-1-	58	38	4	0	0	0	0	0	0
	-2-	32	27	12	11	12	5	1	1	0
APR	-1-	44	38	17	1	0	0	0	0	0
	-2-	20	21	18	10	11	11	6	0	1
MAY	-1-	41	28	27	4	0	0	0	0	0
	-2-	21	18	14	11	11	14	4	6	1
JUN	-1-	40	21	26	12	0	0	0	0	0
	-2-	22	15	11	9	10	15	9	7	1
JUL	-1-	36	17	30	18	0	0	0	0	0
	-2-	25	5	10	7	11	16	13	10	3
AUG	-1-	31	36	27	5	0	0	0	0	0
	-2-	21	9	15	15	16	12	7	3	2
SEP	-1-	42	38	21	0	0	0	0	0	0
	-2-	23	16	19	15	12	8	4	1	0
OCT	-1-	48	45	8	0	0	0	0	0	0
	-2-	26	24	19	16	9	4	1	1	0
NOV	-1-	70	29	1	0	0	0	0	0	0
	-2-	36	26	18	15	5	1	0	0	0
DEC	-1-	84	16	0	0	0	0	0	0	0
	-2-	52	25	18	5	0	0	0	0	0
ANNUAL	-1-	51	29	15	4	0	0	0	0	0
	-2-	30	18	16	11	9	8	4	3	1

PERCENT OF HOURS ILLUMINANCE LEVEL EXCEEDED

ILLUMINANCE LEVEL (FOOTCANDLES)

MONTH	REF PT	0	10	20	30	40	50	60	70	80
JAN	-1-	100	21	1	0	0	0	0	0	0
	-2-	100	55	32	10	3	2	1	1	0
FEB	-1-	100	27	1	0	0	0	0	0	0
	-2-	100	51	33	20	7	2	0	0	0
MAR	-1-	100	42	4	0	0	0	0	0	0
	-2-	100	68	41	29	18	6	2	1	0
APR	-1-	100	56	18	1	0	0	0	0	0
	-2-	100	80	58	40	30	19	7	2	1
MAY	-1-	100	59	31	4	0	0	0	0	0
	-2-	100	79	61	47	36	25	11	7	1
JUN	-1-	100	60	39	12	0	0	0	0	0
	-2-	100	78	63	52	43	33	17	8	1
JUL	-1-	100	64	48	18	0	0	0	0	0
	-2-	100	75	69	59	53	42	26	13	3
AUG	-1-	100	69	33	5	0	0	0	0	0
	-2-	100	79	70	55	40	24	12	5	2
SEP	-1-	100	58	21	0	0	0	0	0	0
	-2-	100	77	61	42	26	14	5	1	0
OCT	-1-	100	52	8	0	0	0	0	0	0
	-2-	100	74	50	31	15	6	2	1	0
NOV	-1-	100	30	1	0	0	0	0	0	0
	-2-	100	64	38	20	5	1	0	0	0
DEC	-1-	100	16	0	0	0	0	0	0	0
	-2-	100	48	23	5	0	0	0	0	0
ANNUAL	-1-	100	49	19	4	0	0	0	0	0
	-2-	100	70	52	37	26	16	8	4	1

TABLE 4-7

DAYLIGHT ILLUMINANCE FREQUENCY OF OCCURRENCE, SOUTH ZONE. VISIBLE TRANSMITTANCE = 0.4, SHADING COEFFICIENT = 0.6, WINDOW/WALL RATIO (WWR) = 0.21. LIGHTING CONTROL IS LOCATED AT REFERENCE POINT #1, TEN FEET FROM THE WINDOW.

SPACE SOUTHZONE

		PERCENT OF HOURS IN ILLUMINANCE RANGE									PERCENT OF HOURS ILLUMINANCE LEVEL EXCEEDED								
		ILLUMINANCE RANGE (FOOTCANDLES)									ILLUMINANCE LEVEL (FOOTCANDLES)								
MONTH	REF PT	0 -- 10	-- 20	-- 30	-- 40	-- 50	-- 60	-- 70	-- 80	-ABOVE	0	10	20	30	40	50	60	70	80
JAN	-1-	50	28	16	5	0	0	0	0	0	100	50	22	5	0	0	0	0	0
	-2-	31	11	24	10	5	10	6	3	0	100	69	57	33	23	18	9	3	0
FEB	-1-	48	27	17	8	0	0	0	0	0	100	52	25	8	0	0	0	0	0
	-2-	31	13	12	14	11	9	8	3	0	100	69	56	45	31	20	11	3	0
MAR	-1-	38	28	27	7	0	0	0	0	0	100	62	34	7	0	0	0	0	0
	-2-	24	11	10	13	16	13	9	3	1	100	76	65	55	42	26	12	3	1
APR	-1-	37	44	9	8	2	0	0	0	0	100	63	19	10	2	0	0	0	0
	-2-	20	14	14	22	14	6	3	2	5	100	80	66	52	30	16	10	7	5
MAY	-1-	38	32	14	13	3	0	0	0	0	100	62	30	17	3	0	0	0	0
	-2-	21	10	15	16	11	8	5	3	10	100	79	69	54	38	27	18	13	10
JUN	-1-	38	22	15	16	8	0	0	0	0	100	62	40	25	9	0	0	0	0
	-2-	22	10	13	10	8	9	6	7	14	100	77	67	54	44	36	27	21	14
JUL	-1-	36	19	14	12	16	4	0	0	0	100	64	45	32	20	4	0	0	0
	-2-	26	5	13	4	9	10	4	6	23	100	74	70	56	52	43	33	29	23
AUG	-1-	33	27	25	8	6	1	0	0	0	100	67	40	15	7	1	0	0	0
	-2-	20	11	7	14	23	6	4	6	9	100	80	69	62	48	25	19	15	9
SEP	-1-	34	36	24	6	1	0	0	0	0	100	66	30	7	1	0	0	0	0
	-2-	23	9	11	21	17	10	4	2	2	100	77	68	57	36	19	8	5	2
OCT	-1-	34	28	24	14	0	0	0	0	0	100	66	38	14	0	0	0	0	0
	-2-	22	10	15	12	11	12	11	5	2	100	78	68	53	41	30	18	7	2
NOV	-1-	50	24	19	7	0	0	0	0	0	100	50	26	7	0	0	0	0	0
	-2-	33	11	16	13	11	7	4	3	1	100	67	56	40	27	16	9	5	1
DEC	-1-	57	20	12	10	2	0	0	0	0	100	43	23	11	2	0	0	0	0
	-2-	44	9	13	9	6	6	4	5	3	100	56	47	34	25	19	12	9	3
ANNUAL	-1-	40	28	18	10	4	1	0	0	0	100	60	32	14	4	1	0	0	0
	-2-	26	10	13	13	12	9	6	4	7	100	74	64	51	38	26	17	11	7

TABLE 4-8

AVERAGE MONTHLY/HOURLY LIGHTING ENERGY REDUCTIONS BY DAYLIGHT, NORTH ZONE. VISIBLE TRANSMITTANCE = 0.4, SHADING COEFFICIENT = 0.6, WINDOW/WALL RATIO (WWR) = 0.21. LIGHTING CONTROL IS LOCATED AT REFERENCE POINT #1, TEN FEET FROM THE WINDOW.

SPACE NORTHZONE

MONTH	HOUR OF DAY 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	ALL HOURS
JAN	0	0	0	0	0	0	0	0	6	10	15	17	19	16	12	7	1	0	0	0	0	0	0	0	9
FEB	0	0	0	0	0	0	0	4	8	13	17	20	22	18	15	10	5	0	0	0	0	0	0	0	11
MAR	0	0	0	0	0	0	2	13	18	22	24	26	26	24	22	19	13	3	0	0	0	0	0	0	17
APR	0	0	0	0	0	12	24	33	29	29	35	32	29	27	22	17	9	0	0	0	0	0	0	0	21
MAY	0	0	0	0	2	13	36	37	36	32	31	36	36	33	30	24	15	4	0	0	0	0	0	0	27
JUN	0	0	0	0	4	19	43	40	41	40	44	41	39	36	31	26	17	6	0	0	0	0	0	0	31
JUL	0	0	0	0	1	9	33	40	44	45	48	48	46	44	43	39	32	16	1	0	0	0	0	0	37
AUG	0	0	0	0	0	5	23	36	38	39	41	40	39	35	32	26	17	6	0	0	0	0	0	0	29
SEP	0	0	0	0	0	4	23	31	32	31	34	30	31	27	19	13	3	0	0	0	0	0	0	0	22
OCT	0	0	0	0	0	0	10	22	25	28	30	29	25	21	14	7	0	0	0	0	0	0	0	0	17
NOV	0	0	0	0	0	0	1	10	15	21	26	23	20	16	9	2	0	0	0	0	0	0	0	0	12
DEC	0	0	0	0	0	0	0	6	12	15	18	16	15	12	5	0	0	0	0	0	0	0	0	0	8
ANNUAL	0	0	0	0	1	6	21	29	26	27	30	29	29	26	22	16	8	2	0	0	0	0	0	0	20

NOTE- THE ENTRIES IN THIS REPORT ARE NOT
SUBJECT TO THE DAYLIGHTING REPORT SCHEDULE

TABLE 4-9

AVERAGE MONTHLY/HOURLY LIGHTING ENERGY REDUCTIONS BY DAYLIGHT, SOUTH ZONE. VISIBLE TRANSMITTANCE = 0.4, SHADING COEFFICIENT = 0.6, WINDOW/WALL RATIO (WWR) = 0.21. LIGHTING CONTROL IS LOCATED AT REFERENCE POINT #1, TEN FEET FROM THE WINDOW.

SPACE SOUTHZCNE

HCUF OF DAY

MONTH	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	ALL HOURS
JAN	0	0	0	0	0	0	0	1	15	28	33	33	35	32	29	14	2	0	0	0	0	0	0	0	19
FEB	0	0	0	0	0	0	0	5	20	31	36	37	41	32	29	20	8	0	0	0	0	0	0	0	22
MAR	0	0	0	0	0	0	2	24	29	33	38	44	43	37	31	28	21	4	0	0	0	0	0	0	27
APR	0	0	0	0	0	10	24	41	36	29	35	33	33	31	31	23	11	0	0	0	0	0	0	0	24
MAY	0	0	0	0	1	16	30	41	49	38	36	42	40	42	41	30	15	3	0	0	0	0	0	0	32
JUN	0	0	0	0	3	18	32	39	49	53	59	45	52	50	39	30	16	4	0	0	0	0	0	0	37
JUL	0	0	0	0	1	8	24	40	53	59	65	61	52	59	59	47	32	12	1	0	0	0	0	0	44
AUG	0	0	0	0	0	5	22	42	52	46	42	38	40	39	44	35	19	5	0	0	0	0	0	0	34
SEP	0	0	0	0	0	4	26	41	35	38	39	40	36	33	25	24	4	0	0	0	0	0	0	0	27
OCT	0	0	0	0	0	0	13	33	42	44	45	44	40	29	23	16	0	0	0	0	0	0	0	0	27
NOV	0	0	0	0	0	0	1	16	35	39	42	39	32	28	22	5	0	0	0	0	0	0	0	0	21
DEC	0	0	0	0	0	0	0	7	26	37	40	37	31	24	15	0	0	0	0	0	0	0	0	0	18
ANNUAL	0	0	0	0	0	6	19	33	37	40	43	41	40	37	32	23	10	2	0	0	0	0	0	0	28

NOTE- THE ENTRIES IN THIS REPORT ARE NOT SUBJECT TO THE DAYLIGHTING REPORT SCHEDULE

TABLE 4-10

REGRESSION COEFFICIENTS FOR NEW YORK FOR ZONE HEATING ENERGY, ZONE COOLING ENERGY, ZONE COOLING PEAK, ZONE TOTAL ELECTRICITY ZONE TOTAL ANNUAL ENERGY, BUILDING ELECTRICITY, BUILDING PEAK ELECTRIC DEMAND, AND BUILDING TOTAL FUEL. THE "BUILDING" FIGURES APPLY TO A TYPICAL FLOOR MODULE WITH A CORE OF 10,000 FT^2 AND FOUR PERIMETER ZONES OF 1500 FT^2 EACH. VERTICAL GLAZING AND SKYLIGHT COEFFICIENTS CAN BE USED WITH EQ. 1; THE DAYLIGHT CORRECTION FACTORS APPLY TO EQ. 2.

NOTE: FOR COEFFICIENTS PROVIDED IN TABLES 4-10 AND 4-11 THE FOLLOWING UNITS ARE APPLICABLE TO THE REGRESSION EQUATIONS:

COOLING PEAK:	BTU/HR
COOLING, HEATING AND ELECTRICITY ENERGY:	KBTU
U_o:	$BTU/HR\text{-}FT^2\text{-}^oF$
A_t, A_g, A_p, A_c:	ft^2
L:	W/ft^2
MEAN (COOLING PEAK):	KBTU/hr
MEAN (COOLING/HEATING ENERGY):	MBTU

NEW YORK PERIMETER VERTICAL GLAZING

		Zone Heating-Annual (Efficiency=.6)	Zone Cooling-Annual (COP = 3.0)	Zone Cooling Peak-Annual (COP = 3.0)	Zone Total Electricity (COP = 3.0)	Zone Total Energy-Annual (COP = 3.0) (Heating Eff.=.6)	Building Site Electricity Total	Building Site Electricity Peak	Building Site Fuel Total
$b_1(U_oA_T)$	N	108.42	-1.21	6.50	18.501	126.94	--	--	--
	S	77.63	-0.0029	8.18	10.075	87.72	--	--	--
	E	83.69	1.12	13.21	18.283	101.99	--	--	--
	W	100.84	-0.77	9.12	12.969	113.83	--	--	--
Module		--	--	--	--	--	24.87	8.88	121.62
$b_2(A_gSC)$	N	-27.35	16.04	20.15	21.516	-5.84	--	--	--
	S	-50.82	26.17	56.21	41.931	-8.90	--	--	--
	E	-46.08	29.48	61.10	46.230	0.14	--	--	--
	W	-38.75	22.50	46.11	34.818	-3.94	--	--	--
Module		--	--	--	--	--	47.17	26.53	-48.61
$b_3(A_fL_p)$	N	-4.54	1.36	0.95	9.947	5.40	--	--	--
	S	-3.12	1.39	0.92	10.287	7.17	--	--	--
	E	-3.45	1.37	0.74	9.939	6.49	--	--	--
	W	-4.06	1.39	0.89	10.169	6.11	--	--	--
Module		--	--	--	--	--	10.30	3.95	-3.17
$b_4(A_f)$		19.68	1.38	3.51	9.667	29.35	--	--	--
Module		--	--	--	--	--	12.40	5.67	16.64
Mean		34.782	10.666	16.337	51.956	86.74	545.358	230.550	262.746
R^2		0.972	0.985	0.980	0.981	0.939	0.995	0.998	0.971
σ		1.992	0.580	0.803	1.995	2.998	10.275	2.727	11.067

Daylight Correction Factor - Windows

	b_5 (Ea)	b_6 (Ea^2)
N	4.17	-7.36
S	5.61	-12.74
E	4.85	-10.01
W	4.68	-9.02
All Zones	4.83	-9.79

HORIZONTAL SKYLIGHTS

$b_1(U_oA_T)$	93.53	0.11	6.74	--	--	20.14	7.55	83.56
$b_2(A_gSC)$	-56.18	54.59	67.22	--	--	48.25	50.94	-49.33
$b_3(A_fL_p)$	-1.89	1.24	1.02	--	--	10.31	3.88	-2.038
$b_4(A_f)$	15.64	1.55	2.98	--	--	13.01	5.62	14.33
Mean	194.419	46.248	65.065	--	--	333.20	137.90	176.10
R^2	0.989	0.999	0.999	--	--	0.9994	0.9998	0.9760
σ	4.861	0.416	0.394	--	--	2.176	0.4292	4.654

Daylight Correction Factor - Skylights b_5 (Ea) 44.66 b_6 (Ea^2) -731.12

TABLE 4-11

REGRESSION COEFFICIENTS FOR ALBANY FOR ZONE HEATING ENERGY, ZONE COOLING ENERGY, ZONE COOLING PEAK, ZONE TOTAL ELECTRICITY ZONE TOTAL ANNUAL ENERGY, BUILDING ELECTRICITY, BUILDING PEAK ELECTRIC DEMAND, AND BUILDING TOTAL FUEL. THE "BUILDING" FIGURES APPLY TO A TYPICAL FLOOR MOULE WITH A CORE OF 10,000 FT^2 AND FOUR PERIMETER ZONES OF 1500 FT^2 EACH. VERTICAL GLAZING AND SKYLIGHT COEFFICIENTS CAN BE USED WITH EQ. 1; THE DAYLIGHT CORRECTION FACTORS APPLY TO EQ. 2.

ALBANY

PERIMETER ZONE VERTICAL GLAZING

	Zone Heating-Annual (Efficiency=.6)	Zone Cooling-Annual (COP = 3.0)	Zone Cooling Peak-Annual (COP = 3.0)	Zone Total Electricity (COP = 3.0)	Zone Total Energy-Annual (COP = 3.0) (Heating Eff.=.6)	Building Site Electricity Total	Building Site Electricity Peak	Building Site Fuel Total
$b_1(U_oA_T)$ N	167.450	-3.000	4.069	24.654	192.137	--	--	--
S	126.688	-1.943	7.548	14.093	140.806	--	--	--
E	146.752	-2.214	9.061	19.362	166.144	--	--	--
W	152.100	-2.722	7.822	18.217	170.350	--	--	--
Module	--	--	--	--	--	30.143	7.074	187.765
$b_2(A_gSC)$ N	-31.733	13.855	13.779	11.925	-19.814	--	--	--
S	-56.220	24.061	28.873	30.798	-25.433	--	--	--
E	-48.660	23.569	27.391	31.345	-17.325	--	--	--
W	-50.465	24.466	29.998	36.375	-14.100	--	--	--
Module	--	--	--	--	--	36.413	21.333	-59.370
$b_3(A_fL_p)$ N	-5.403	1.159	1.058	9.713	4.309	--	--	--
S	-3.948	1.207	1.028	10.050	6.100	--	--	--
E	-4.565	1.199	0.981	9.826	5.260	--	--	--
W	-4.597	1.192	1.000	9.794	5.197	--	--	--
Module	--	--	--	--	--	10.160	4.034	-3.436
$b_4(A_f)$	19.118	1.311	3.605	9.422	28.543	--	--	--
Module	--	--	--	--	--	12.105	5.670	15.511
Mean	38.258	8.829	14.995	49.336	87.603	527.539	262.572	262.993
R^2	0.975	0.986	0.981	0.984	0.942	0.995	0.998	0.973
σ	2.362	0.504	0.678	1.737	3.402	9.747	2.300	12.951

Daylight Correction Factor - Windows

b_5 (Ea)	N	4.805
	S	5.843
	E	5.301
	W	5.274
All Zones		5.306
b_6 (Ea^2)	N	-8.710
	S	-13.033
	E	-10.780
	W	-10.627
All Zones		-10.788

HORIZONTAL SKYLIGHTS

	Zone Heating-Annual (Efficiency=.6)	Zone Cooling-Annual (COP = 3.0)	Zone Cooling Peak-Annual (COP = 3.0)	Zone Total Electricity (COP = 3.0)	Zone Total Energy-Annual (COP = 3.0) (Heating Eff.=.6)	Building Site Electricity Total	Building Site Electricity Peak	Building Site Fuel Total
$b_1(U_oA_T)$	166.382	-1.543	9.195	--	--	25.640	6.249	151.300
$b_2(A_gSC)$	-69.485	56.404	75.925	--	--	43.340	60.520	-64.390
$b_3(A_fL_p)$	-2.525	1.053	1.077	--	--	10.080	3.925	-2.395
$b_4(A_f)$	13.652	1.277	2.729	--	--	13.020	5.689	12.880
Mean	180.158	39.624	64.338	--	--	324.400	137.900	166.600
R^2	0.982	0.999	0.999	--	--	0.9995	0.9999	0.9778
σ	5.158	0.411	0.447	--	--	1.989	.401	5.258

Daylight Correction Factor - Skylights

b_5 (Ea) 48.468

b_6 (Ea^2) -800.387

TYPICAL ELECTRICITY RATES FOR NEW YORK CITY.

Con Edison

Current Electricity Rates

Service Classification No. 9 (Electric)
General/Large
Effective September 23, 1983

Monthly Rate (WINTER)

Demand Charge	Low Tension Service	High Tension Service
First 5 kw (or Less)	$76 14	$64 72
Next 895 kw	$16 64 per kw	$14 14 per kw
Over 900 kw	$14.46 per kw	$12 29 per kw

Energy Charge	Low Tension Service	High Tension Service
First 15.000 kwhr	7.13¢ per kwhr	6 63¢ per kwhr
Over 15.000 kwhr	6.74¢ per kwhr	6 27¢ per kwhr

Monthly Rate (SUMMER)

Demand Charge	Low Tension Service	High Tension Service
First 5 kw (or Less)	$98 64	$87 22
Next 895 kw	$21 14 per kw	$18 64 per kw
Over 900 kw	$18 96 per kw	$16 79 per kw

Energy Charge	Low Tension Service	High Tension Service
First 15.000 kwhr	7.13¢ per kwhr	6 63¢ per kwhr
Over 15.000 kwhr	6.74¢ per kwhr	6 27¢ per kwhr

Winter and Summer Billing Periods
The summer period is defined as the four-month period from June 1 to September 30. The winter billing period is the balance of the year. When a bill includes periods both before and after the summer billing period, the rates and charges applicable will be prorated based on the number of days in the winter billing period and the number of days in the summer billing period related to the total number of days in the billing period.

See **SPECIAL PROVISION D** which applies to customers whose space heating requirements are supplied exclusively by electricity.

Maximum Rate
Whenever the application of the foregoing demand and energy charges to the customer's use in a given monthly period results in a rate per kwhr in excess of 34.70 cents, an amount equal to 34.70 cents per kwhr will be billed in lieu thereof, except where such 34.70 cents rate would result in a reduction in the minimum charge otherwise applicable.

Fuel Adjustment
As the cost of fuel we use to produce electricity changes, your bill is adjusted accordingly. The factor, expressed as ¢ per kwhr, and the amount of the fuel adjustment included in the total charges are shown on the face of the bill.

Gross Receipts Tax Charge*
We are taxed on our revenues from the sales of electricity. Your bill includes a charge computed at the rate in your community as shown below.

Yonkers..... (NY State 3.75%; Yonkers 3%).................. 6.75%
New York City..... (NY State 3.75%; New York City 2.35%) 6.10%
The cities of Mount Vernon, New Rochelle, Peekskill, Rye and White Plains; the villages of Ardsley, Bronxville, Croton-on-Hudson, Dobbs Ferry, Elmsford, Hastings-on-Hudson, Irvington, Larchmont, Mamaroneck, Mount Kisco, North Tarrytown, Ossining, Pelham, Pelham Manor, Pleasantville, Port Chester, Rye Brook, Scarsdale, Tarrytown, Tuckahoe ..... (NY State 3.75%; local 1%) 4.75%
All other Westchester municipalities do not impose a local tax and are subject only to the New York State rate ... 3.75%

*Effective April 1, 1983, gross receipts tax totals increased by 0.68 percent for the MTA surcharge to support mass transit.

Sales Tax
We are required to collect any applicable sales taxes, and these taxes are added to your bill.

Partial Sales Tax Exemptions for Some Commercial Customers
New York State and some localities in Westchester exempt residential energy use from sales taxes. Residential customers automatically qualify for such an exemption and are billed accordingly by us. In addition, certain commercial customers who use a portion of their service for residential purposes may be eligible for a reduced tax based on the percentage of residential use. In order to qualify, an Exemption Certificate (Form TP-385), which also explains the necessary qualifications, must be completed and submitted to Con Edison. You may obtain this certificate by contacting any New York State District Tax Office or from the main office of the Sales Tax Bureau, State Campus, Albany, New York 12227.

Minimum Monthly Charge— Low Tension
For 5 kw of demand, $76.14 during the winter period; $98.64 during the summer period, plus adjustments related to our fuel costs and the taxes as discussed above.

Minimum Monthly Charge— High Tension
For 5 kw of demand, $64.72 during the winter period; $87.22 during the summer period, plus adjustments related to our fuel costs and the taxes as discussed above.

TABLE 4-13

REGRESSION COEFFICIENTS FOR PSEG BUILDING WITh VAV AND FPIU SYSTEMS FOR ANNUAL HEATING ENERGY, ANNUAL COOLING ENERGY, PEAK COOLING LOAD, ANNUAL ELECTRICITY CONSUMPTION, AND TOTAL ANNUAL ENERGY USE. THE DAYLIGHT CORRECTION FACTORS CAN BE USED FOR BOTH SYSTEMS.

NEW YORK - PSEG/ BUILDING WITH VAV SYSTEMS

REGRESSION COEFFICIENTS

	Building Heating-Annual (Heat eff. = .6)	Building Cooling-Annual (COP = 3.0)	Building Cooling Peak-Annual (COP = 3.0)	Building Total Elec.-Annual (COP = 3.0)	Building Site Total Energy COP = 3.0 (Heat eff. = .6)
b_1 (U_oA_T)	138.923	3.596	5.309	14.417	153.368
b_2 (A_gSC)	7.048	22.826	37.075	44.116	51.166
b_3 (A_fL_p)	-6.970	0.574	0.776	.922	-6.049
b_4 (A_f)	15.003	1.781	3.375	3.338	18.344
Mean	29,987.74	1930.204	3160.072	4005.286	12,419.411
R^2	0.986	0.981	0.974	0.970	0.956
σ	1147.04	109.084	204.002	265.800	660.175

DAYLIGHTING CORRECTION FACTOR

REGRESSION COEFFICIENTS

b_5 (E_a) = 4.58

b_6 (E_a^2) = -7.298

NEW YORK - PSEG/ BUILDING WITH FPIU SYSTEMS

REGRESSION COEFFICIENTS

	Building Heating-Annual (Heat eff. = .6)	Building Cooling-Annual (COP = 3.0)	Building Cooling Peak-Annual (COP = 3.0)	Building Total Elec.-Annual (COP = 3.0)	Building Site Total COP = 3.0 (Heat eff. = .6)
b_1 (U_oA_T)	312.990	15.985	16.444	103.641	416.693
b_2 (A_gSC)	-125.842	25.096	17.150	20.070	-105.797
b_3 (A_fL_p)	-10.808	0.485	0.302	-1.061	-11.871
b_4 (A_f)	59.122	6.512	7.303	28.980	88.113
Mean	18,665.43	4009.55	3759.20	13187.84	31,857.0
R^2	0.985	0.901	0.963	0.926	0.974
σ	843.986	299.936	126.033	488.614	1273.743

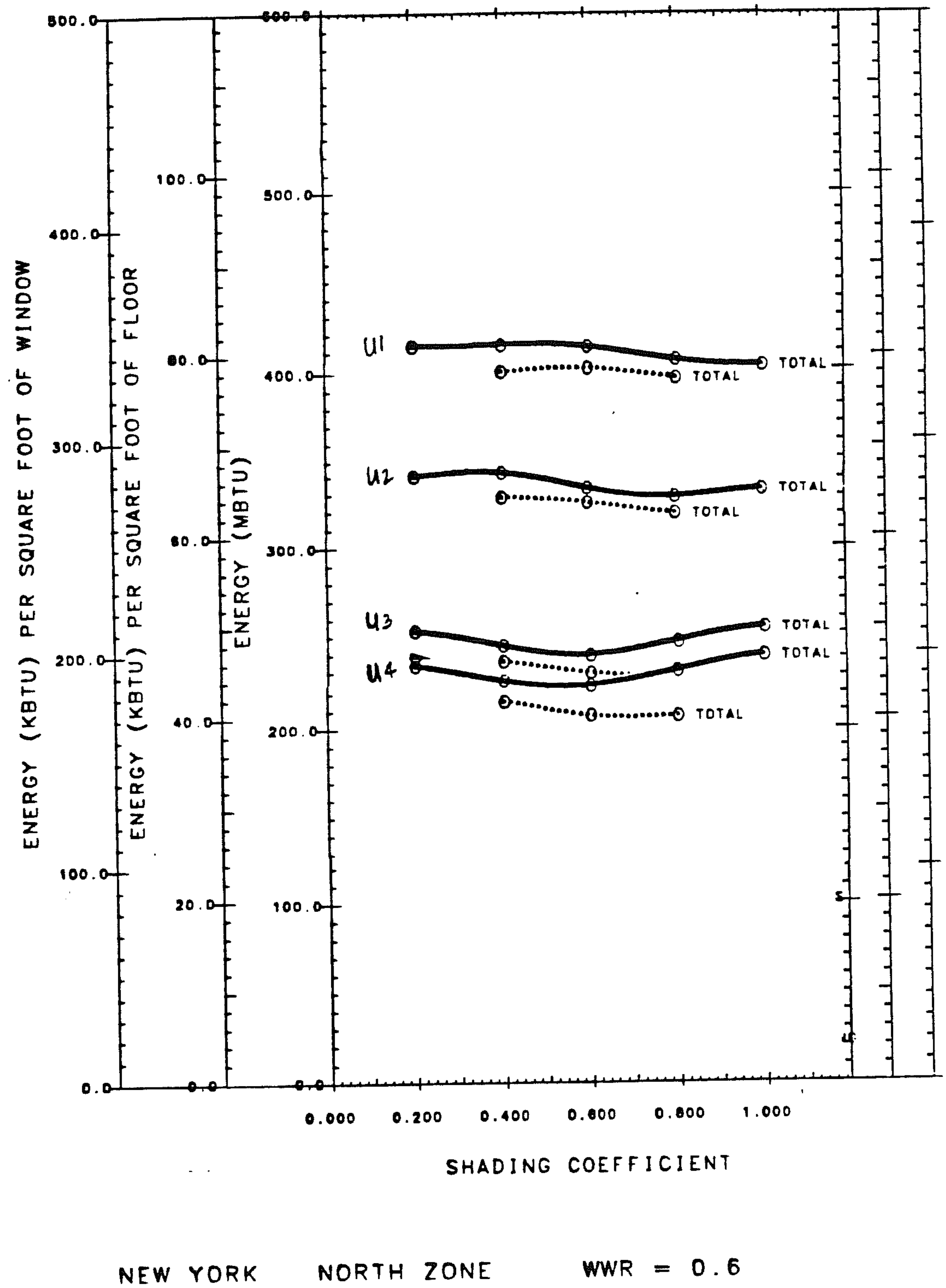
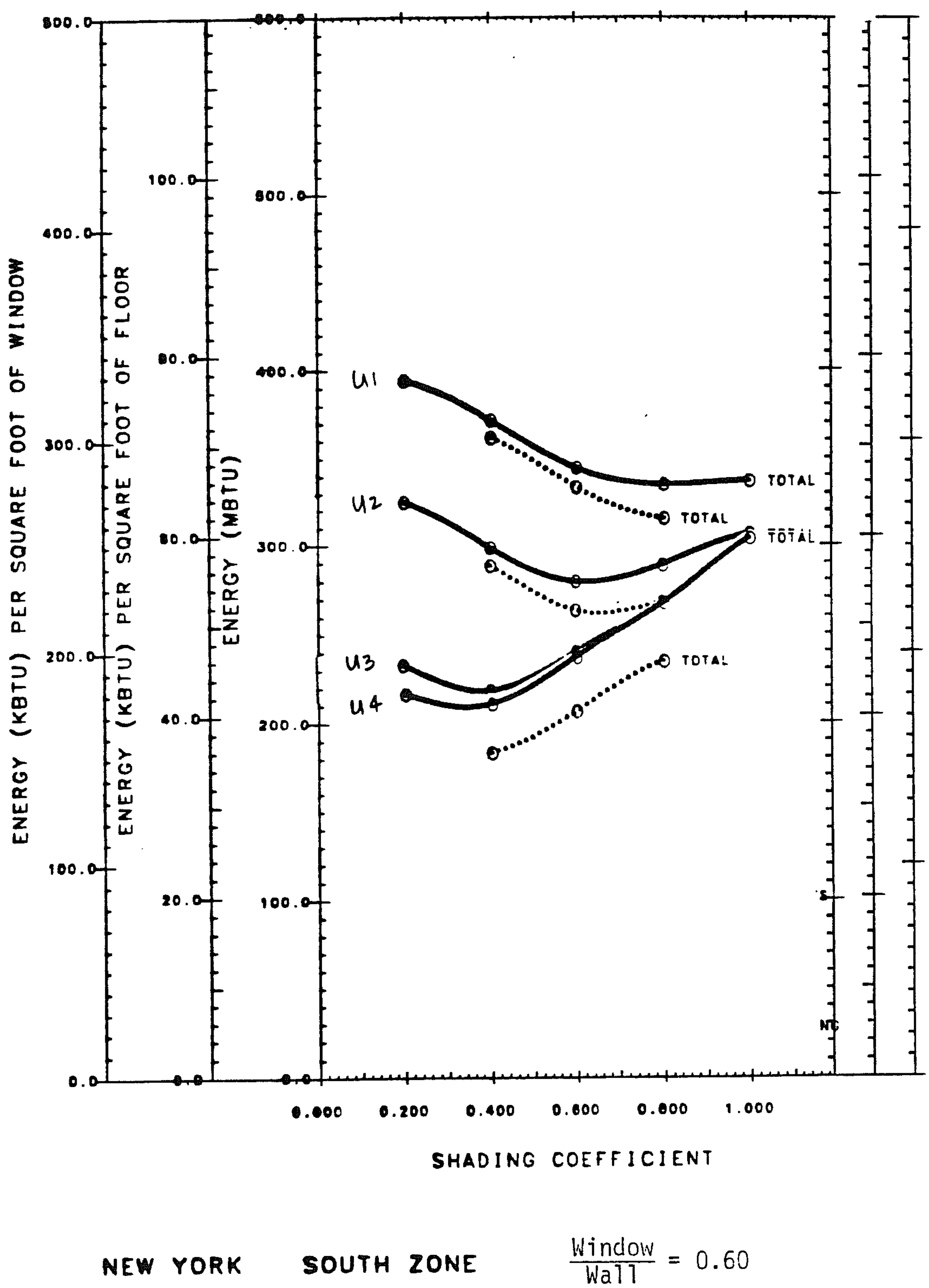


Figure 4-1. Annual energy requirements for an office module in New York City with (---------) and without (————) daylight utilization as a function of window shading coefficient and U-value for window/wall ratio = 0.6, lighting power density = 2 W/ft^2.



$\frac{\text{Window}}{\text{Wall}} = 0.60$

Figure 4-2. Annual energy requirements for an office module in New York City with (---------) and without (————) daylight utilization as a function of window shading coefficient and U-value for window/wall ratio = 0.6, lighting power density = 2 W/ft^2.

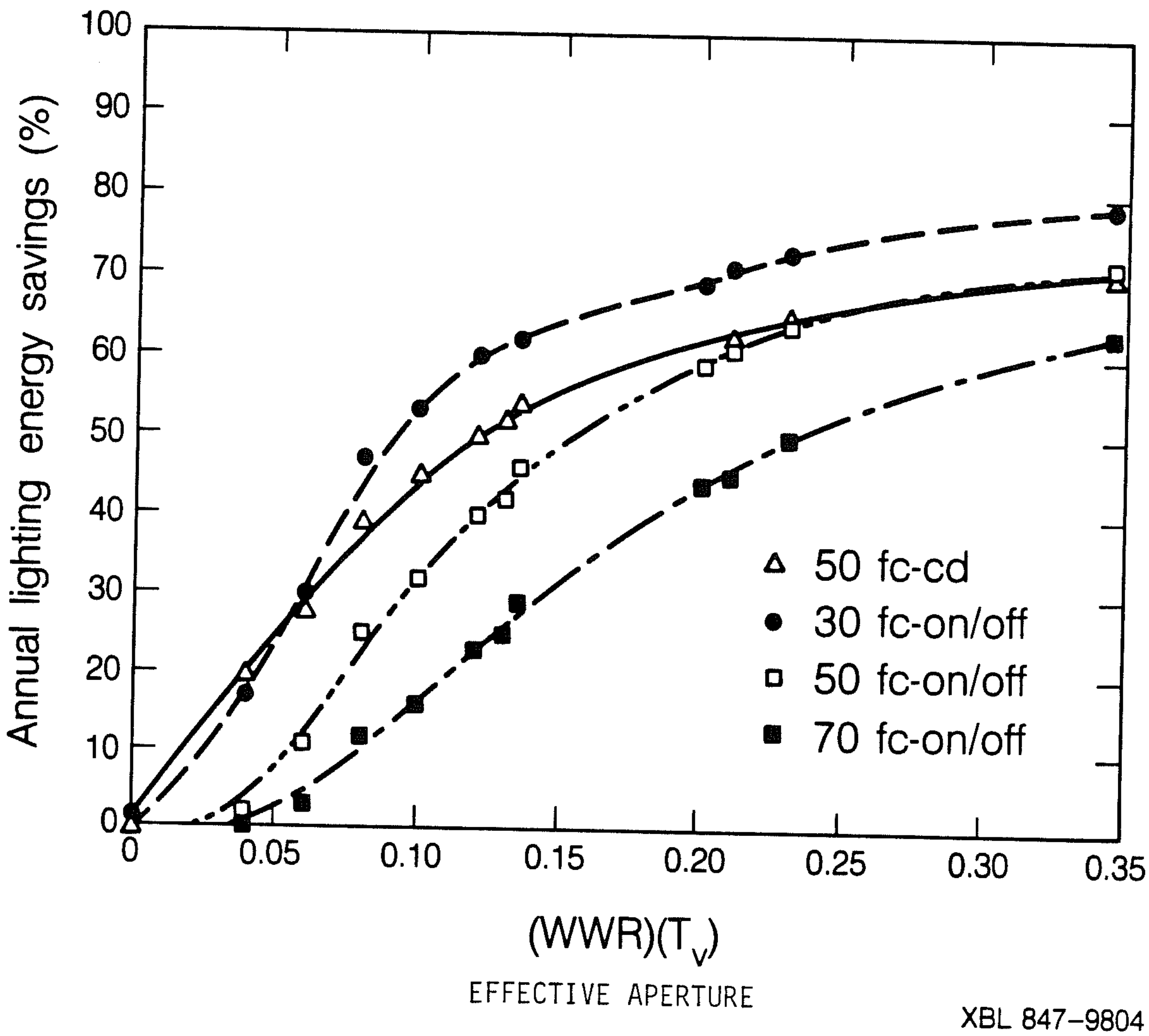


Figure 4-3. Annual lighting energy savings in "Albany" vs. effective aperture as a function of lighting control type (on/off = switching, cd = continuous dimming), and illuminance setpoint (30, 50, or 70 fc).

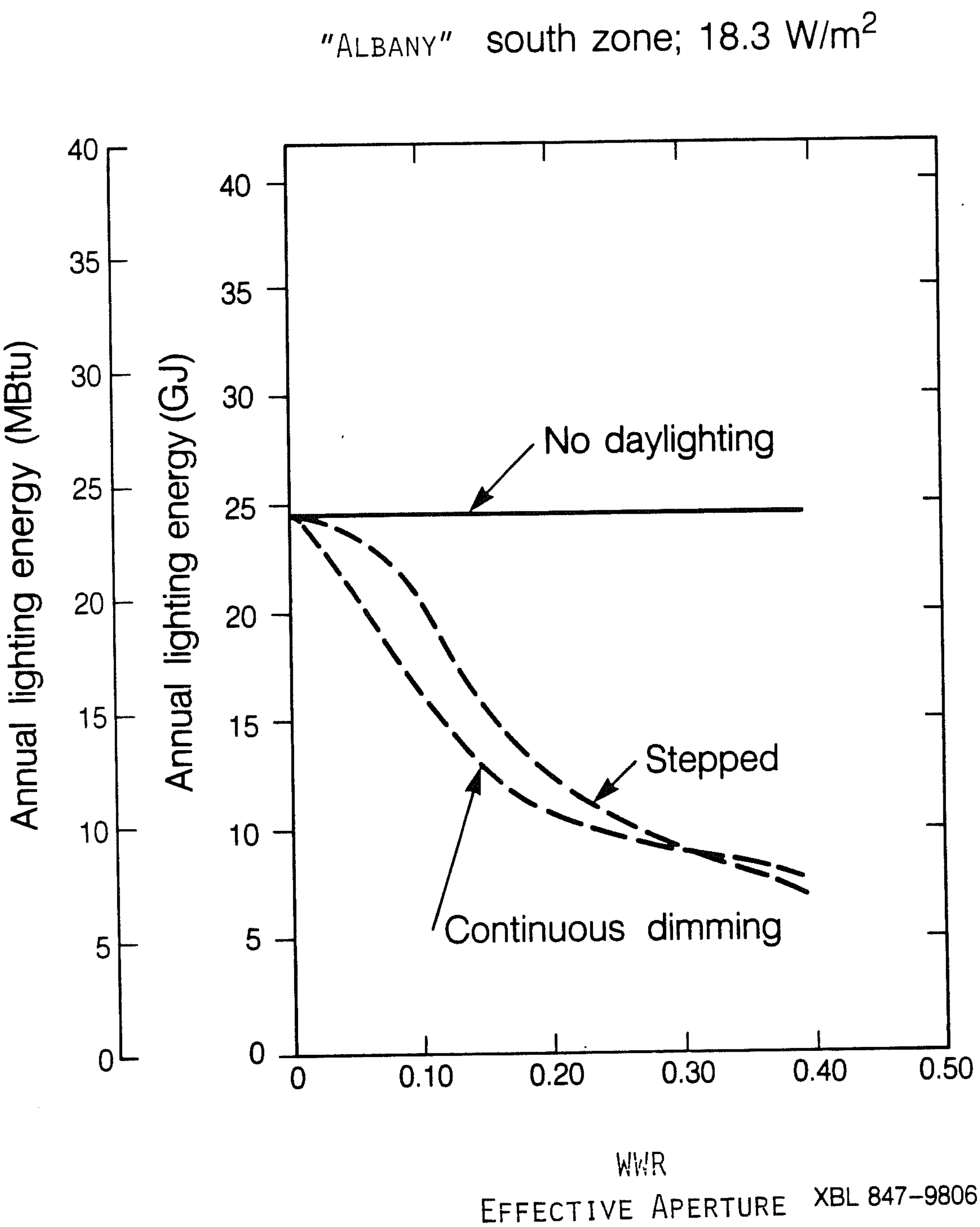


Figure 4-4. Annual lighting energy vs. effective aperture for stepped switching and continuous dimming control; for a south office module in "Albany", with installed lighting power density of 18.3 W/m^2.

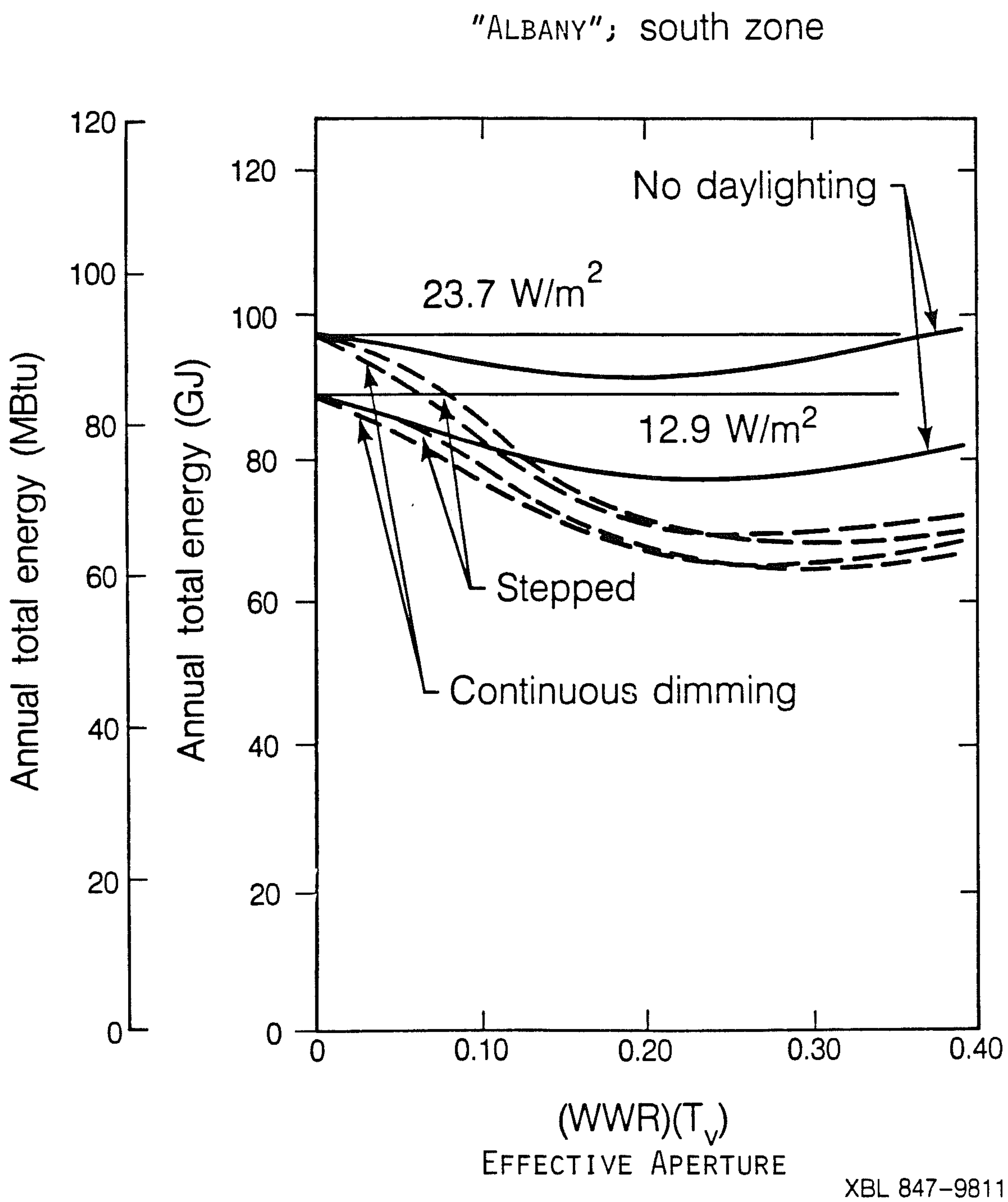


Figure 4-5. Annual total energy use as a function of effective aperture for a south perimeter zone, "Albany", with installed lighting power density of 23.7 W/m^2 (2.2 W/ft^2) and 12.9 W/m^2 (1.2 W/ft^2).

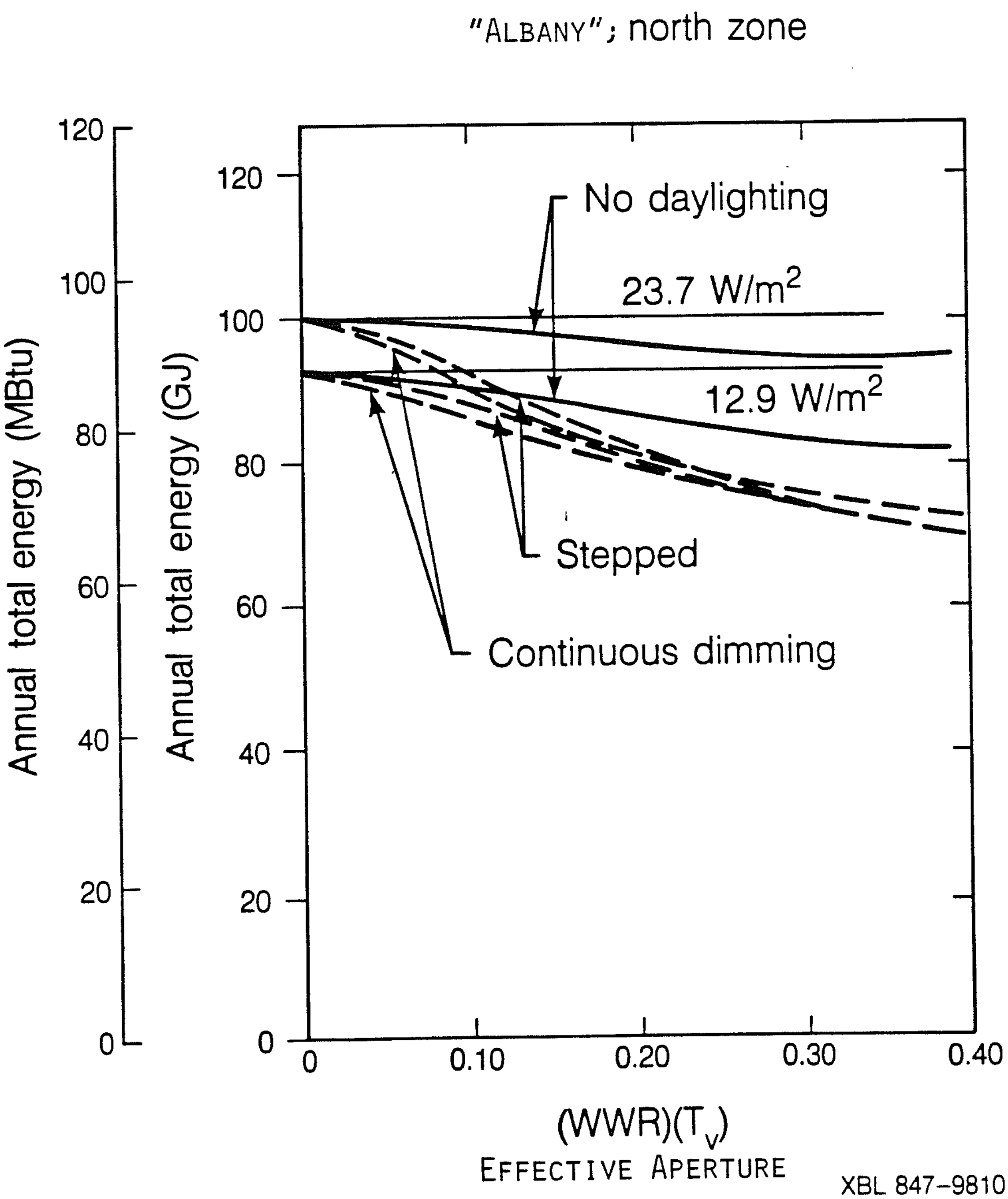


Figure 4-6. Annual total energy use as a function of effective aperture for a north perimeter zone, "Albany", with installed lighting power density of 23.7 W/m^2 (2.2 W/ft^2) and 12.9 W/m^2 (1.2 W/ft^2).

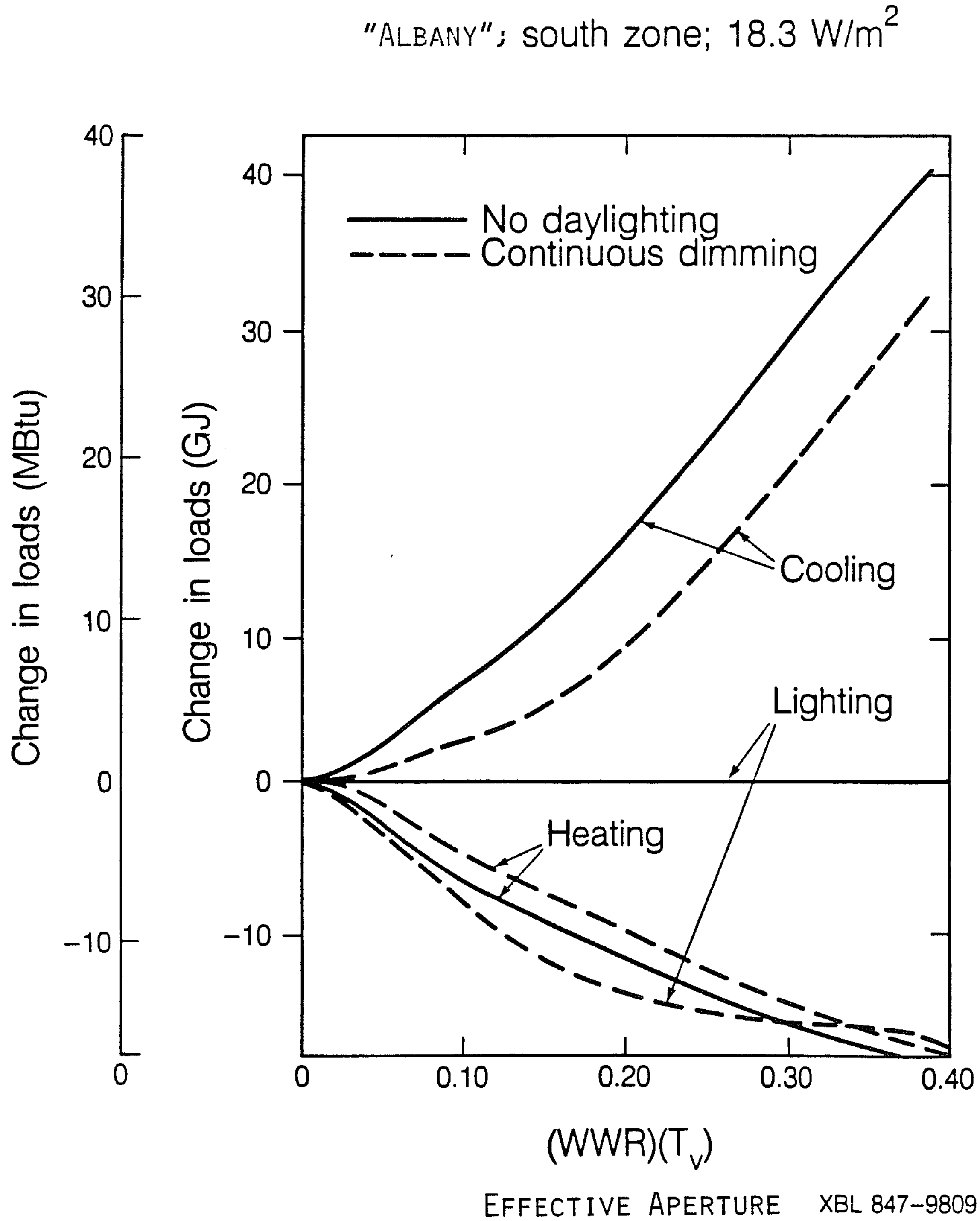


Figure 4-7. Changes in annual zone load components as a function of effective aperture, south zone, "Albany", with installed lighting power density of 18.3 W/m^2 (1.7 W/ft^2).

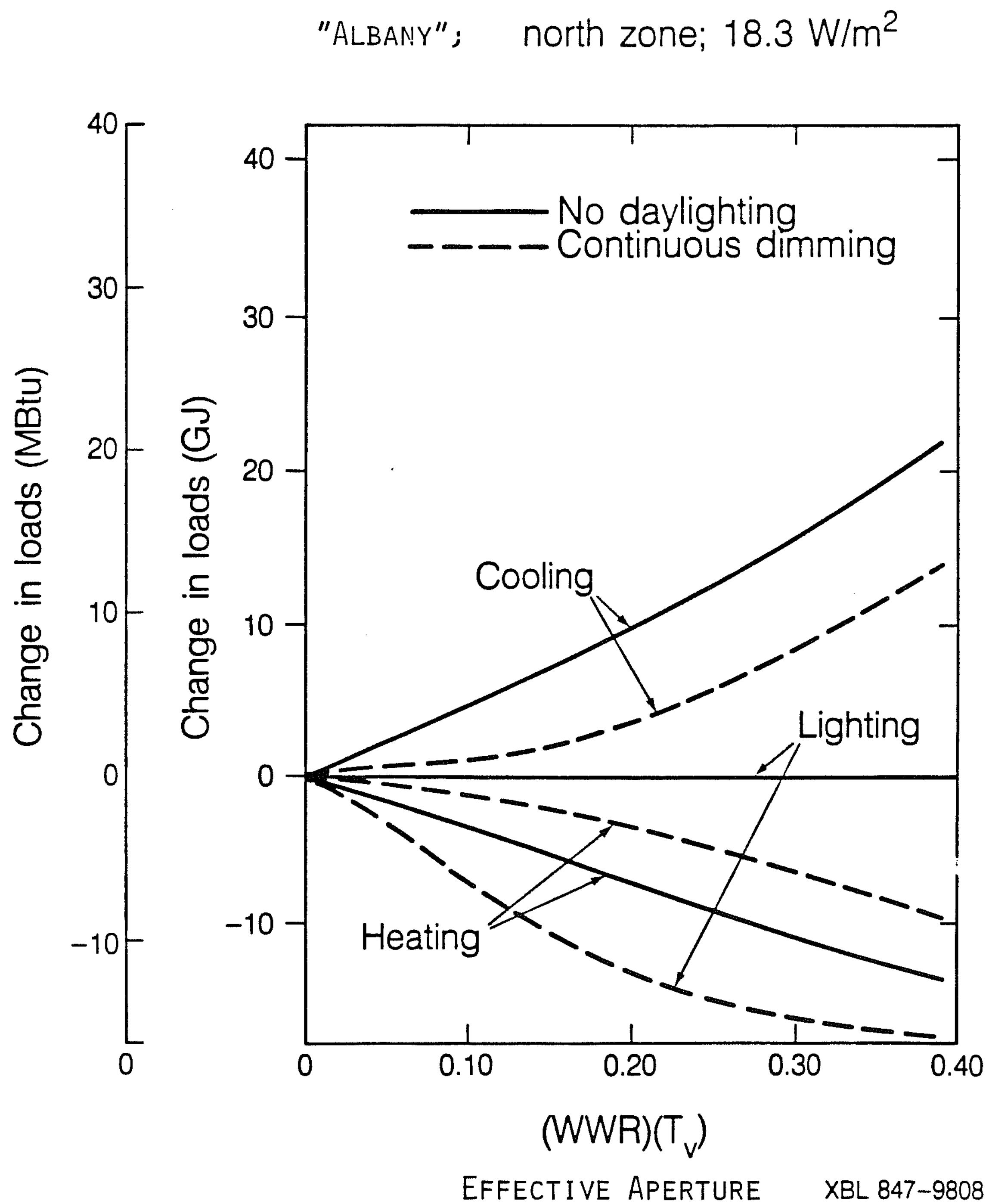


Figure 4-8. Changes in annual zone load components as a function of effective aperture, north zone, "Albany", with installed lighting power density of 18.3 W/m^2 (1.7 W/ft^2).

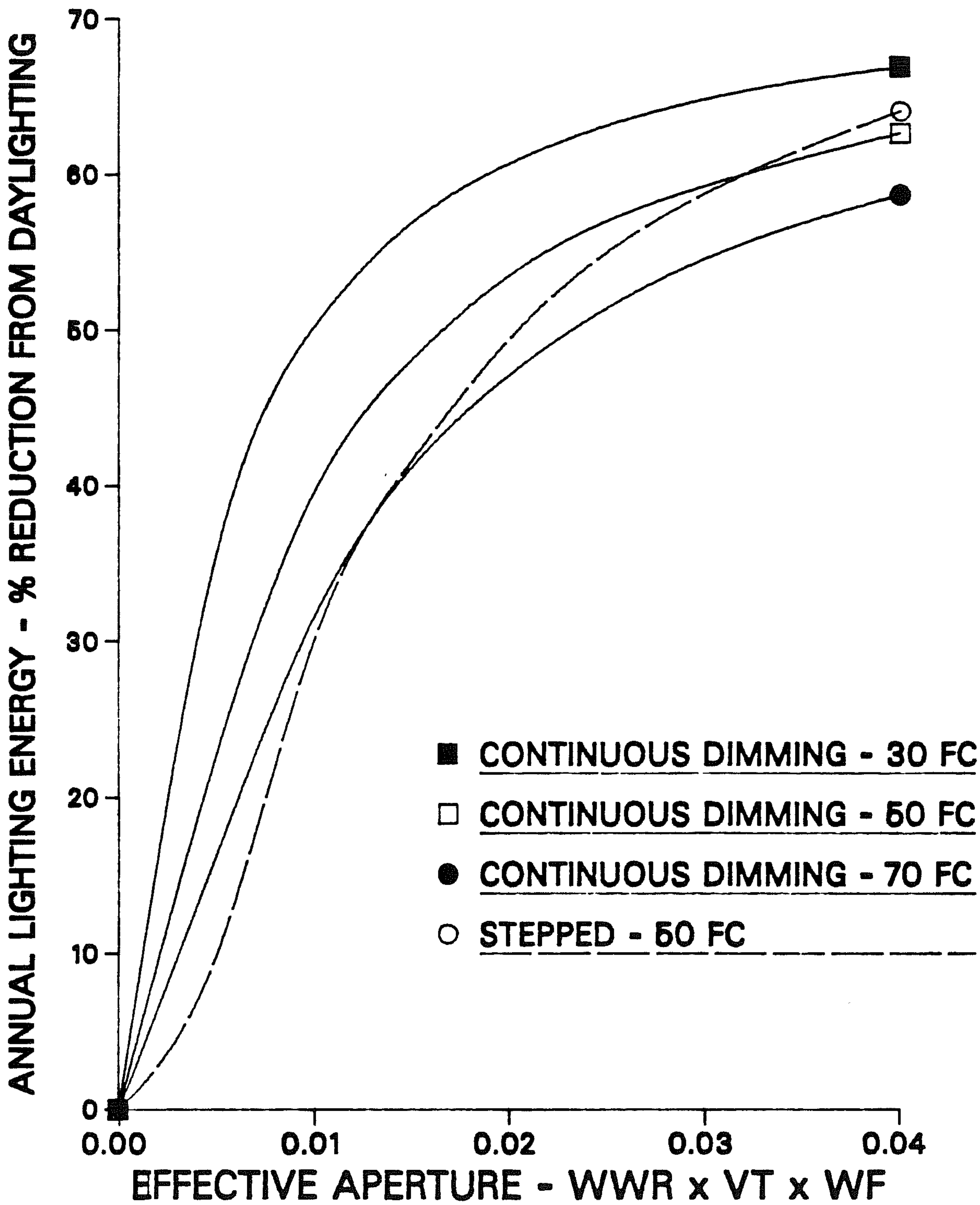


Figure 4-9. Reduction in annual lighting energy vs. effective aperture in a skylighted building in New York City, as a function of lighting control type and illuminance setpoint with installed lighting power density of 1.7 W/ft^2. (For this figure, SC = 0.8, and U_{roof} = 0.084 Btu/hr-ft^2-F^o.)

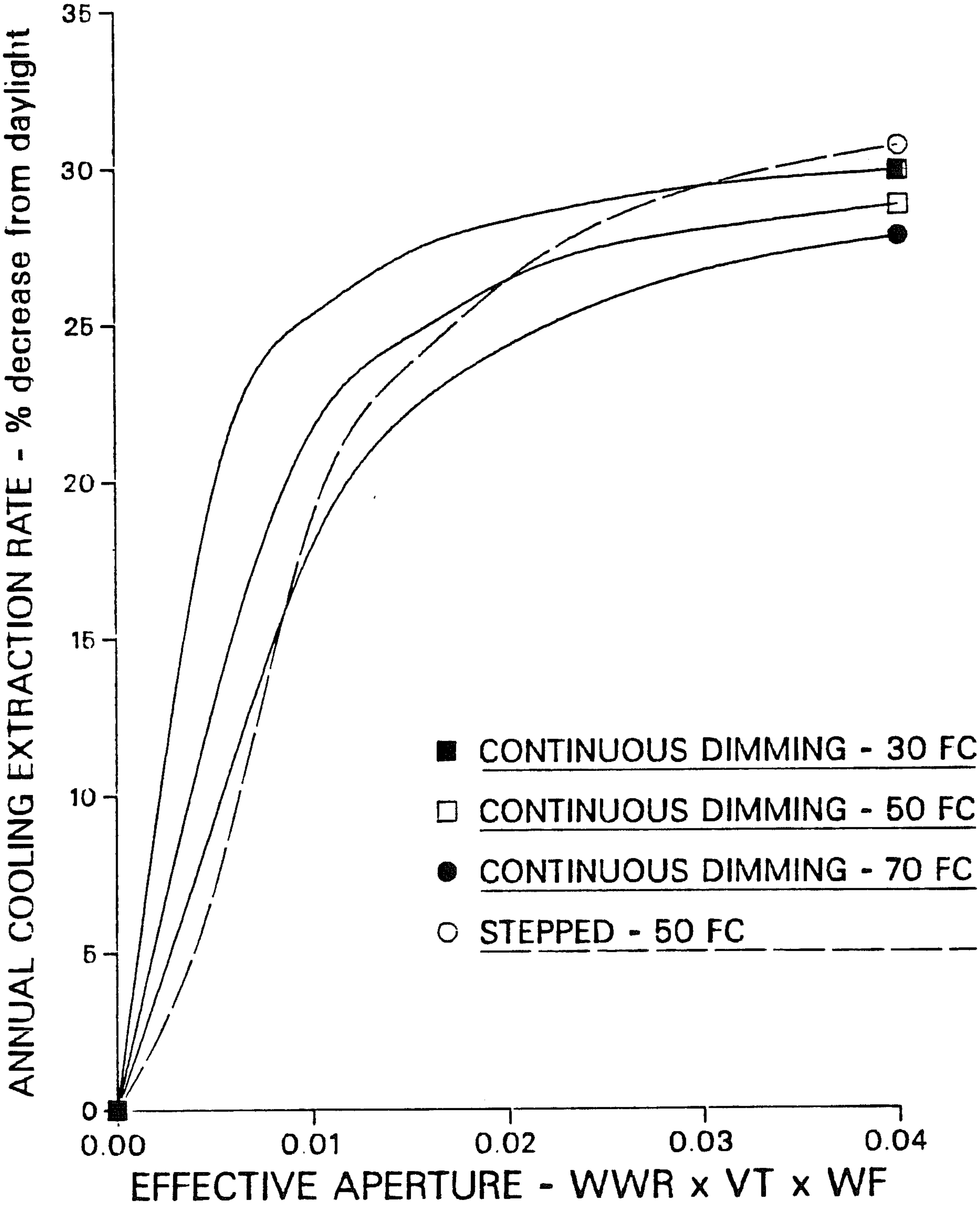


Figure 4-10. Reduction in annual cooling extraction rate vs. effective aperture in a skylighted building in New York City, as a function of lighting control type and illuminance setpoint with installed lighting power density of 1.7 W/ft^2. (For this figure, SC = 0.8, and U_{roof} = 0.084 Btu/hr-ft^2-F^o.)

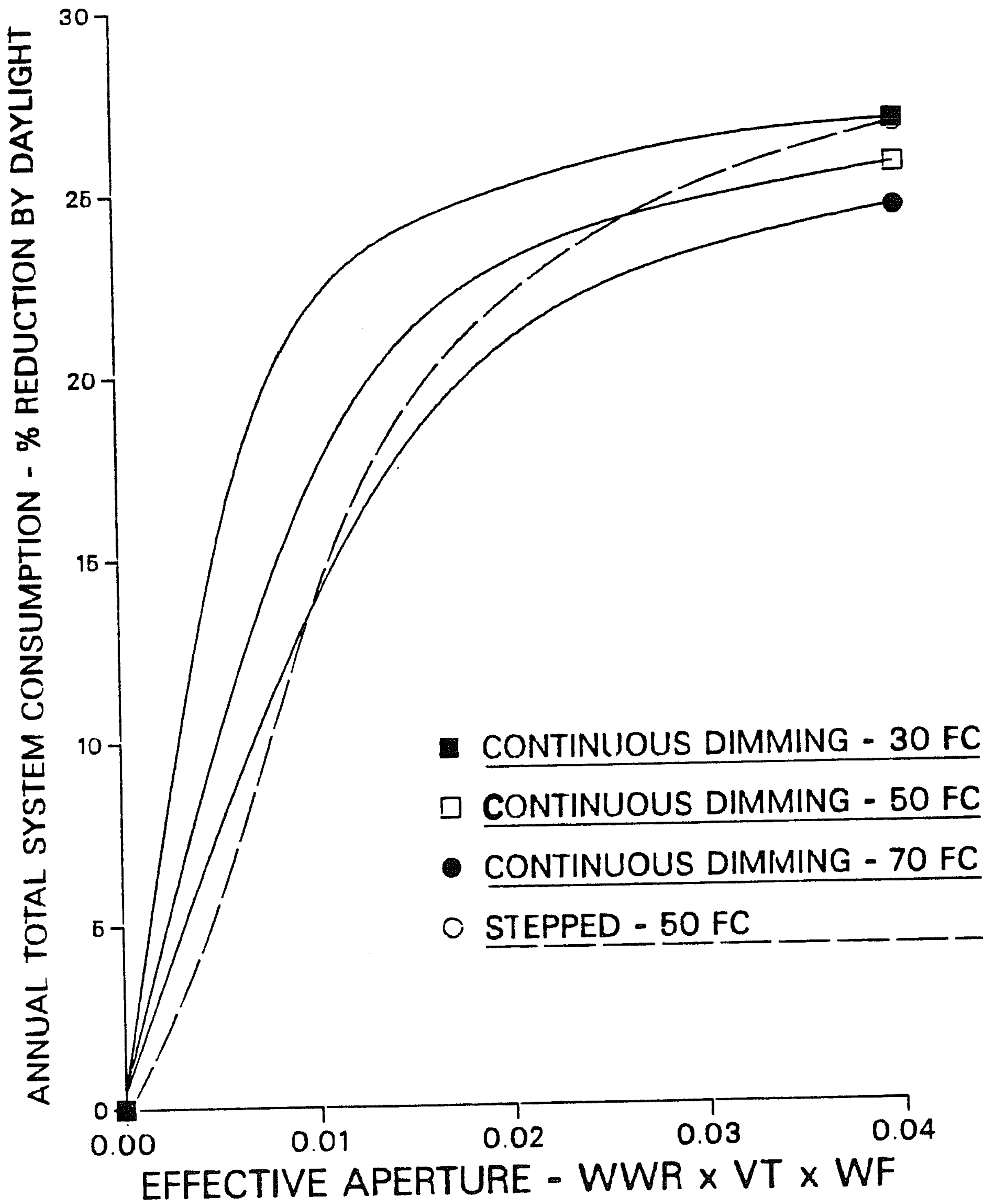


Figure 4-11. Reduction in total plant energy consumption vs. effective aperture in a skylighted building in New York City, as a function of lighting control type and illuminance setpoint with installed lighting power density of 1.7 W/ft^2. (For this figure, SC = 0.8, and U_{roof} = 0.084 $Btu/hr\text{-}ft^2\text{-}F^o$).

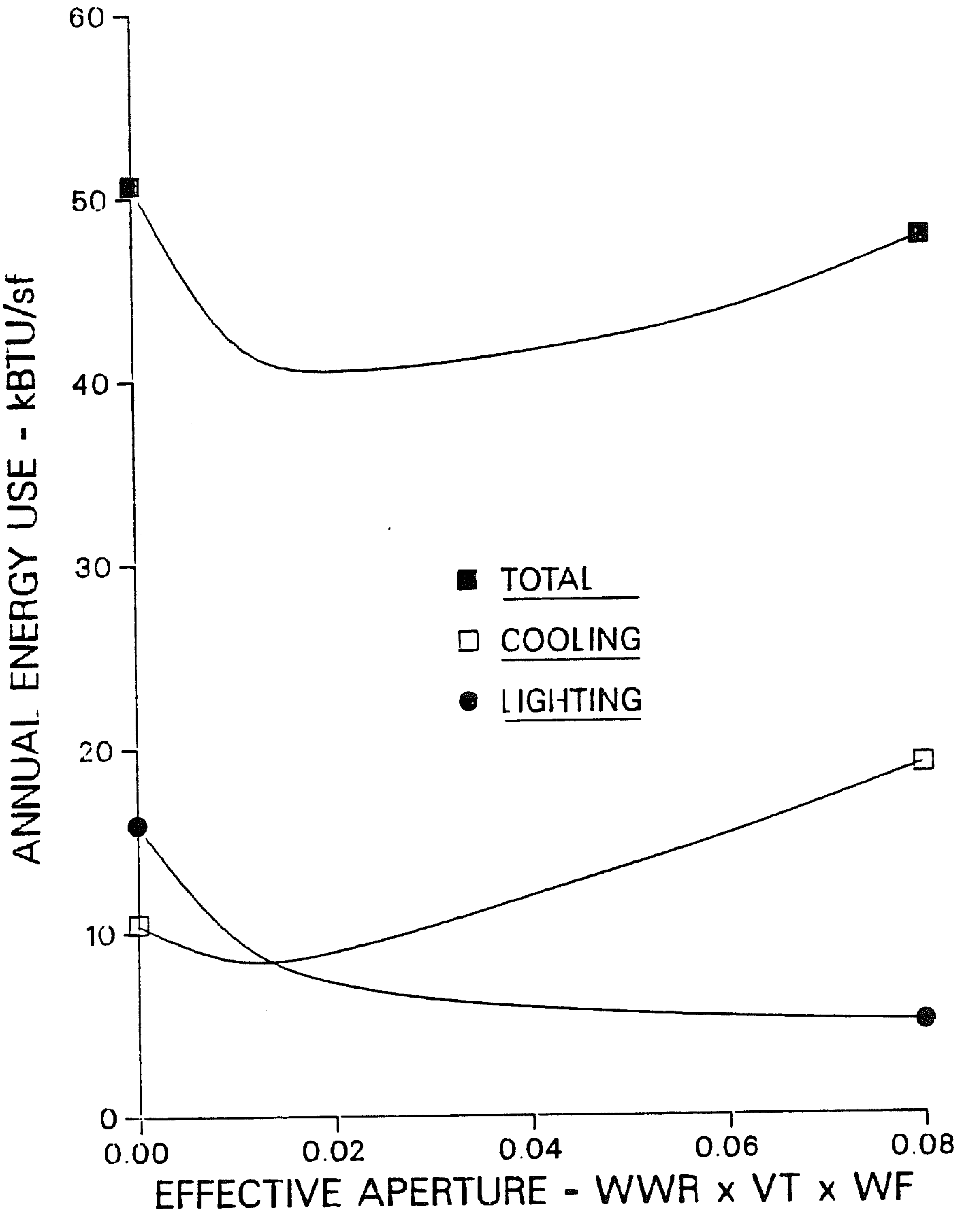


Figure 4-12. Annual plant energy use in a skylighted building vs. effective aperture showing cooling and lighting component load trends; visible transmittance = shading coefficient; installed lighting power density = 1.7 W/ft^2 with continuous dimming set at 50 fc.

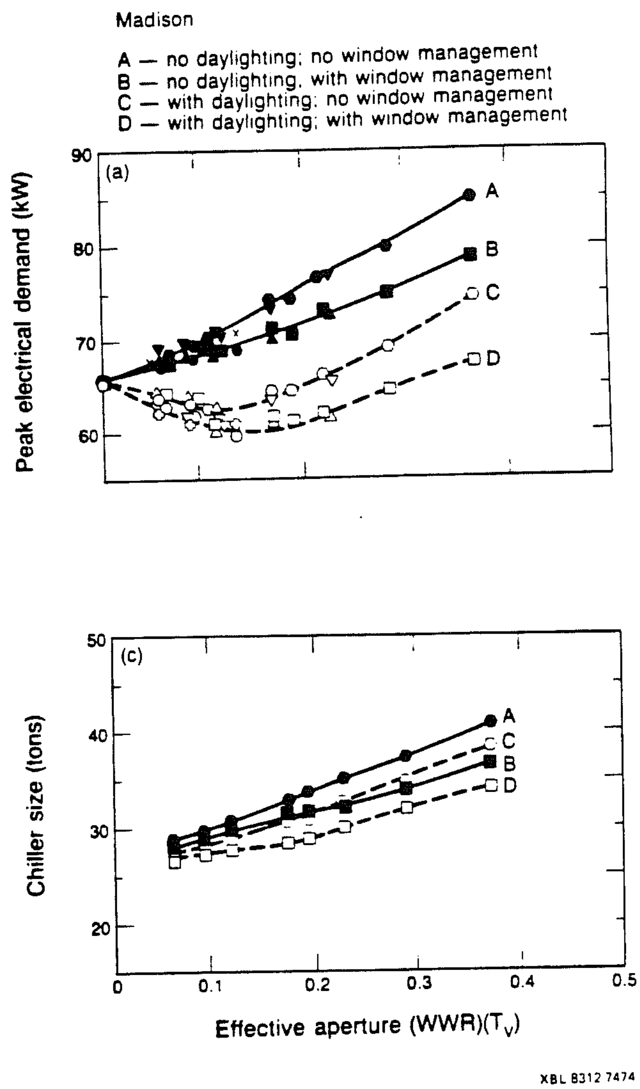


Figure 4-13. Peak electric load and chiller size as a function of effective aperture for various daylighting and window management options, "Albany"; installed lighting power density is 1.7 W/ft^2.

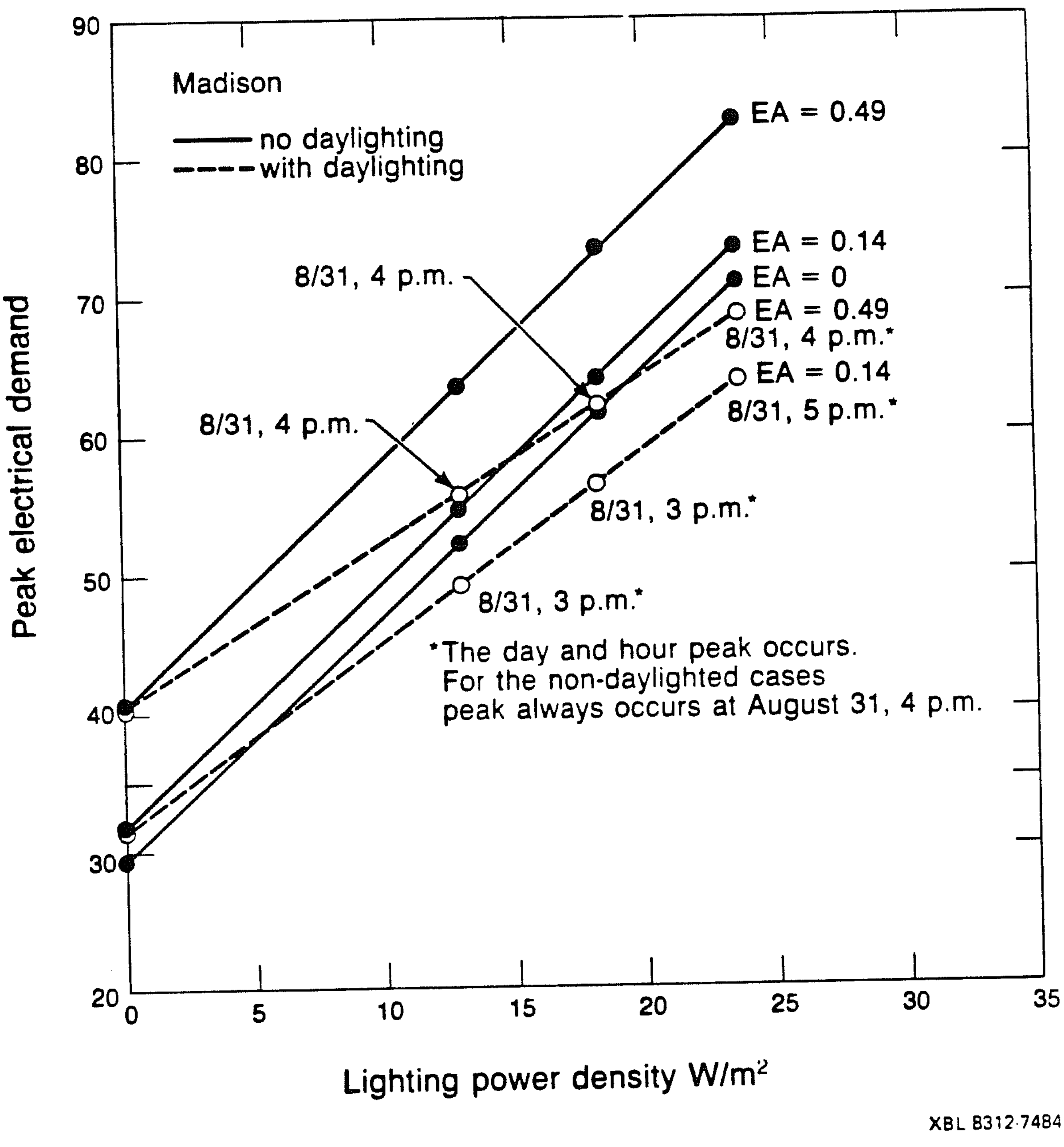


Figure 4-14. Peak electric load vs. installed lighting power density for daylighted and nondaylighted cases for several window areas, "Albany"; window/wall ratio = 0.21, 0.71. For all cases, T_v = 0.69, SC = 0.78, design illuminance level = 50 fc.

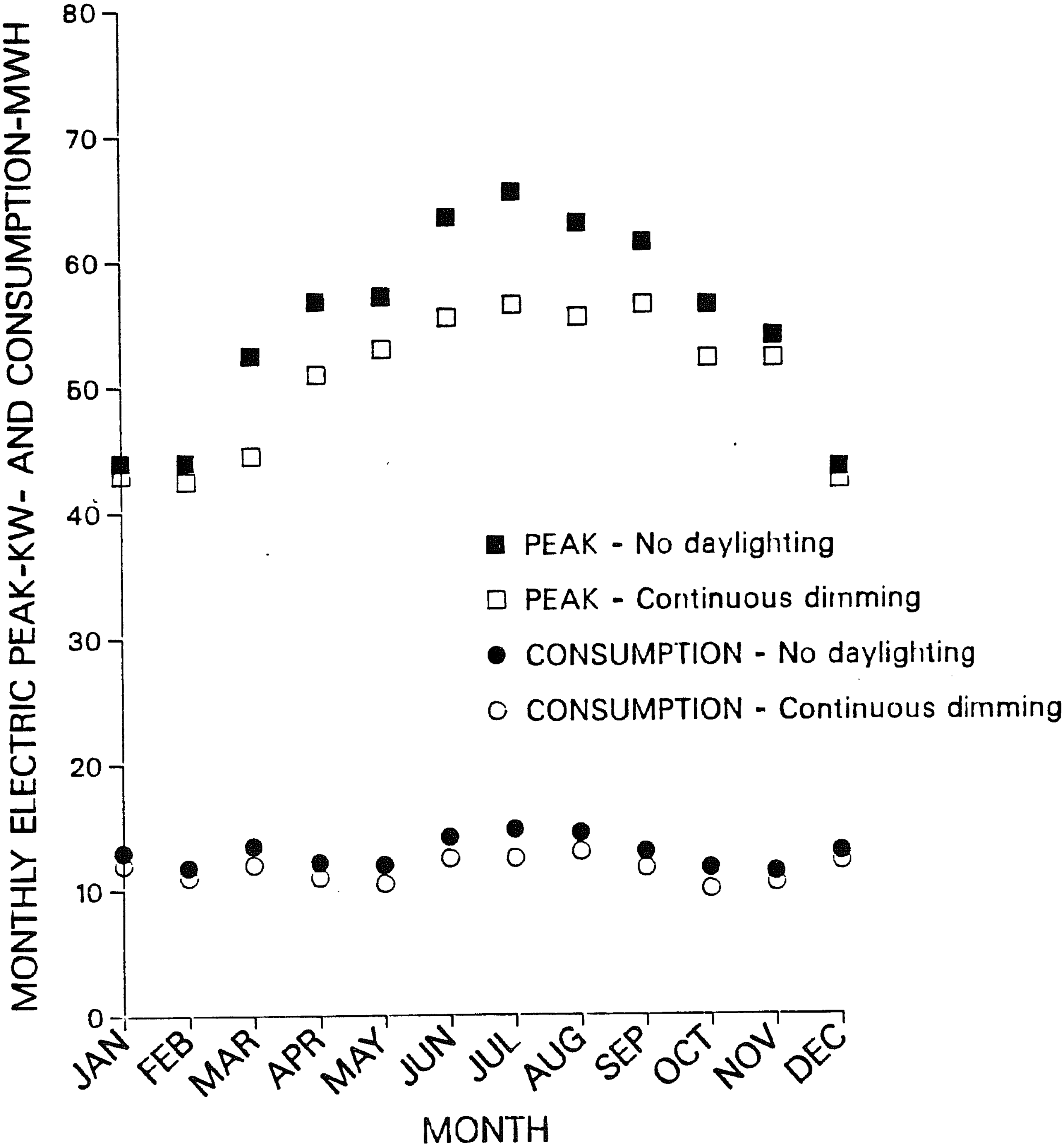


Figure 4-15. Monthly peak electric demand and electricity consumption with and without daylight controls for an office module in New York City (16,000 ft^2). Effective aperture = 0.20, installed lighting power density = 1.7 W/ft^2.

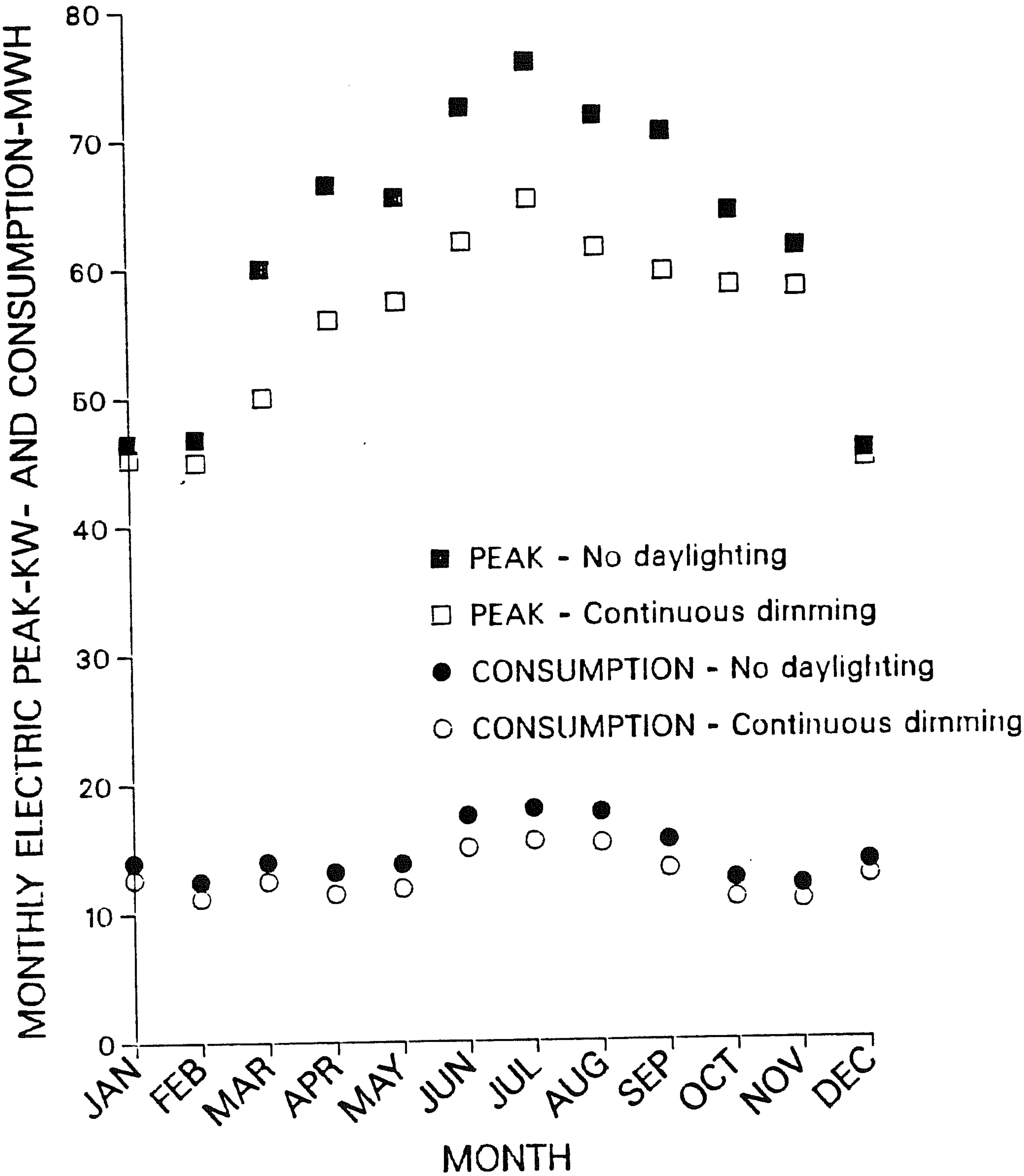


Figure 4-16. Monthly peak electric demand and electricity consumption with and without daylight controls for an office module in New York City (16,000 ft^2). Effective aperture = 0.55, installed lighting power density = 1.7 W/ft^2.

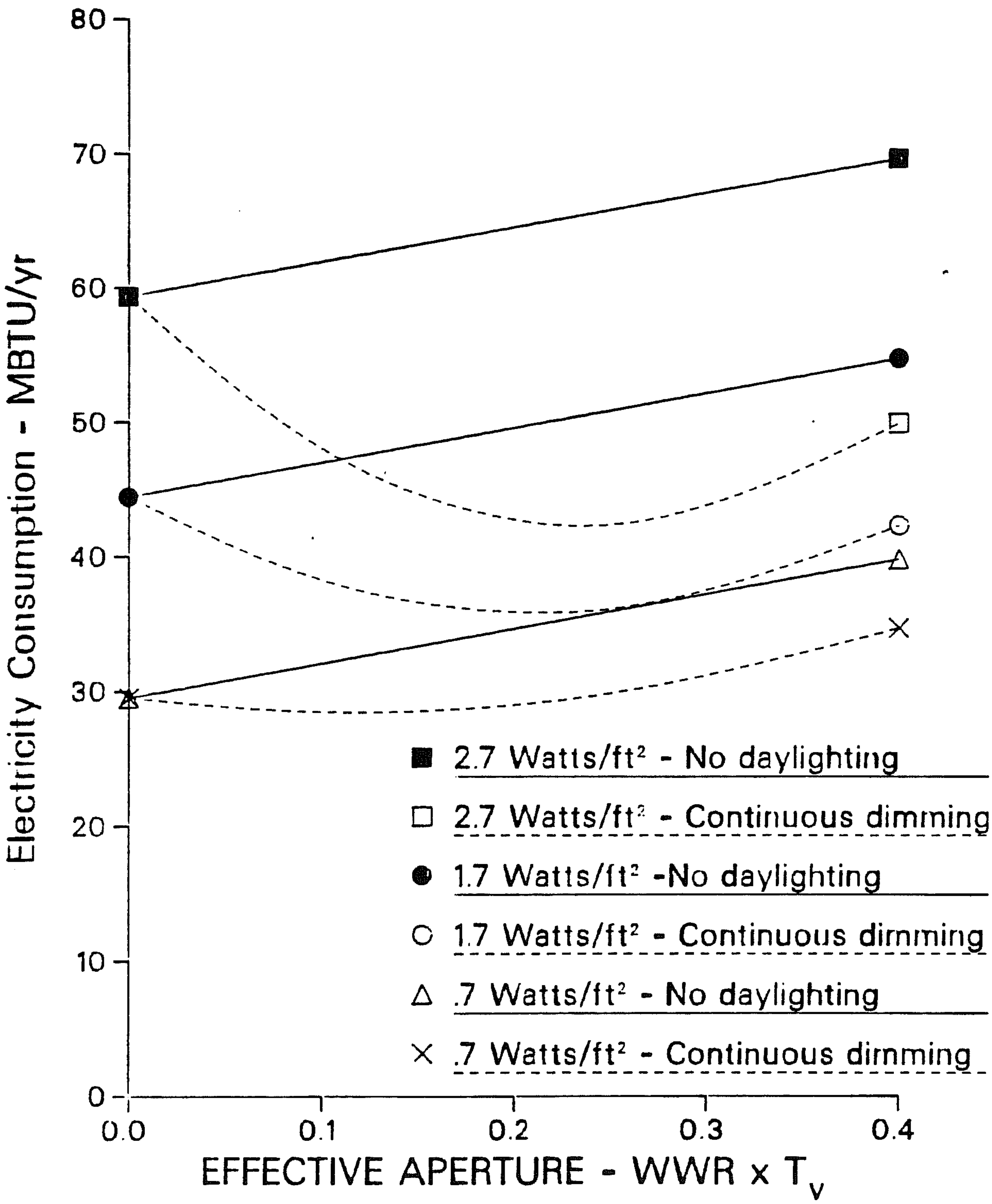


Figure 4-17. Effect of daylighting on north zone (1500 ft^2) electricity consumption vs. effective aperture and lighting power density.

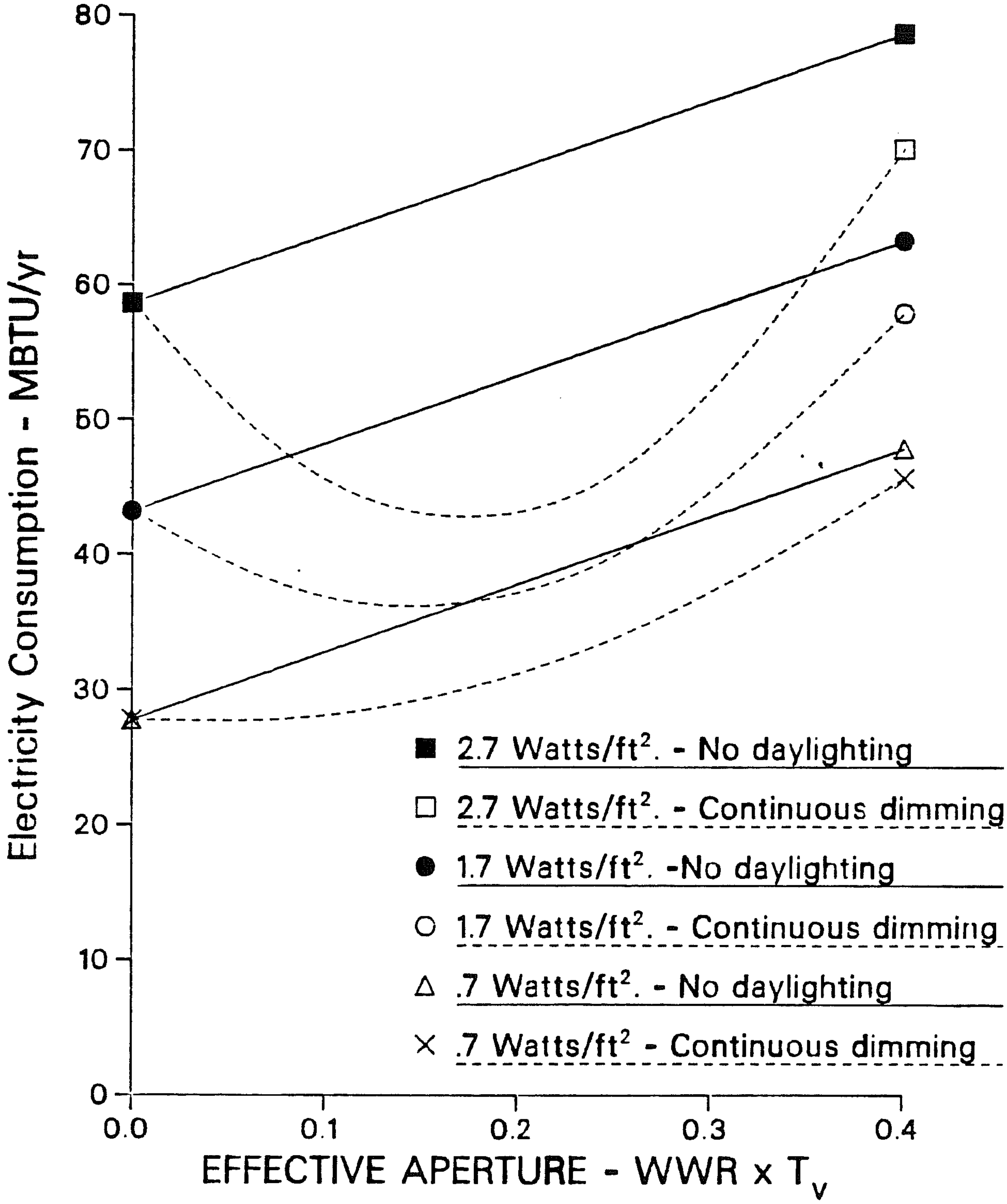


Figure 4-18. Effect of daylighting on south zone (1500 ft^2) electricity consumption vs. effective aperture and lighting power density.

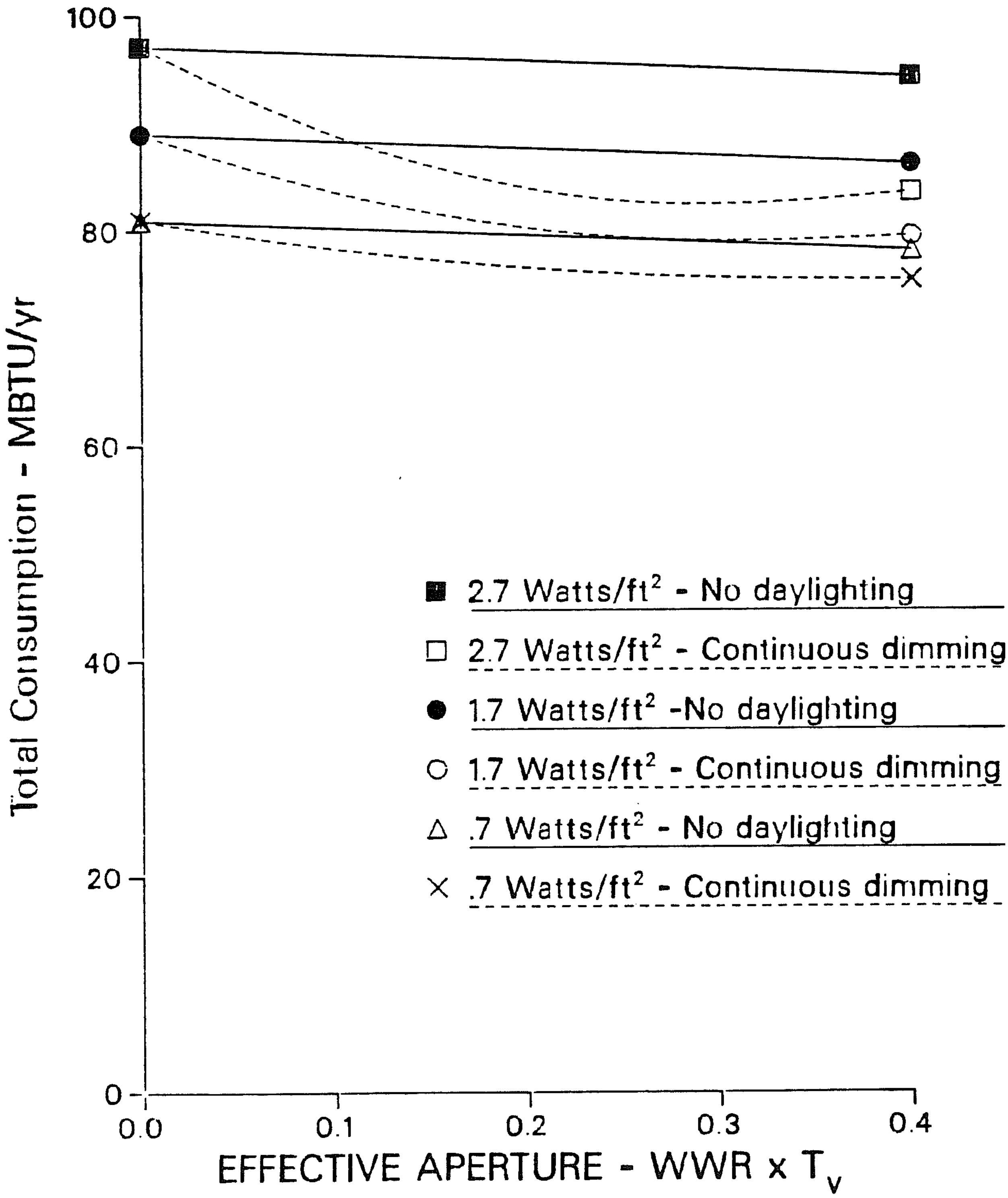


Figure 4-19. Effect of daylighting on north zone (1500 ft^2) total energy consumption vs. effective aperture and lighting power density. Annual cooling COP = 3.0, annual heating system efficiency = 0.6, U_o = 0.205 Btu/hr-ft^2-^oF.

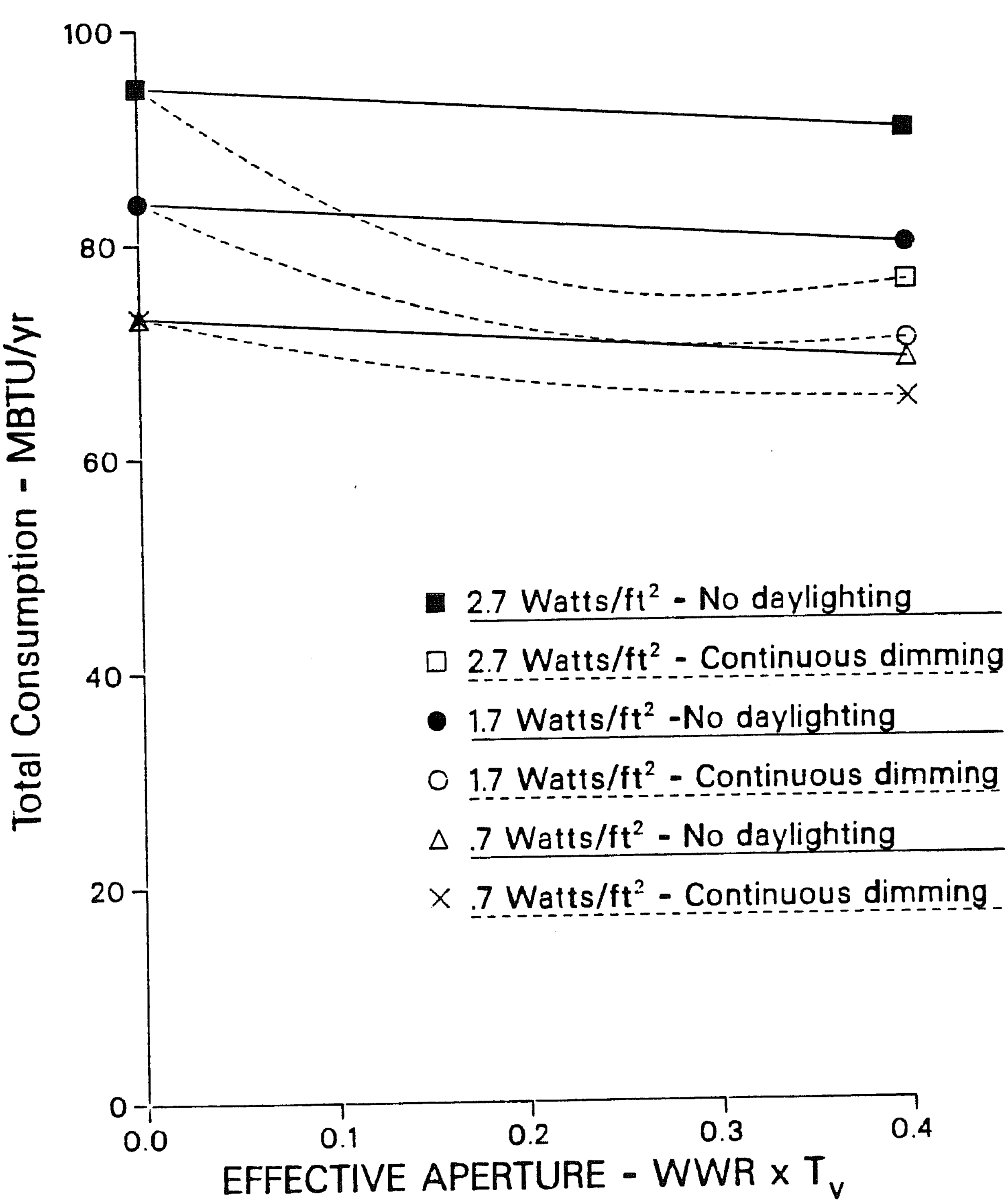


Figure 4-20. Effect of daylighting on south zone (1500 ft^2) total energy consumption vs. effective aperture and lighting power density. Annual cooling COP = 3.0, annual heating system efficiency = 0.6, U_o = 0.205 Btu/hr-ft^2-^{o}F.

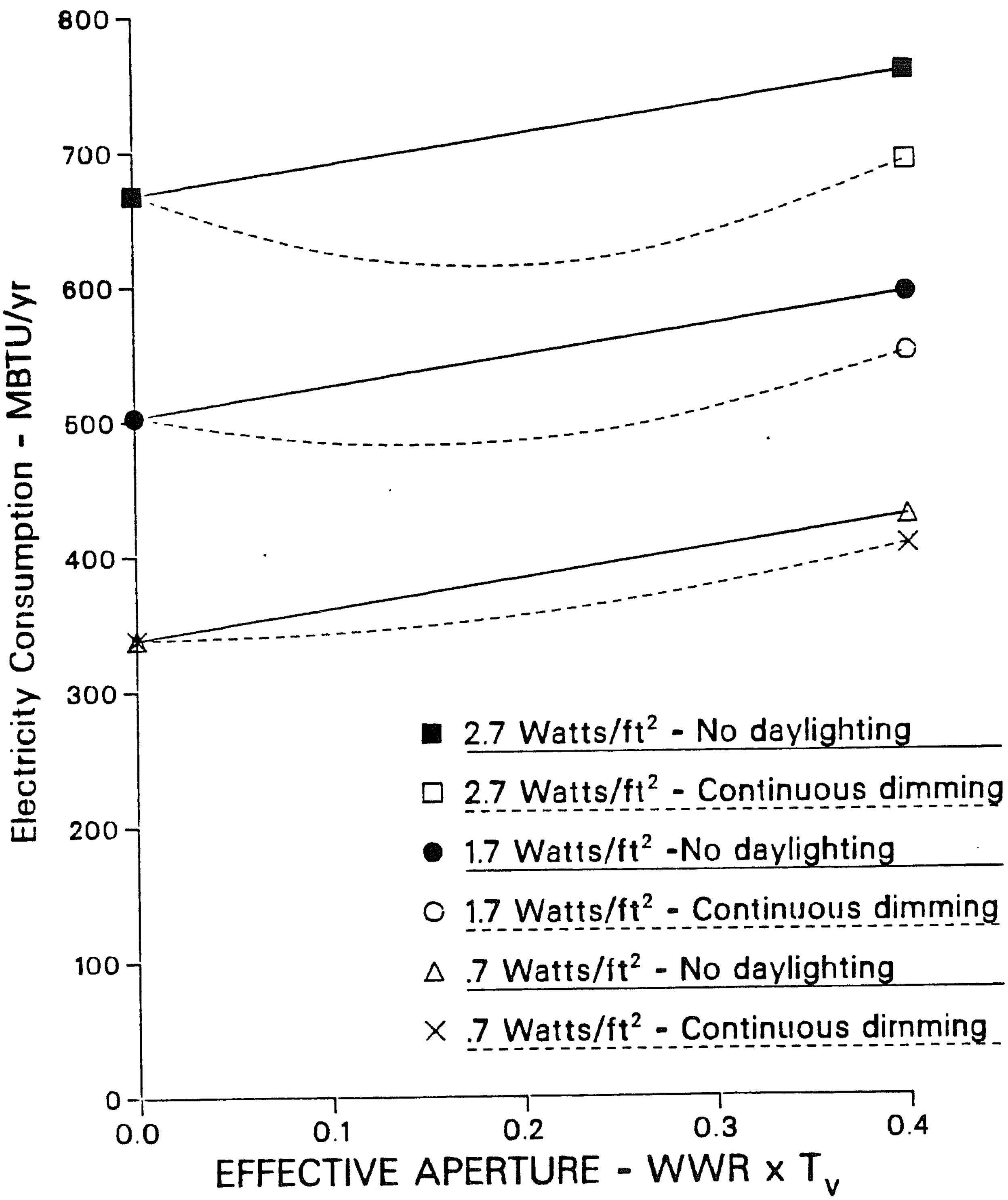


Figure 4-21. Effect of daylighting on electricity consumption for one floor (16,000 ft^2) vs. effective aperture and lighting power density.

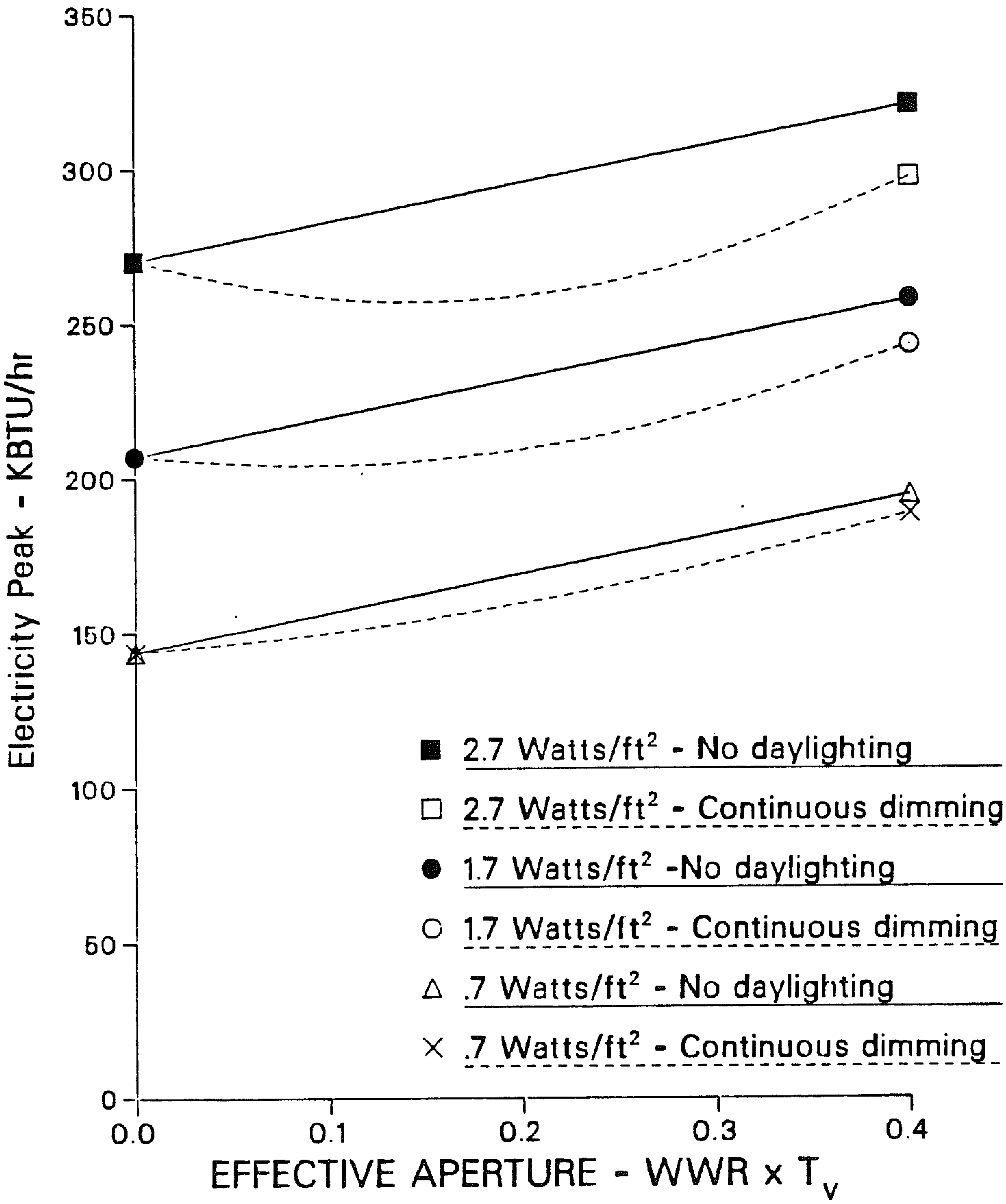


Figure 4-22. Effect of daylighting on electric peak demand for one floor (16,000 ft^2) vs. effective aperture and lighting power density.

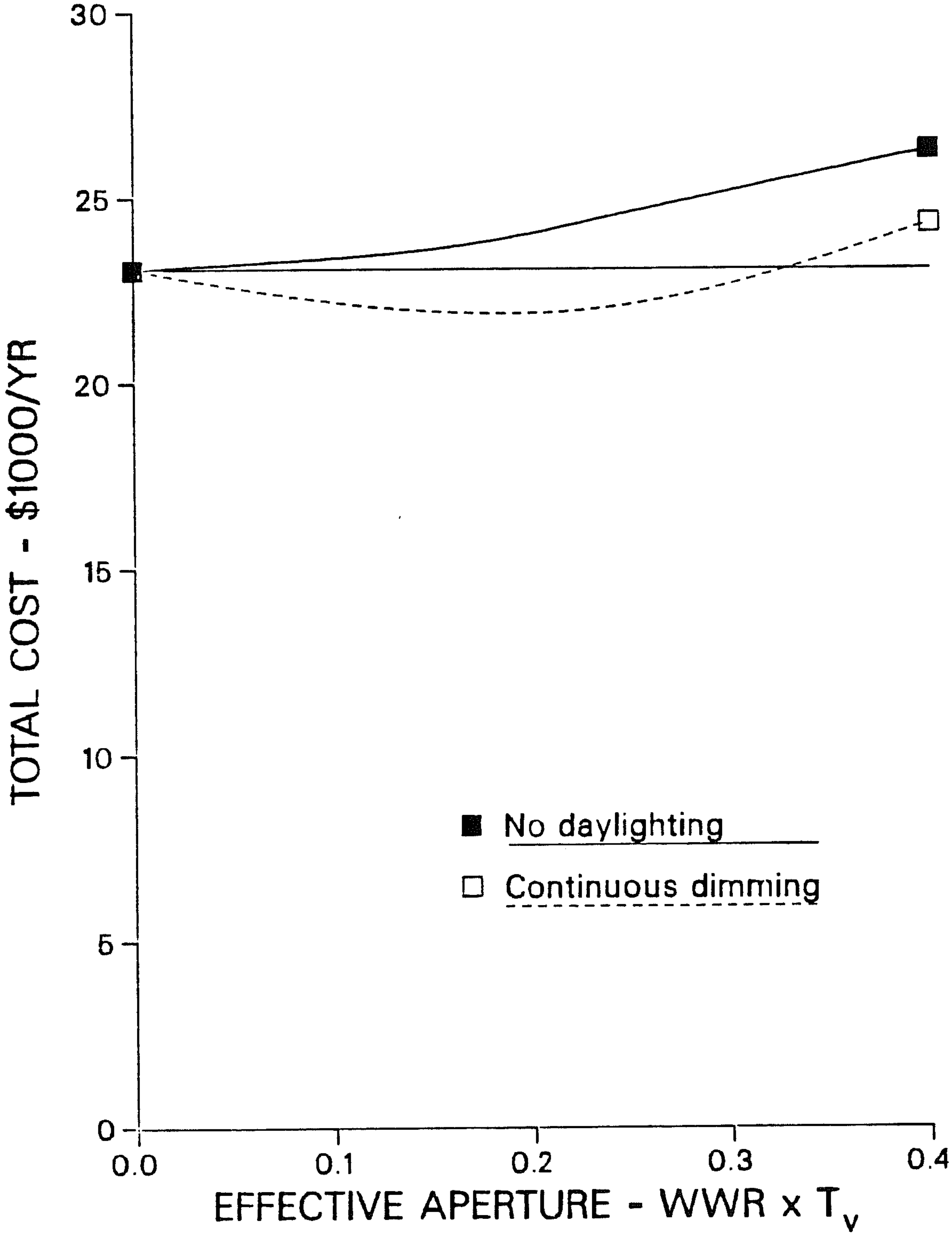


Figure 4-23. Total annual electricity and gas costs for a prototypical floor (16,000 ft^2) in an office building in New York City, comparing continuous dimming to a building without daylight controls. (Lighting power density = 1.7 W/ft^2.)

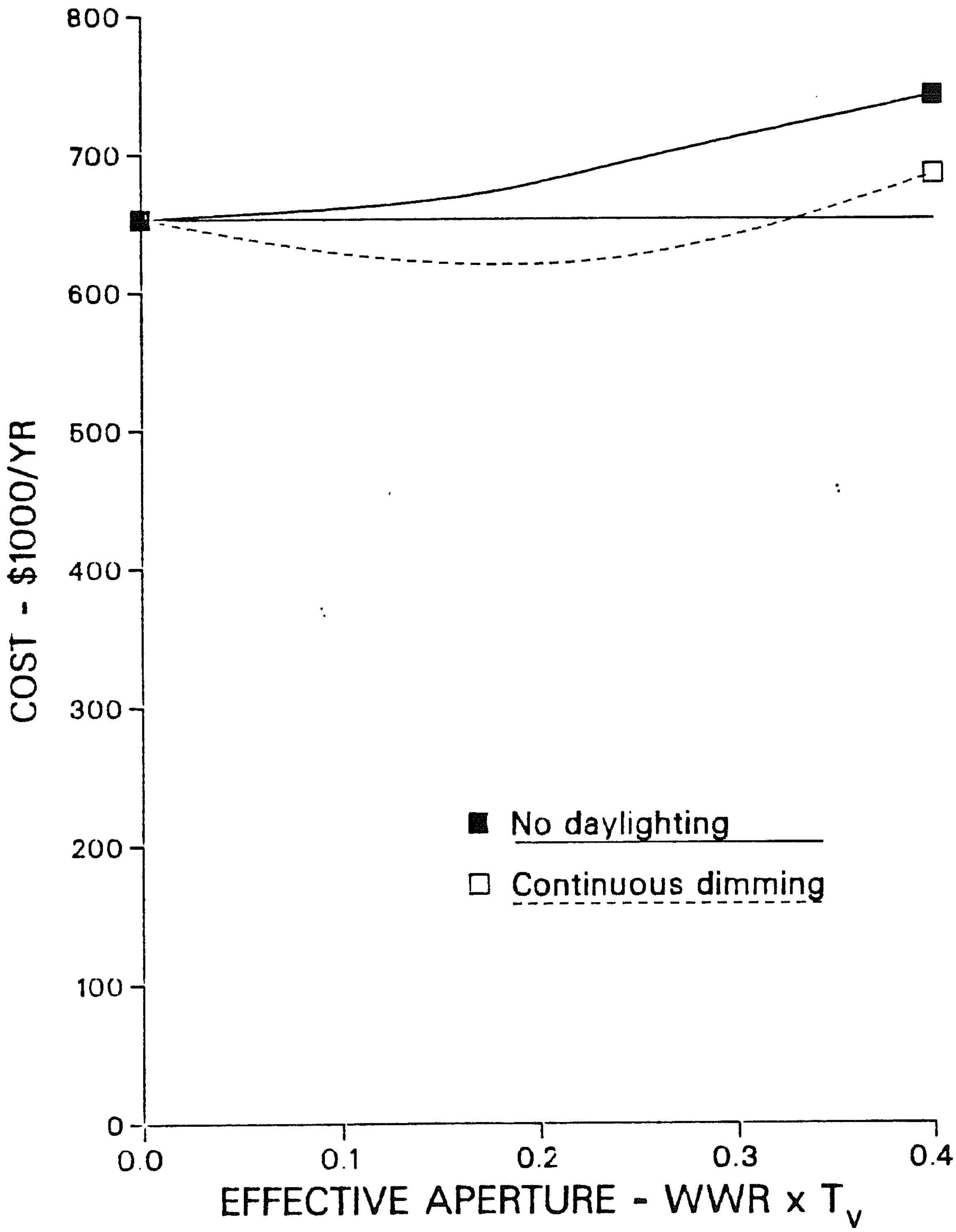


Figure 4-24. Total annual electricity and gas costs for a prototypical 30-story office building (480,000 ft^2) in New York City, comparing continuous dimming to a building without daylight controls. (Lighting power density = 1.7 W/ft^2.)

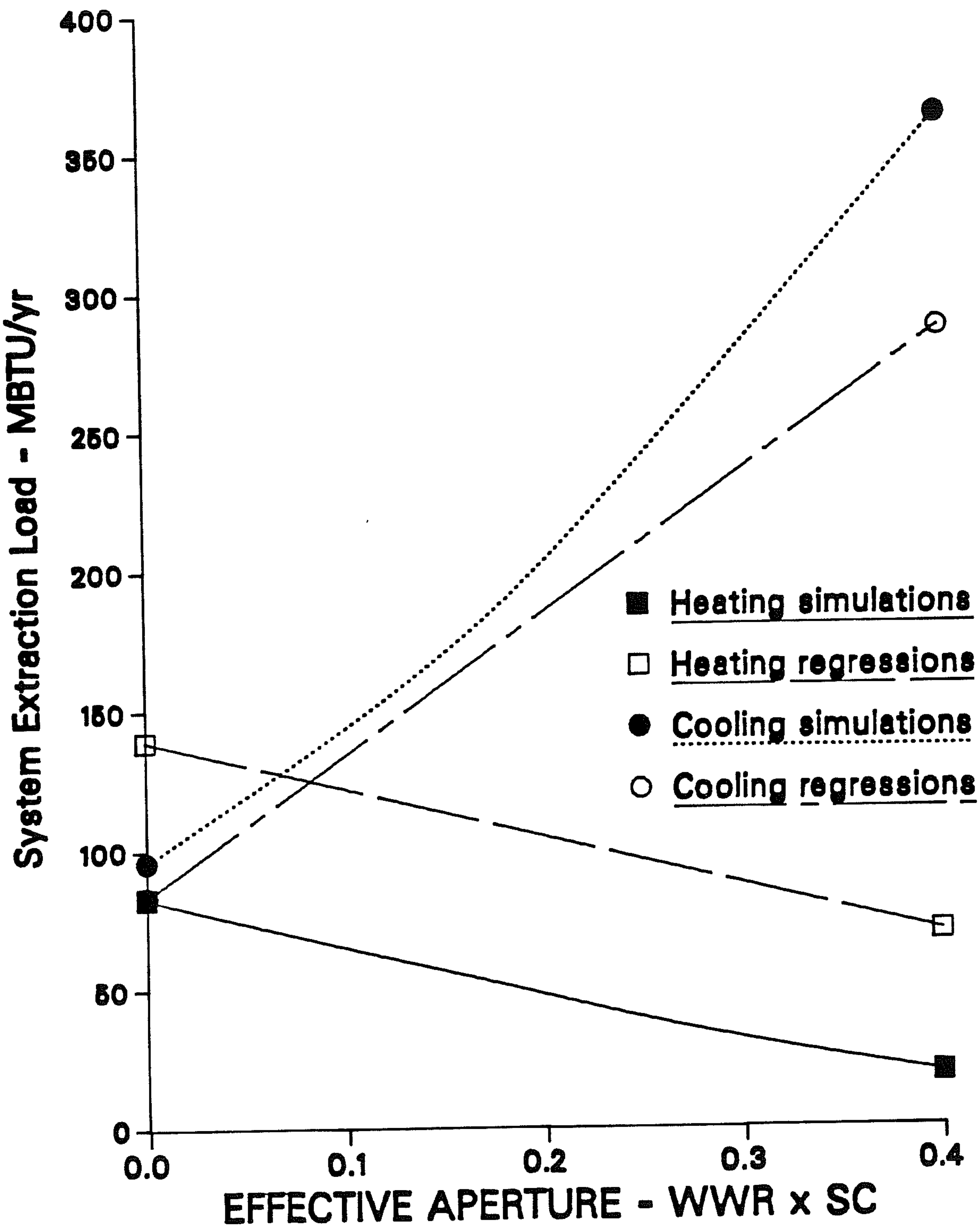


Figure 4-25. Heating and cooling loads (extraction loads) vs. effective aperture, comparing PSEG building simulation results to predictions from the regression model for a constant-volume, variable-temperature system. Results shown for perimeter zones on one floor with no daylight controls.

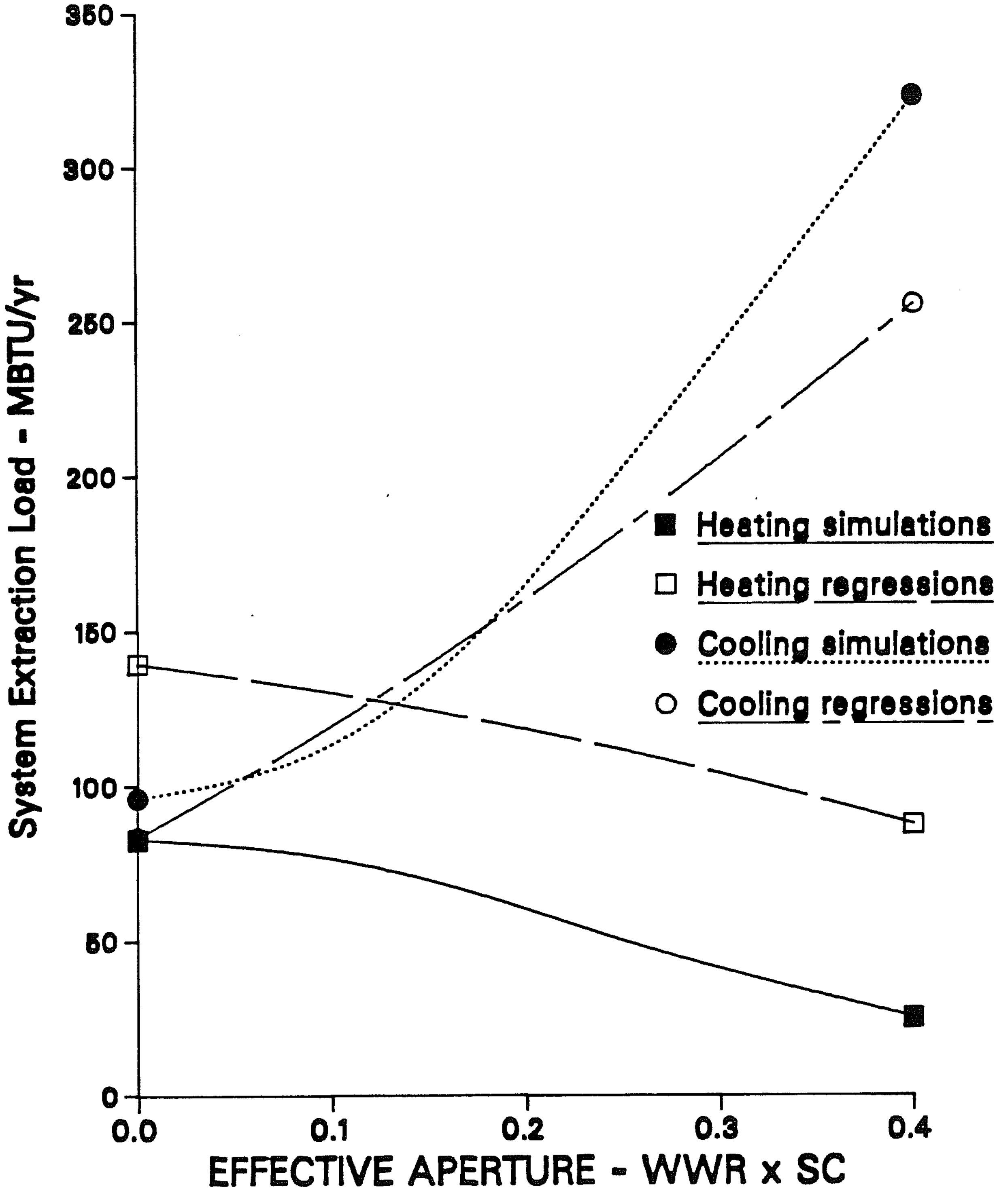


Figure 4-26. Heating and cooling loads (extraction loads) vs. effective aperture, comparing PSEG building simulation results to predictions from the regression model for a constant-volume, variable-temperature system. Results shown for perimeter zones on one floor with continuous dimming daylight controls.

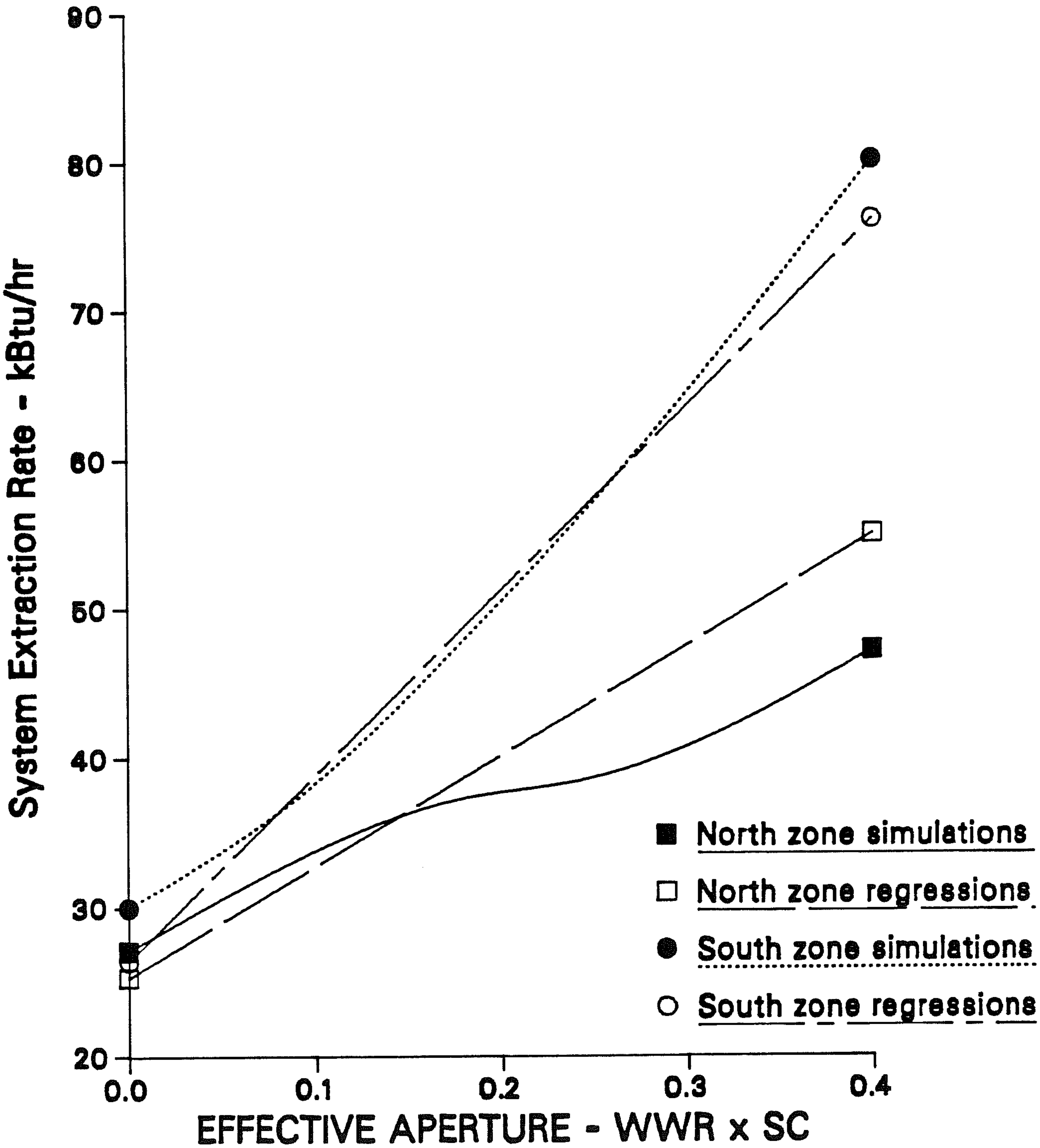


Figure 4-27. Peak cooling extraction rate vs. effective aperture, comparing PSEG building simulation results to predictions from the regression model for a constant-volume, variable-temperature system. Results shown for north and south perimeter zones on one floor with no daylight controls.

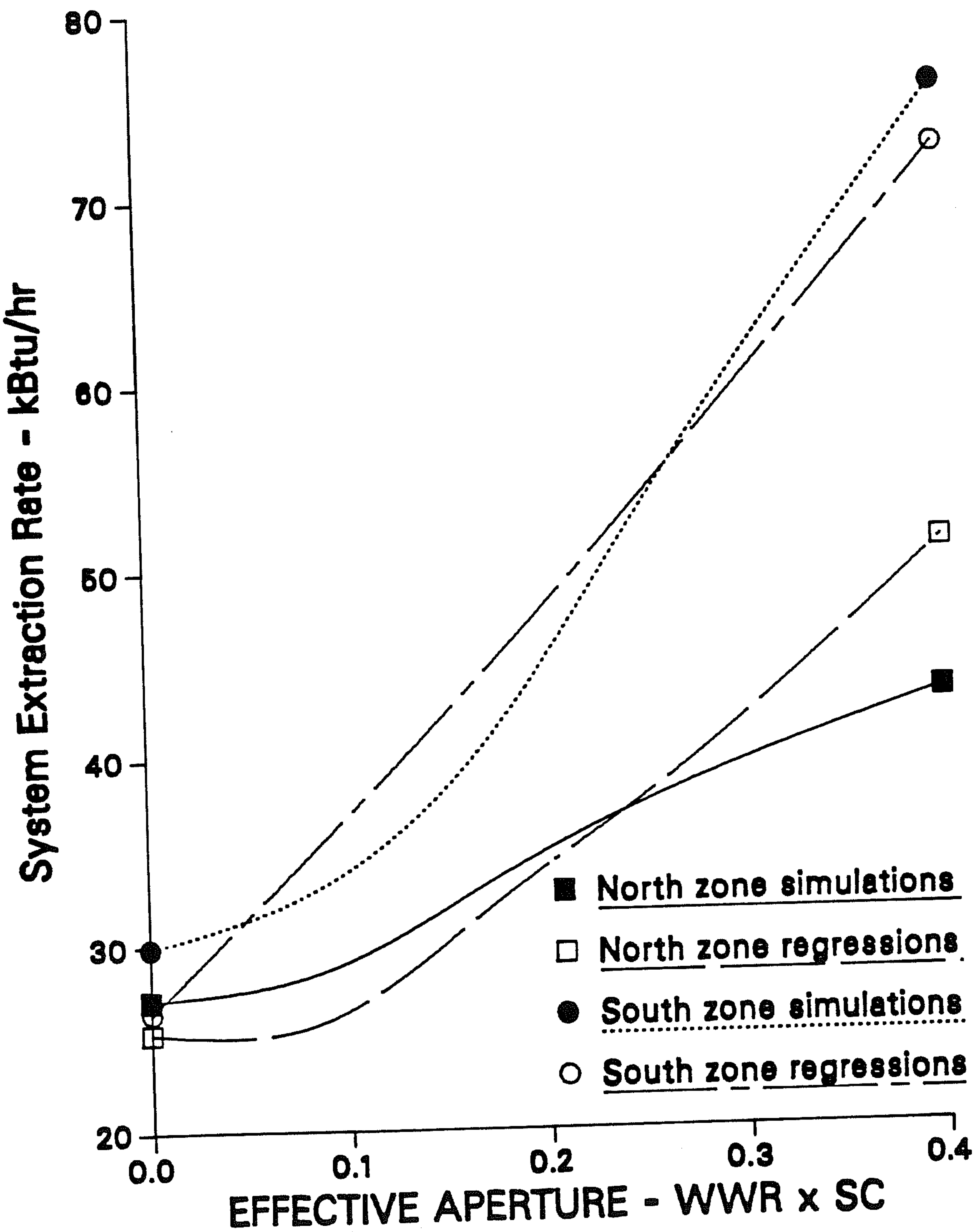


Figure 4-28. Peak cooling extraction rate vs. effective aperture, comparing PSEG building simulation results to predictions from the regression model for a constant-volume, variable-temperature system. Results shown for north and south perimeter zones on one floor with continuous dimming daylight controls.

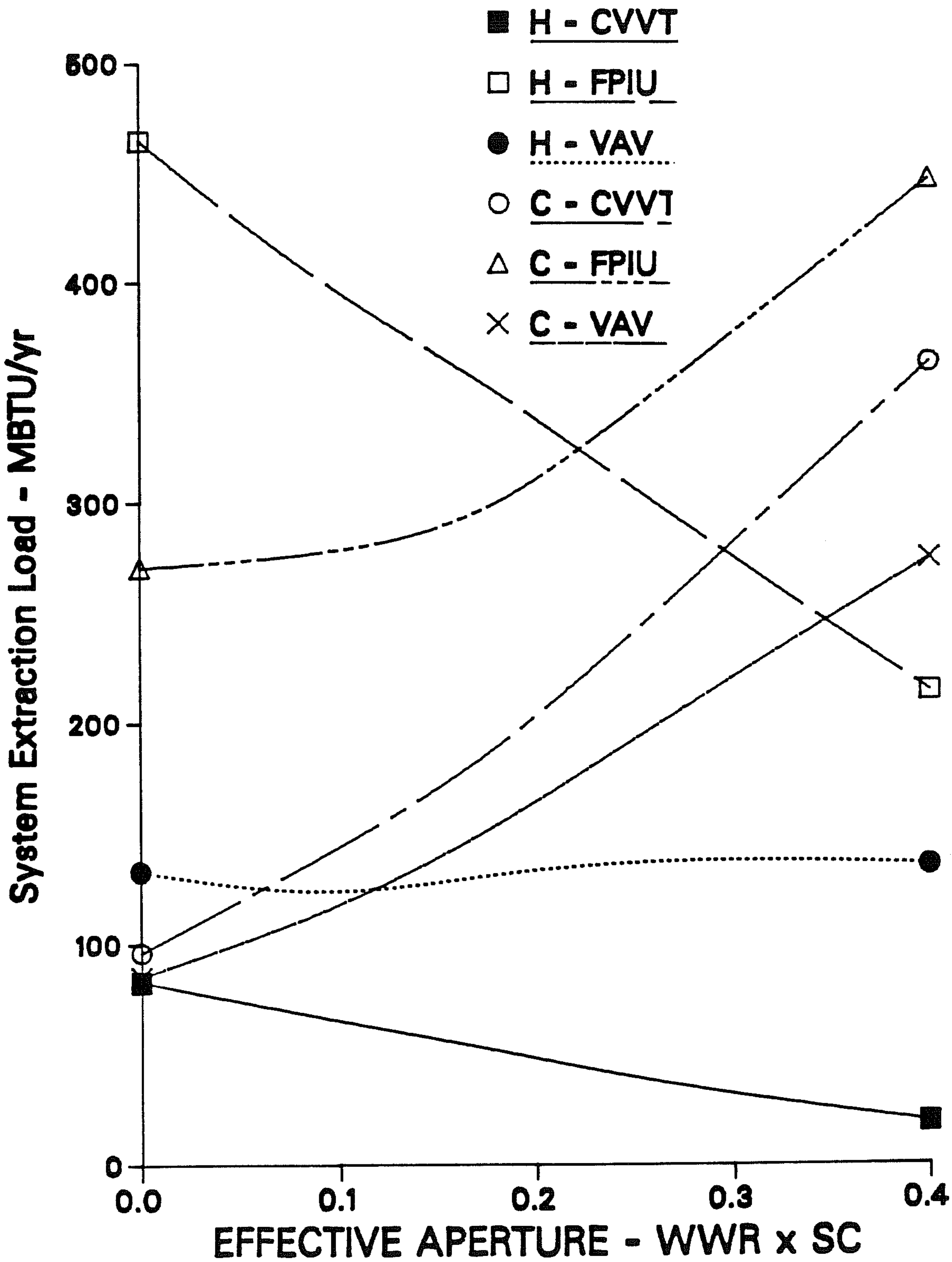


Figure 4-29. Heating and cooling loads (extraction loads) vs. effective aperture, without daylight controls, comparing PSEG building results for three different HVAC system configurations (perimeter zones only, 7,520 ft^2; 1.7 W/ft^2 lighting power).

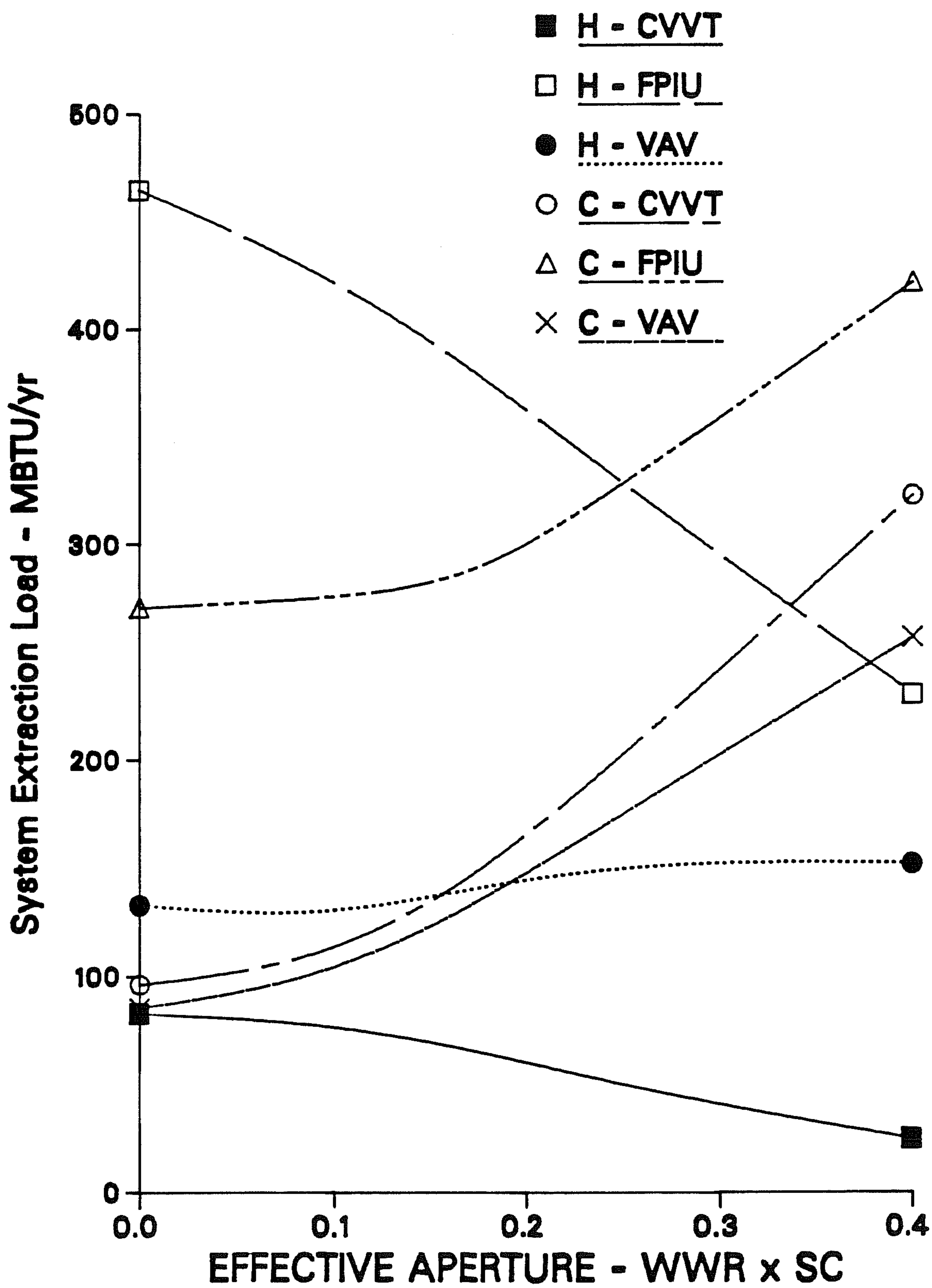


Figure 4-30. Heating and cooling loads (extraction loads) vs. effective aperture, with continuous dimming daylight controls, comparing PSEG building results for three different HVAC system configurations (perimeter zones only, 7,520 ft^2; 1.7 W/ft^2 lighting power).

Section 5

THE INTEGRATION OF DAYLIGHT AND ELECTRIC LIGHT IN BUILDINGS

INTRODUCTION

Integration of daylight and electric light in buildings during daytime hours can be described as a holistic design issue for the visual environment. In this process the merits and deficiencies of both daylight and electric light are considered in order to arrive at the optimal design for a specific project. This optimal solution depends on the type of building, activity patterns in it, and local environmental factors. Simultaneous utilization of daylight and electric light during daytime, if not closely coordinated during the design process, seldom achieves optimal results.

Hopkinson developed one of the first formal concepts of integration, known as Permanent Supplementary Artificial Lighting of Interiors (PSALI) (1,2). Recommendations based on PSALI were later made by the British Illuminating Engineering Society (3).

The original PSALI concept of the late 1940s was based on conditions that no longer exist. At that time the recommended illuminance for school classrooms was 15 footcandles (fc) or about 160 lux, and for offices 20 fc or about 215 lux. It was clear that in deep interiors, available daylight produced a harsh contrast between interior background surfaces and the bright sky visible through the windows, thus affecting the adaptation of the eye. As a result, glare was unavoidable when looking from the depth of the room at the windows on the one hand, and a gloomy appearance was created at the back of the room.

The simplest way to counteract the gloom and reduce contrasts was to switch on the electric lighting. However, the established levels of that time (160-215 lux) proved inadequate, so higher levels were recommended for daytime electric lighting at the depth of the room than were recommended for nighttime hours. Furthermore, the higher the daylight level in the room, the higher the electric illuminance had to be.

One of the basic requirements of PSALI was that daylight should be the major light source, would be supplemented by electric light in the deeper parts of the interior, and should have spectral properties as similar as possible to daylight. Less clearly defined in the original PSALI concept were the directional requirements of the integrated lighting system.

Since then, recommended illuminance levels have increased, and deeper and larger buildings have been built, requiring extension of the integration concept. Ne'eman (4) and later Ne'eman and Longmore (5) and others suggested that the scope of integration should be widened to include various types of buildings, and PSALI should become one of several types of integration. In a paper entitled "The Successor to PSALI" (6), Collins suggested that IDAL--Integration of Daylight and Artificial Light--should succeed PSALI.

We will summarize the development of concepts of integrating daylight and electric light in view of modern trends in architecture and the growing awareness of energy conservation and suggest several areas where new research is needed.

Proper understanding of the integration process is of utmost importance for planners in countries where the design of the visual environment has involved extremes. Windowless buildings with no access to daylight or view on the one hand, and overglazed buildings with tremendous energy and glare problems on the other, have been common design fashions for more than half a century.

DESIGN OBJECTIVES

The design objectives of the early integration method (PSALI), were intended mainly to improve the visual environment by adding electric light to available daylight. Later, the importance of the view out through windows was recognized as an inseparable part of an integrated design. The window came to be considered not solely as a source of natural light, but also as a means of visual communication through which valuable information is obtained. As a result, the evolution of the integration concept has reduced reliance on the dominance of daylight.

The design objectives have been transformed into the provision of task, or functional, illuminances by electric sources, while daylight is assumed to provide the ambient or background illuminance as well as the subjective requirements for a view and contact with the outside. These requirements influence acceptable window size, as discussed in detail later.

Energy considerations were not ignored by the early integration methods. However, energy savings and cost-effectiveness became major features in daylight integration only during the 1970s, due to the energy crisis.

The motto of integration at present should be: utilize daylight to the maximum possible extent, and use electric light minimally. However, human performance and well-being should not be sacrificed. Although well-being, energy savings, and lowest overall cost do not necessarily achieve their optimums simultaneously, we believe that basic human needs should always be met.

The dilemma between maximum energy savings and optimal overall costs is a serious one in daylight design. Oversized windows in some cases can minimize the use of electricity for lighting. Because of increased requirements for heating and cooling, however, the overall operating costs of building management may be higher than with a solution based on an integrated scheme. In our opinion the design objectives should seek a solution in which minimal overall costs are obtained with the greatest possible energy savings, visual performance, and well-being. The logic behind these design objectives is that buildings last a long time, while energy costs are unpredictable (although it seems unlikely that electricity costs would fall substantially in the foreseeable future). It is possible that they could fall on a short-term basis. The average rate of increase, however, is subject to large uncertainty. Furthermore, the value of occupant productivity currently exceeds the energy costs (and always will), so that any solution that maximizes energy savings but reduces productivity will be counterproductive.

Current design objectives can be divided into the major categories described below.

Human Performance and Well-Being

This category primarily concerns the visual environment, including visual performance and well-being. Thermal and acoustical comfort should not be overlooked, however.

The quality of the visual environment generally depends on adequate illuminance for visual activity, limitation of glare, and subjective considerations such as avoiding a gloomy interior, achieving a color scheme, and providing an acceptable size and shape of windows to maintain contact with the outside world. Daylight admitted through windows is also considered essential for photobiological processes, such as controlling the physiological biorhythyms and stimulating metabolic functions.

Effective Energy Management

The total energy balance should be examined in terms of optimal energy efficiency. Regarding daylight admission, the energy balance of heat gains and losses due to solar radiation, conduction, and air leaks should be evaluated. For electric light, overall system efficacy, not only lamp efficacy, should be considerated. Designs that minimize peak electric loads as well as total annual energy consumption are more desirable.

Cost-Effectiveness

The overall cost mentioned above should include depreciation and interest on the investment as well as the operating costs for fenestration, shading, and the electric lighting system. The value of occupant productivity may also be included in this analysis.

Dynamic Controls

Fixed or static shading systems are almost always less efficient than operable systems. For example, fixed shading devices unnecessarily reduce the amount of daylight indoors even when the sun is not shining on them. As a result, more electric light will have to be used than with adjustable or operable shades. Similarly, any large electric lignt system that is controlled by a single master switch will tend to use more energy than justified by functional needs. Again, the more controllable the system is, the higher the energy-saving potential.

The highest degree of flexibility is obtained by an integrated control system that monitors the electric lighting and shading systems simultaneously for maximum utilization of daylight and minimum consumption of electricity for lighting and cooling.

THE WINDOW IN THE INTEGRATED SYSTEM

The role of windows was mentioned earlier. In addition to admitting light and providing ventilation in non-air-conditioned buildings, windows have a subjective psychological role, providing visual contact with the outside, as described by Marcus (7), Ne'eman and Hopkinson (8), Keighley (9), and Seidl (10).

In their study on critical minimum acceptable window size, Ne'eman and Hopkinson (8) suggested that satisfaction with a window depends on the information conveyed by the view. It was shown that in working interiors, satisfaction with window width increases until the window reaches about 30% of the window wall width, provided the window is located within a horizontal angle of about 60°.

It was also shown that whenever the view provides little information, such as a view of the sky through high-up vertical windows or through rooflights (skylights), the windows are perceived merely as sources of daylight and have little psychological-subjective significance as sources of meaningful visual contact and relief from the sense of enclosure. It is interesting to note that satisfaction with a space that has windows does not necessarily imply that the view out will be available to every occupant in every place or work station. Most people are satisfied if they know they have the option of looking out, if they wish to, by turning their heads or by standing up.

The choice of sill and window height is also related to the view content. The lower part of the window provides more information than the upper part. Thus relatively wide and lower windows are more satisfactory from a subjective point of view. However, higher windows are more efficient in admitting daylight to the deeper parts of the interior. We see that by specifying the glazed area of fenestration, we do not necessarily meet the well-being requirements for the minimal window opening. Thus, it is recommended that the above-suggested minimum width of the window(s) be applied to any size and shape of openings on vertical walls.

A simple way of specifying window size and area is recommended as a standard in Germany--see Seidl (10) and Krochmann (11). It is suggested there that a daylight factor of 0.9% at half the depth of a room, near the side wall, can provide sufficient brightness in winter for at least two hours at noontime. In addition, a minimum window area of 30% of the window wall is required for subjective well-being, and a window height of 1.2 m is considered optimal.

It should be stressed that fully glazed exterior walls (floor to ceiling) do not bring any subjective advantage, in addition to creating thermal deficiencies and glare problems. In some cases such a solution may lead occupants to complain of lack of privacy and personal security.

In our opinion, the final choice of window area should be left to the designer, although energy and safety codes may impose some constraints. For working interiors, the minimum width should always be provided. Beyond that, the size of the glazed area should be dictated by the design objectives discussed above. In dwellings, even more emphasis should be given to subjective-psychological considerations. This is particularly true in cold climates, where short periods of winter daylight and frequent overcast suggest the need for good daylight exposure.

DAYLIGHT PENETRATION AND RELATIONSHIP TO ELECTRIC LIGHT

It is well known that in interiors where daylight comes through the windows on one wall, illuminance near the windows is relatively high. It falls rapidly the farther we move from the windows. The actual illuminance depends on the available daylight outdoors, external obstructions, and internal reflectances. The depth to which daylight can provide the required illuminance also depends on the activity pattern. An interesting investigation was carried out by Matsuura on the "Turning-off Line in Perimeter Areas for Saving Lighting Energy in Side-Lit Offices"(12). He suggested dividing the electric lighting installation into two parts. The lighting at the depth of the room does not interact with daylight and remains on throughout the working day. The perimeter area lighting can be switched off during daytime hours if conditions allow. The depth of this perimeter zone can be determined with the aid of nomograms proposed by Matsuura.

Switching off the lighting in the area close to windows can be performed by the simplest manual on-off operation. More recently, other solutions have been introduced. Groups of luminaires can be connected to photoelectric sensors that automatically control the on-off switching according to the distance from windows. The most sophisticated system involves the automatic dimming of the electric lighting in all the parts of a building that can utilize daylight. Control strategies are discussed in detail elsewhere in this report.

Obviously, the more sophisticated the lighting system, the more expensive it becomes. As mentioned before, the economical feasibility and pay-back time snould be examined in addition to energy savings. In many cases the simpler solutions of automatic on-off switching may prove to be more cost-effective. However, a proper evaluation of each control technology should include all costs and benefits.

It is worth mentioning that for maximum energy saving the most efficient lamps and ballasts should be used, and regular cleaning, maintenance, and relamping should be carried out.

DAYLIGHT GLARE

Visual comfort is one of the most important criteria in lighting design; however, it cannot be achieved in the presence of glare. Light sources of any kind naturally present the brightest surface to the field of view, where they create the most intense glare. Generally speaking, the degree of glare depends on the luminance of the source and its background and on the size of the source and its location in relation to the direction of view.

The sources of daylight glare are direct sunlight and bright sky as seen through daylight-admitting openings. Direct sunlight must always be controlled to avoid intolerable glare. On bright days the sky may cause quite severe discomfort glare. In particular, if light is admitted through windows that are located at eye level, these windows are likely to be in the occupants' major directions of view. Furthermore, windows are larger than luminaires so that the distinction between the glare source and its background as perceived by the retina of the eye is not clearly definable. As a result, daylight glare cannot be evaluated by the same calculation procedures as the glare from electric luminaires.

In a recent paper on the state of the art in daylight glare, Collins et al. (13) indicated that laboratory experiments have shown reasonable correlation with predictions by the Hopkinson-Cornell large-source glare formula. They also show that if the window area is greater than about 2% of the floor area of the room, window size has relatively little effect on the glare perceived by a person looking directly at the window--the primary variable is the brightness of the sky as viewed from indoors.

We recommend that designers provide means to reduce the discomfort glare from daylight by properly locating work stations so that occupants' main directions of view do not include the sky or other external bright surfaces, and to reduce window luminance by using suitable shading devices. They also recommend light-colored surfaces around windows.

The addition of electric light away from the windows merely to reduce contrasts, and thus reduce discomfort glare, is not recommended because of energy considerations. However, in integrated systems, electric light is needed anyway; if properly designed, it can become a successful means of controlling daylight glare.

In summary, an integrated design involving daylight admission, controllable shading devices, and proper use of electric light can limit discomfort glare and keep it below annoyance levels.

SPECTRAL CHARACTERISTICS

Daylight is continuously variable in intensity, direction, and spectral characteristics. In special cases where the visual task involves accurate color judgements, reference should be made to the particular spectral distributions concerned--see Henderson and Hodgkiss (14) and (2).

Electric light sources have fixed spectral distributions that can be defined precisely. Data can be obtained from manufacturers' literature and guides on lighting, such as Refs. (15) and (16).

For most work activities, however, there are no strict demands for accurate color discrimination, and a wide range of lamps can be selected for integrating with daylight according to criteria that relate to the qualitative aspects of the total visual environment. Nevertheless, the electric lighting should have a color appearance and color-rendering characteristics compatible with those of the daylight. It should also be compatible with the interior color finishes.

Effective integration calls for lamps that make the occupants unaware, or at least unconcerned, that part of the interior is lit by daylight and the remainder by electric light.

The efficient types of fluorescent lamps are the favorite sources for general-purpose integration. For accurate color judgement, the less efficient "de-Luxe" types, having superior color-rendering properties, should be used. The new generation of so-called "tri-phosphor" lamps, which are more efficient than the de-Luxe lamps, should be used with caution in situations in which color comparisons are important.

THE DIRECTION OF THE FLOW OF LIGHT

The directional properties of daylight, which comes in the majority of cases through vertical side windows, differ from those of the general electric lighting, which usually comes from above. However, it should be borne in mind that the resultant flow of light is not highly directional from either diffused daylight or electric light inside interiors having interreflections from all surfaces. The exception is direct sunlight, which is generally limited in its penetration or excluded altogether.

The importance of the directional properties of lighting in a working space depends greatly on the activity pattern. Just as people usually pay little attention to the spectral properties of integrated lighting, in most cases they tend to ignore the differences in the directions from which light reaches their working surfaces. This does not mean that directional characteristics are unimportant, but that they are satisfactory for the majority of visual activities. However, in some visual tasks, such as detection of fine details in texture or enhancement of form and shape, directional properties can markedly influence visibility.

The concept of modeling was suggested by Lynes et al. (17,18) as a way to describe the directional characteristics of light. Ne'eman and Longmore (5) proposed an Integration Factor as a quantitative measure of the integration of daylight and electric light. This factor is defined by using the vectorial representation of the light field--see Gershun (19) and Helwig and Krochmann (20). However, we believe that more work should be done to quantify the directional properties of the light flux in integrated systems.

INTEGRATION, CLIMATE, AND ENERGY

The preferred type of integration is naturally related to local factors such as climate, daylight availability, cost of electric power, peak demand, etc. In predominantly cold climates, such as New York State, emphasis on the use of electric lighting is often justified because the lighting power contributes to the heating requirements. Also, in cold climates daylight tends to be less available on an annual basis than in warmer regions. These effects are discussed in more detail in the energy section.

On the other hand, even in cold climates, substantial air conditioning is required in summer. Daylight should be utilized as much as possible whenever its actual luminous efficacy in spaces is greater than that of electric light sources of similar spectral distribution (40-70 lumens per watt, including ballast losses). The nominal efficacy of daylight is 100-120 lumens per watt; however, actual efficacy in terms of cooling load impacts is often less. As discussed elsewhere, daylight must be effectively utilized in order to achieve these potential savings.

We see that lighting power consumption is an integral part of the overall energy management of a building. It should be mentioned that from energy considerations alone, the more efficient the electric lighting becomes, the less advantageous the utilization of daylight. As mentioned before, however, there are other considerations that make daylight the preferred source for interior lighting. Furthermore, the integration of daylight and electric light can utilize both sources optimally.

METHODS OF INTEGRATION

Because it was recognized that a single integration technique cannot cover all types of buildings and activities, attempts have been made to find a comprehensive classification of integration methods.

A draft report on the integration of artificial light with daylight, submitted by Longmore (21) to the CIE Daylignting Committee TC-4.2, suggested classifying the design guidelines for integration according to building type. Consequently, a wide range of buildings was selected: offices, offices where machines are used, computer rooms, drafting rooms, industrial buildings, hospital wards, libraries, and commercial kitchens and laundries. Long as it is, such a list cannot cover all building types.

An opposite approach has been adopted in Germany (11) where buildings are classified as residential or non-residential for purposes of integration design.

A more comprehensive approach seems to be a classification of integration methods, rather than building types (4,5). Every building can then be designed using the appropriate integration method, which can also takes into account specific local requirements and constraints. The proposed methods of integration are:

1. Single (mono) space integration with daylight dominant:

1a. with daylight entering through windows on vertical walls;

1b. with daylight entering through rooflights (skylights).

2. Single (mono) space integration with electric light dominant:

2a. as 1a above;

2b. as 1b above.

3. Interspace integration--using daylight in peripheral rooms and electric light in inner rooms.

4. Transitional integration--the coordination of adaptation levels in areas where people enter or leave a windowless building.

5. Outdoor Integration--for outdoor activities extending from daylight hours into dark hours. There is no change in location or space, but a time-dependent transition into which the lighting should be integrated throughout

the activity.

The major characteristics of these integration methods are listed in Table 5-1.

DYNAMIC INTEGRATION OF DAYLIGHT AND ELECTRIC LIGHT--DIDEL

We now add a new dimension to the known integration techniques--dynamic controls. The ultimate control system should include all environmental factors, i.e., thermal, visual, and, to some extent, acoustical. However, at this stage we are concerned primarily with the visual environment where electric lighting and shading devices are involved.

Manual switching of sections of the electric lighting system already provides a kind of dynamic option. Regretfully, it is well known that manual lighting controls have not been widely used. For this reason an effective dynamic integration can probably be achieved only with automatic controls.

We can currently utilize high-technology automatic devices, which provide a wide variety of control options. A few examples are studies by many research centers, such as work by Crisp (22) at the Building Research Establishment in England; and by Selkowitz (23), Rubinstein (24), and others at the Lawrence Berkeley Laboratory. Surprisingly, there are still few data on actual building performance--this remains a high-priority need.

Strangely enough, we have much knowledge of the technical aspects of lighting controls, while the human acceptance of such controls has not been investigated thoroughly. Occupant response to high-technology control is now being studied at the Lawrence Berkeley Laboratory by Ne'eman and Sweitzer (25).

In conclusion, we suggest that DIDEL aim at the maximum utilization of daylight and the minimum use of electric light to create an efficient and pleasant visual environment. Lighting energy consumption should be analyzed as part of the total energy use of the building. The proper design strategy is overall minimal cost of the lighting environment, not maximal energy saving.

Special care should be given to visual well-being by providing an acceptable view through windows and by avoiding excess glare from windows and luminaires.

SUMMARY AND RECOMMENDATIONS

Proper integration of electric lighting is essential from the perspective of both energy savings and occupant response to the building design. An effective lighting control system is a prerequisite to energy savings in a daylighted space; an appropriate strategy by which electric lighting and daylight are properly integrated is in turn a prerequisite to the overall acceptance of any system. In our historical review of attempts to integrate electric light with daylight and in our observations in current buildings that attempt to use daylight as a energy-saving strategy, several themes emerge:

- Any scheme for integrating electric lighting and daylight must recognize and account for the possibly unique circumstances and user needs associated with that specific design problem. Various integration strategies emphasize one or more aspects of lighting design, but not equally. It is therefore important to select the integration strategy that provides the greatest benefits for the specific situation being considered.

- The ability to select an integration strategy that meets user needs implies that those needs have been or can be adequately defined. At the present time, there is no unanimous agreement on the quantitative and qualitative aspects of lighting requirements for various visual tasks. More work is needed to understand and quantify occupant satisfaction and preferences given a variety of elements and individual environments. For example, daylight adds a dynamic quality to light level, luminance ratios, and modeling effects in a space. Assuming that minimum or maximum criteria for each of these are not exceeded, to what extent is variability in these parameters a desired or desirable feature in a daylighted space? The answer to that and similar questions will partially determine the relative dominance of an electric light source versus daylighting and thus begin to define some aspects of lighting hardware and control selection. These concerns extend to the issues of window size, window location in the wall, and view from window --all of which may have some impact on occupant reaction to a daylighted space. It should be emphasized that some of these issues can ultimately be reduced to simplified quantitative guidelines; however, others are more qualitative and subjective in nature and must remain so, although more information would be desirable and useful to design professionals.

- Once we have established the need for lighting integration strategies that go beyond task footcandles, we are likely to need more sophisticated lighting control systems and sensor systems that respond through software or hardware in a way that pleases occupants. The technology for such systems is probably available today; we lack a sufficient understanding, however, of the appropriate and desired reactions for the range of lighting conditions that would normally be encountered in a daylighted space. Some related issues in this area of controls are discussed in the section on lighting controls.

- A further dimension of the control problem is integration of electric light and daylight with fenestration controls to modulate solar gain and with other building operating systems such as the HVAC and security systems. It is fair to assume that in the future increasingly sophisticated building automation systems will be specified; to the extent that their operation has impact on electric light and daylight in a space, it must be designed with the appropriate integration in mind.

- The final decisions regarding lighting integration issues will often be made with some bottom-line criteria in mind, which will usually be cost-based. It is thus important to recognize that design decisions made in the context of providing an integrated lighting system must address not only the lighting energy and visual performance concerns but also a variety of other constraints that may be totally unrelated to lighting issues.

On the basis of the concerns outlined above, two important but fairly general needs are apparent. First, a variety of research studies are needed on a number of different aspects of user response and user preference to those aspects of lighting parameters that are critical when dealing with the integration of daylight and electric light. A complementary set of studies is required to extend the analysis of the integration strategies that are described here to a design handbook that building designers could use in several different stages of the building design process. Much of the information is such that a document might be based on a careful study of existing buildings in which the problem of daylight integration has been effectively handled. However, it would also be useful to extend the analysis from specific case studies to more general cases that would encompass the broad range of typical design conditions faced by architects. While information is available for many aspects of electric lighting design alone and daylighting alone, there are few relevant available data for modern buildings that address the problem of integrated lighting systems.

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TABLE 5-1

METHODS OF INTEGRATION OF DAYLIGHT WITH ELECTRICAL LIGHT

NUMBER	1a	1b	2a	2b	3	4	5
SPACE INTER-RELATIONSHIP	Single (mono) Space Integration				*Interspace—Spatial Transition* Buildings with daylighted peripheral rooms & windowless inner rooms	Entry to and exit from a windowless building	Outdoor activity—temporal transition
DOMINANT LIGHT SOURCE	Daylight (PSALI)		Electric Light		Daylight in peripheral rooms; electric light in inner rooms	Daylight outdoors; electric light indoors	Daylight during light hours; electric light during dark hours
HOW DAYLIGHT IS ADMITTED	Vertical outer walls	Rooflights: possible only on top floors	Vertical outer walls	Rooflights: possible only on top floors	Vertical outer walls	Indoors: windowless; outdoors: full daylight	-
ROLE OF DAYLIGHT	Dominant source: for at least part of the space. Allows view and contact with the outside	For the whole space. Limited contact with the outside	To add quality to the lighting and allow a view and contact with the outside	Background lighting and as a supplement to electric light electric light	Dominant source in peripheral room; little deeper penetration	Graduation of intensities according to fluctuations of daylight	Exclusive source during light hours; mixed with electric light during semi-dark periods
SIZE OF OPENINGS	Large windows exceeding minimum acceptable size	Large rooflights to illuminate the entire space	Smaller windows—however, not smaller than the minimum acceptable size	Smaller rooflights to admit a noticable amount of daylight	For peripheral rooms as 1a; no windows in inner rooms	-	-
ROLE OF ELECTIRC LIGHT	Zonal supplement to poorly daylighted areas; local lighting	Uniform supplement to daylight throughout the space on cloudy dull days; local lighting	Functional (task) lighting General lighting		Exclusive source in inner rooms	Exclusive source in windowless buidlings	Exclusive source during dark hours
SIMILARITY OF SPECTRAL PROPERTIES OF ELECTRIC SOURCES TO DAYLIGHT	Important Critical for accurate color judgments		Important Any good color-rendering source can be used for accurate color judgments		As 1a	As 2a	Prime importance for TV coverage
DIRECTIONAL PROPERTIES: DAYLIGHT	Side	Above	Side	Above	side for peripheral rooms	-	-
ELECTRIC LIGHT	Above	Above	Above	Above	Above for all rooms	Above	
EXAMPLES OF SUITABLE USE	Schools; small offices and workshops	Factories; museums	Large landscaped (open-space) offices, large factories, public buildigns, operating theatres	Small or large factories, public buildings	Deep-plan hospitals, offices, public buildings	Large factories, underground structures	Sports stadia, swimming pools
BENEFITS	Visual comfort, optimal energy savings; subjective well-being		Reduced thermal exchange with the outside in cold regions and less exposure to outside noise; in many cases optimal economical solution		Improved visual comfort, particularly for occupants who frequently move from one area to the other	Elimination of "visual shock" on entering or or leaving the building	Uninterrupted visual conditions on field and TV screens with transition from daylight to electric light

Section 6
REVIEW OF DAYLIGHTING DESIGN STRATEGIES

INTRODUCTION

This section reviews the major design approaches that incorporate daylighting into building designs. We emphasize the proven techniques that have provided effective daylighted spaces as well as discussing some of the more innovative but speculative approaches whose performance has not yet been convincingly demonstrated. We discuss several design approaches, some of which provide effective daylighting energy savings, while others provide esthetic or psychological benefits without energy savings being the major concern. We divide this section on the basis of the technique by which daylight is introduced into the space: sidelighting versus toplighting. In the case of sidelighting, we consider either an intermediate floor in a multistory building or a situation in a single-story building where roof penetration is not feasible or desirable. In addition, we consider the use of atriums as a combination of rooflighting and toplighting. Finally, we discuss other techniques that do not fit easily into these categories.

SIDELIGHTING

Sidelighting is typically the most common daylighting strategy, simply because of the preponderance of buildings with vertical glazing. These approaches can be divided into two major categories: 1) perimeter sidelighting, and 2) sidelighting with enhanced light distribution deeper into the space. A rule of thumb developed many years ago is that useful daylight penetration rarely exceeds 2 to 3 times the height of the window. Using this guideline, we define perimeter daylighting as encompassing those situations that provide daylight as deep as 20 to 25 feet into a typical office space having 9 to 10-foot ceiling heights. These techniques can be accomplished using relatively conventional window designs and relying primarily on the diffuse component of daylight. In these circumstances control of direct sunlight to prevent overheating and glare is a more important issue than utilizing direct sunlight to enhance daylight in the space.

Daylight penetration deeper than 20 to 25 feet typically requires utilization of direct sunlight and more sophisticated optical control of its penetration into the building. Some approaches to enhanced daylight penetration utilize simple architectural elements as well more sophisticated optical systems. By virtue of the fact that this approach relies more heavily on direct sunlight, hours of useful operation are more climate dependent and fewer than in perimeter daylighting schemes.

Sidelighting in Perimeter Zones

The greatest opportunity for daylight utilization exists in perimeter zones where glazing is already present to provide view or contact with the outdoors. We define the perimeter zone as limited to a depth of 15 to 20 feet, corresponding to the depth of typical individual offices at the perimeter as well as a useful boundary for a portion of an open-landscaped zone. In a zone less than 20 feet deep, it should be possible to provide daylighting for 60 to 80 percent of the operating hours in the year, depending on details of climate and orientation. In fact, in a perimeter zone it is relatively easy to provide daylight levels substantially in excess of the nominal 50 footcandles levels one might desire, at least in an office environment. Selections of glazing area, glazing transmittance, and shading system are necessary requirements to control the variability of daylight. Higher daylight levels can be tolerated if they can be introduced in a manner consistent with good vision and thermal control.

While in principle daylighting the perimeter zone should be routinely accomplished without difficulty, one need only survey buildings to see that this is not the case. At a minimum it requires suitable lighting controls and, as discussed in the lighting control system review, this has proved a problem. The two major problems are fenestration control and lighting control in the perimeter office. Fenestration control is necessary if the thermal loads and glare controls are to be effectively managed. Without meeting these two requirements, visual and thermal comfort in the perimeter zone will become the dominant issues affecting occupants, and daylighting energy savings will take a distant third place. Even if window systems are controlled adequately, the electric lighting must be controlled in a way that is responsive to both visual requirements and energy savings. An ideal system might integrate the two; such a system would probably be moderately costly, and few have yet been demonstrated. The single perimeter office has the additional problem that the relatively small floor area being controlled, perhaps 150 ft^2, will generate only moderate total savings even under the best of circumstances. It is these savings that must be balanced against the cost of both of the control systems described previously.

The complexity and cost of these systems will also be a function of the expectations regarding occupant interaction with fenestration and lighting control. Although it is reasonable to expect office occupants to take simple actions to adjust their environments, it is unreasonable to expect them to expend any large amount of time and concern with the system. This would detract from the productive function for which they are paid. The boundary between reasonable and unreasonable expectations is not well defined, and clearly will be highly variable depending on individual and situation. Because American office workers have not historically worked in environments where occupant control has been a major theme, it seems less likely that strategies based primarily on occupant control of fenestration and lighting will be most effective. Balancing this conclusion against the cost of fully automated control systems leads one to the primary conclusion that in a perimeter office, as much as possible of the fenestration control function should be provided by a fixed control solution. The equivalent conclusion for lighting controls would be to separate requirements for task lighting from ambient lighting and to use available daylight primarily for ambient purposes. In fact, in a perimeter office it should be possible to consistently provide task illuminance levels, but the additional design and hardware costs may exceed the extra savings. This depends largely on relative costs and savings and on details of the lighting system integration, which were discussed in the previous section.

We conclude that in a perimeter zone, defined as the outer 10 to 20 feet of a building, it should be possible to provide acceptable daylight levels throughout most of the working year, on the order of 80%, with conventional glazing and wall systems. The "optimum" cost-effective design (at the present time) probably includes a well-designed but simple fenestration system coupled with an automatic lighting control system that provides control of either full lighting or ambient lighting with additional task lighting under the control of the office occupant. It should be noted that the fenestration designs mentioned above will be orientation-sensitive, suggesting that the skin design of a building would differ depending on orientation. In new buildings designed for energy efficiency, this theme shows up more frequently. However, examination of existing building stock suggests that the vast majority of buildings utilize identical fenestration on all building facades. This places greater demands on occupant control of fenestration properties and introduces greater uncertainity in the likelihood of effective daylight utilization.

Enhanced Sidelight Penetration

To introduce daylight beyond the 20-foot boundary in most sidelighted offices requires designs that differ from the simple perimeter systems. Several new concerns emerge in these circumstances. First, the aperture that allows daylight penetration would typically be larger than that providing daylight for the perimeter zone. Second, even with an enlarged aperture, daylight levels in the space may be insufficient. This suggests that direct sunlight must be used to provide adequate levels. The difficulty with utilization of direct sunlight is primarily one of controlling distribution in the deeper perimeter zone as well as reducing the likelihood of thermal discomfort and glare. There are two primary approaches to admitting additional sunlight and daylight. The first increases glazing area, primarily by increasing ceiling height. Adding glazing to the lower end of the window near sill height does almost nothing for horizontal illuminance deep in the space. Raising the ceiling from a typical 9 or 9 1/2-foot level to 10 or 11 feet provides some improvement in penetration deep in the space due both to the increased area and to the angle of the light source relative to task areas deep within the space.

Finally, deeper penetration of daylight and/or sunlight requires special attention to work station/office design in buildings. Many work stations in modern offices utilize movable partition systems that block direct view of the window at the task location. Daylight at these locations will be limited largely due to the ceiling-reflected component, and performance analyses must properly account for these and other optical effects. If raised ceiling heights are utilized to increase the admitted flux, or even if clear glazing is used above a vision strip in which the luminance of the view outdoors is controlled, it is important to control the light admitted near the top of the window. First, occupants sitting in the vicinity of the window need to be protected from direct sunlight. Second, the daylight flux is probably sufficiently large that more is available than is needed immediately at the vicinity of the window. Therefore, it would be useful to "push" some of the available light flux deeper into the space. One architectural approach that can accomplish both objectives is to introduce a light-reflecting shading element behind the upper portion of the clear glazing. One such design solution is the use of a horizontal reflective light shelf, typically located 6 to 7 feet above the floor with several feet of clear glazing above it. It acts as an interior overhang to provide control of direct light penetration (at least for some solar positions), while using a diffuse or specular upper surface to bounce the intercepted light deeper into the space. Solutions of this type have obtained some degree of acceptance in part due to their apparent simplicity. However, there are few performance data to suggest the real performance of such systems. Under conditions in which direct sun is not present, these systems will reduce light relative to an unshaded window. A more appropriate comparison is with an alternative device that provides similar sun protection and some light distribution, such as a venetian blind or louver system. There appears to be insufficient technical information at the moment to determine the strengths and weaknesses of such systems and their energy-saving potentials. It should be noted that such systems have been used in hospitals in England for some time, primarily to control glare.

A more elaborate version of this approach would optimize the light shelf to specularly reflect light deep within the space. This might be accomplished with a fixed reflective geometry, necessarily a compromise between optical efficiency and varying sun position. Alternatively, operable tracking systems could be used to provide at least a one-axis tracking capability (i.e., varying with solar altitude but not azimuth). A variety of reflective or refractive optical systems can, in principle, provide this capability, and several have been developed and tested. None, however, has advanced to the point of being commercially offered on a wide scale. The operational reliability of mechanically complex systems is always a concern, and devices that provide good optical control with few or no moving parts will generally be preferred.

Deeper penetration of daylight can also be improved by modifying ceiling characteristics. There is limited experience with this area, which is receiving increased research interest. Three major changes might be considered. The first would be to slope the ceiling from a high level near the perimeter to a lower, more conventional, height deeper in the space. One advantage to this is the improved reflecting surface presented by the ceiling to the light admitted at the aperture. In addition, this allows the advantage of the higher ceiling without a substantial increase in floor-to-floor height, which is important to keep construction costs down. This approach would require additional attention to the location and placement of HVAC systems and other elements in the plenum space if it is to be obtained without an increase in overall floor-to-floor height. A second approach is to introduce light into a modified plenum cavity designed to transmit light. The ability to dedicate large plenum areas to this function and the ability to keep the surfaces highly reflective is questionable. The final approach is to modify the ceiling characteristics by changing texture and local geometry to provide enhanced daylight distribution deeper within the space. One approach might be the use of a more specular surface near the outer edge of the room to push light at grazing angles deeper into the space. A series of tilted ceiling panels deep within the space could be utilized to catch the light reflected off at grazing angles and distribute it diffusely into the area below. Design schemes of this type would require additional development to test their effectiveness.

While there is room for innovation and improved effectiveness in this area, one should note that high ceilings have always been recognized as an appropriate means for deeper daylight penetration. Older buildings, built prior to air conditioning and extensive mechanical systems, were often built without hung ceilings in plenum spaces and utilized the entire floor-to-ceiling height, frequently 11 to 13 feet. As described in the historical overview, building construction practices and costs generally have eliminated this design approach. It suggests, however, that there may be a useful retrofit potential in some of our older building stock.

Daylight utilization in the deeper interior zones also requires different lighting design strategies. In these instances it is typically unreasonable to expect daylight to produce adequate task illuminance levels; therefore daylight is seen primarily as an ambient light source.

TOPLIGHTING

Toplighting refers to those strategies by which light is admitted from a generally overhead direction as distinct from vertical windows near floor level. Sloped glazing such as that used to cover large atria are treated in a separate section following this one. Toplighting generally has its greatest impact in single-story buildings where most or all of the floor area is seen by the roof or ceiling. It could also be applied in the top floor of a multistoried building, and occasionally will be used to light more than a single floor if appropriate holes are cut in the intermediate floors. Systems that collect light at the roof and then funnel that light through lightpipes or conduits are treated later.

Unlike sidelighting where the spatial relationship between the light-admitting source and the space to be lighted limits the useful penetration of daylight, a toplighted space, in principle, can be entirely daylighted if appropriately sized apertures are uniformly spaced over the floor area. We consider two major types of toplighting: those in which simple flat glazing or bubble glazing is used over a simple opening in a horizontal or sloped roof membrane, and those in which roof monitors incorporating one or more vertical, sloped, or horizontal glazing elements are utilized to admit light and redirect it through the ceiling plane. An examination of warehouses and industrial buildings in the older section of any major city should reveal a striking diversity of roof monitor systems. In such older buildings with high ceilings, these systems allowed good control of incident daylight and sunlight as well as providing openings for natural ventilation. They are, however, structurally more complex than cutting a hole in a roof membrane. In the last several decades simple glazed openings in flat or sloped roof membranes were designed as the predominant form of toplighting. The fundamental difficulty with horizontal or approximately horizontal glazing is that transmission peaks in the summer and drops in the winter, exactly the opposite of what one would desire for good annual performance in most climates. Bubble-type skylights (which are used primarily for structural purposes) pick up some additional low-altitude sun if they are diffusing. We review below the key features of both types of rooflighting systems.

Conventional skylights are available in a variety of forms. The most common, however, are either rectangular or square elements with one or more sheets of plastic vacuum-formed into a bubble shape to provide added structural integrity. Typical construction utilizes an aluminum frame made from extrusions that hold the glazing in an appropriate gasketing system. Skylights are now commonly available as double-glazed units and in some areas are triple-glazed. In the past few years more attention has been paid to improving the insulating qualities of the metal frame and reducing the air leakage of skylights. Multiple glazing and insulated metal frames help reduce the likelihood of condensation on the underside of skylights, which can be annoying if it drips into the space. Gutter systems are frequently provided in the aluminum extrusions to catch any water that might form on the surface.

Glazing options for either vacuum-formed plastic or flat glass skylights are numerous. Clear, tinted, and white diffusing plastics are the most common. Diffusing plastics play an important role in spreading the light from a relatively small opening over a large floor area. This is particularly important when ceiling heights are low. However, good diffusion is achieved with some loss of transmissivity. Some newer skylights employ a double layer of acrylic lens material that diffuses the transmitted light without a substantial loss in transmission. Flat glass skylights are available in an array of types including reflective coated glass. The use of overhead glass in any installation must address safety in the event of breakage. Tempered glass, laminated glass, and wired glass may be appropriate choices.

In addition to optical losses through glazing materials, losses may occur as the light is transmitted through the thickness of a roof or plenum structure. In the simplest case in small buildings this depth may be well under one foot, which for a large skylight will have little effect. However, in a space with a hung ceiling, the plenum depth may be several feet. The light traveling through the skylight may also have to pass through a lightwell having a depth of several feet or more. This introduces optical losses approximately equivalent to those that would result from a reduction in transmittance in the glazing material, at least in the case of a diffusing skylight. In cases where nondiffusing glazing is used the lightwell itself can act as a light-diffusing element if the dimensions are such that direct sunlight will never penetrate.

In the energy analysis section of this report, we show that the potential savings through skylighted spaces are very large. Despite this fact skylights are not used nearly as frequently as they might be to provide natural light. One reason repeated frequently by building owners is the fear of water leakage. For a well-designed and carefully installed skylight system, this should not be a problem; however, it appears to be a major concern based perhaps on historical information.

From the perspective of interior design, skylights can be described simply as holes in the roof that admit light. In other situations, it is desirable to make the skylights appear as if they were light fixtures, and in these cases lightwells that terminate into diffusers can be utilized. A relatively small percentage of the roof area suffices to provide substantial daylight in the space. Energy analysis studies described in Section 6 indicate that for highly transmitting skylights, 2 to 5% roof coverage is probably optimal. From an installation point of view, it would be cheaper to provide this area in a relatively small number of large skylights. However, the penalty to be paid by such a strategy would be a highly nonuniform light distribution at the workplane. Calculation, model experiments, and experience in real buildings suggest that to preserve good uniformity, skylight spacing should not be greater than 1.5 times the ceiling height. This will suggest the grid over which the roof coverage should be spread. With lower transmittance, larger areas can be used but will incur greater heating energy losses. In situations where high ceilings are acceptable, the rule of thumb permits greater separation between skylights.

It should be possible to enhance the performance of even simple skylight systems by considering the slope of the roof (or tilting the base of the skylight in the case of a horizontal roof). One could also use other elements surrounding or covering the skylight that act to either reduce solar transmittance on a selective basis or enhance transmittance through the system by collecting additional light. Active mechanical tracking skylight systems are commercially available. Tradeoffs between useful daylight and cooling loads must be carefully considered. At the present time there appear to be few instances where the optimal benefits of such approaches have been carefully tested and evaluated.

The uniformity of interior daylight distribution is dependent on the spacing between skylights. To improve uniformity, one should increase skylight area (and correspondingly decrease transmittance). Carrying this to its logical extreme, one would make the roof structure, or a large portion thereof, a translucent, glazed surface which would have to have better insulating properties due to the increased area. A number of firms offer such translucent roof systems, typically double-fiberglass-skinned structural panels with insulating, light-diffusing matrix materials between the inner and outer layers. They can be fabricated in a variety of standard and custom dimensions, and can be used in vertical and sloped as well as roof applications. The daylight transmittance can be varied but is related to the insulating value since both depend on the density of the insulated filling. This technology has been used successfully in varied applications in many building types.

Another basic approach to toplighting is the use of roof monitor systems. This approach normally utilizes long, linear light-admitting structures over slots in the roof, often with vertical or sloped glazings. In some cases the monitor systems are attached to flat roof systems; in other cases the roof structure itself (e.g., a truss system) may be an integral part of the roof monitors. A great variety of roof monitor systems was used in the late 1800s through about 1950, primarily in warehouses and industrial buildings. Some utilize north-facing vertical glazing to admit diffuse light only; others utilize south-facing vertical or sloped glass to admit direct sunlight which may then be diffused by other optical elements in the monitor system, while still others have utilized combinations of glazing elements. These typically use more glazing per square foot of floor area than the horizontal skylights mentioned previously, but since many of the older buildings were not heated or cooled, this did not represent a severe penalty. These design approaches are rarely used today for warehouses, but there has been a rediscovery of the potential daylighting benefits of roof monitor systems for small offices and schools. In the 1950s a number of very successfully daylighted schools were built in California utilizing several different types of roof lighting systems. In moderate or cold climates, south-facing monitors are often used since the winter solar heat collected may be useful in addition to the daylight. The geometry of the south-facing monitor, the placement of the glazing, and interior baffles are all used to diffuse incoming direct-beam sunlight and to provide some summer sun control. In warmer, more southerly climates, north-facing monitors are also used. Control of direct sun penetration is a critical requirement in offices and schools. Louvers, baffles, lenses, shades, and other systems have been used for sun and light control.

To provide daylight over the entire floor area, a uniformly spaced set of roof monitors would be utilized. In smaller buildings with at least one major wall with windows, roof glazing might be added adjacent to a rear wall, far from the windows to provide a wall-wash lighting effect to balance daylight from the window glazing.

Recent DOE-supported studies have investigated the possibilities of integrating linear roof monitor systems with building structural systems to reduce total system costs. The glazing areas found to be optimal for use on vertical or south-facing monitors are consistent with the findings for horizontal skylights, 2-5% of roof area. For larger areas, increasing cooling loads negate additional daylighting savings.

A final application of roof lighting systems is the use of translucent fabric structures to enclose spaces. Air-supported and cable-supported translucent fabric roofs have been used for several decades to cover sports arenas and for short-term events such as World's Fairs. However, sufficient confidence has been gained in structural design and fabric system performance so that these roof systems are now being used for a greater variety of permanent structures, including retail stores and offices. In typical construction, an outer weather-resistant structural skin with 40 - 80% solar transmittance is combined with several different types of inner skins to provide the desired sun control and thermal control. For a fully covered roof, net transmittance is typically 4%. The major weakness until recently has been the poor thermal insulating value of these systems. However, recent advances in the use of higher-transmittance outer skins in conjunction with very thick (2 feet), fibrous batts (to maintain about 4% net transmittance) have resulted in translucent roofs with insulating values approaching those of conventional opaque insulated roofs. These roof systems can provide uniform light or, by using fewer inner layers in some locations, can vary the local roof transmittance and thus the interior illuminance. Researchers have worked on many mechanisms to dynamically control solar gain, daylight, and thermal properties, but none have yet been used in a major permanent building. Their ability to provide architecturally interesting large-span roof systems with potential structural cost savings and good daylighting/energy performance suggests that these systems will be used more extensively in the future. At the present time, each roof structure is a custom-designed project and only a few firms in the US have substantial experience and expertise in this field. However, the same technology could be applied to standard modules (e.g., 20' x 20', 100' x 100') which could be employed as pre-engineered elements in a wide variety of building applications. Continued improvements in coated fabrics and insulating systems and new technologies for dynamic control of optical properties could all advance the use of this design approach.

ATRIA

The use of atrium spaces in commercial buildings is attracting increased attention in the architectural community for a variety of reasons. Although there has been a resurgence in the use of atria in the United States, there is a long history of their use in European cities as well as a more limited historical precedent in American cities. Covered markets and large enclosed circulation areas have been important in urban design for hundreds of years. The recent interest in atria appears to stem partly from a perception of these spaces as energy-conservation strategies, and partly from the positive visual and aesthetic responses they evoke. We use the term atrium here to refer to any large enclosed space, typically with a combination of roof lighting and sidelighting.

The energy-related rationale for atria is based on their function as a source of illumination and their thermal performance. In many cases, they are used primarily to provide a dramatic change of scale within a building envelope. In the latter cases, an atrium space may be heavily planted, and the functions glazing primarily to provide adequate light to ensure that the planting survives. Providing the opportunity for office workers or hotel guests to stumble across a dramatically lighted and luxuriously planted monumental space within a building has been sufficient motivation to encourage use of atria without energy considerations. In milder climates, a plaza adjacent to a building may serve a similar purpose. However, in areas with climatic extremes, either very hot and humid or very cold, the beauty and drama of the plaza can be brought indoors and accompanied by a controlled environment. Covered circulation malls in large shopping centers serve similar purposes. In a number of urban environments, covered malls or arcades are becoming increasingly popular as weatherproof circulation areas between a large number of stores.

The potential energy benefits of such structures depend largely on the base case against which they are compared. Compared with an unconditioned open-air situation, they will generally use more energy because some climate control must be provided in the atrium space. Countering this perspective is the observation that the energy consumption of the store fronts that open to these spaces would be reduced because there may be no heating or cooling required relative to the circulation area. In some cases the enclosed area is controlled as a buffer zone where climate conditions are maintained intermediate between the fully conditioned spaces and the outdoors. This allows for many of the functions of these climate-moderated spaces without incurring the full energy penalty for conditioning such spaces. There appears to be little or no energy performance data on such approaches, although they are being studied now by several groups. However, the desire for such designs is strongly based on current architectural interests and design styles, and it seems unlikely that even a strong negative energy impact in these systems would radically alter interest in their use.

In at least a few situations, atrium spaces have been specifically designed as part of an energy-saving element in a building. In the Bateson building, a state government office building in Sacramento, California, the atrium space was designed with a carefully conceived roof lighting system that provided managed south solar gain with diffuse light from the north throughout the year. The intent was to use the solar gain in winter months as part of a heat-collection system and to use the daylight available in the atrium space to provide some spill light into adjacent office areas in the four-story building. The building has not worked entirely as planned for a variety of reasons, but it was one of the first buildings in which an explicit energy-performance criteria for the atrium space was laid out. A number of other buildings have been designed over the past few years to utilize large atrium spaces for both thermal and daylighting purposes. Simulation of the performance of such spaces is an evolving art, and much of the recent interest has centered on problems of HVAC design to control fire and smoke spread within the space.

We emphasize that presently there are no measured performance data to demonstrate whether these spaces perform as intended and whether they provide net energy benefits to the building. Looking at these spaces as daylight sources, the illumination levels provided in the atrium space itself are generally pleasant and suitable for virtually any casual tasks within those areas. In many cases, some direct sunlight is admitted to provide appropriate visual highlighting contrast. However, two critical lighting-related functions must be extensively examined. First, the role of these spaces as sources of light to adjacent office spaces seems highly questionable. In principle, it should be possible in a two- or three-story space with an appropriately designed roof glazing to provide adequate access to light in an office adjacent to the atrium. However, when building heights rise much above 3 stories, unless the atria have very large cross sections, quick calculations suggest that insufficient light flux would be transferred through the adjacent vertical glazing to provide useful light in those perimeter office spaces. Second, the ability of a deep atrium to provide adequate light for plants to thrive is questionable. Plants typically require 100 to 200 fc for 12 hours per day. In deep atria, or even shallow atria with limited glazing, these levels are not provided; supplementary electric lighting is required. Additional calculation, modeling, and field measurement studies are required to develop appropriate design guidelines.

Atria with extensive glazing may also produce large cooling loads, thermal discomfort, and glare. Proper design and improved materials should eliminate these potential problems. Operable shading systems can provide good control capability, but designers have been somewhat reluctant to specify these systems for relatively inaccessible locations.

Since atria are popular and desirable features, they will be incorporated in large and small buildings with increasing frequency. It will therefore be important to develop a performance data base from which we can derive sound design guidelines to assist designers in critical decisions regarding daylight in atria.

ADVANCED OPTICAL SYSTEMS

Much of this section has centered on new possibilities for daylight utilization based upon improved architectural designs. Our review of the opportunities in this area suggests that while significant improvements can be made relative to simple conventional fenestration systems, there are limited additional opportunities to squeeze even higher levels of performance from refinements in design alone. However, it may be possible to create significant advances if one utilizes new optical materials whose light control properties differ significantly from materials now in common use. The use of improved optics to improve daylighting performance is not a new thought. If one investigates the patent literature going as far back as the late 1800s one finds numerous examples of the use of clever optical systems to enhance daylight performance in buildings. At the present time, we can take advantage not only of the well-established reflective and refractive optic systems that have been known for more than a century, but we can also investigate more recent innovations such as those based upon fiber optic systems, or holographic coatings. In addition we must examine the use of optical systems whose basic performance has been understood for some time, but which were not previously economically feasible. For example, new advances in large-area thin-film deposition and other low-cost, high-volume production techniques may make optical systems practical and economical now that might not have been considered feasible some years ago.

In this section, we outline several technical approaches for introducing daylight and sunlight deep within buildings. In previous sections we have discussed the possibility of using new optical techniques to introduce light into extended perimeter zones in buildings, 20 to 40 feet back from the window wall. We now consider situations where light transmission is desired over even longer distances and where it may be desirable to penetrate either horizontally or vertically through the core of a building. Such optical systems typically require three major elements. First, a collection system is required to gather the available light flux and, in many cases, to concentrate it. Second, the light flux must be transmitted through a transmission system to the point of use in a building. Third, the light flux must be distributed in a way consistent with the end use of the lighting. While the latter function represents a number of practical concerns, not the least of which is spatial control and integration with electric lighting, the problems are less of a fundamental optical nature than they are engineering/design issues, and will not be considered further here. The collection/concentration problem and the transmission problem are closely related in that each represents potential constraints on the performance of the other. A number of these technologies have been investigated to varying degrees by researchers. Investigations of some of the architectural implications of several of these alternatives are being funded by the Department of Energy. However, there are not yet definitive research results or any practical operating systems so that this area remains ripe for significant research advances.

Collection/Concentration Systems

There are several types of optical systems for collecting and concentrating sunlight. A fundamental limitation of most of these systems is that they are designed to introduce direct sunlight into the building and therefore require a tracking function. Tracking systems include double-axis polar trackers which can introduce a beam of light with approximately constant cross section into an opening on the roof of a building for almost all sun and sky conditions. A simpler system would utilize an altitude-azimuth tracker where the primary mirror rotates in azimuth, and changes in altitude, to constantly direct sunlight down a shaft. Such a system is less efficient in intercepting light flux, but is simpler in that it uses only a single mirror. Skylights with these types of tracking systems are commercially available in the United States, although there is little or no definitive performance data at this time. Prototypes of the more complex double-axis polar trackers have been built and operated, but once again, we have only limited operating data. In principle, concentrating lens systems can be placed at the output of each mirror system to condense the cross section of the solar beam. In the limiting case, where a solid fiber optic guide was used as a transmission system, such concentration would be essential. Where an open shaft was used, the concentration issue is largely dependent upon the value of the shaft space used in the building. These issues are discussed later in the transmission section. Any tracking system designed to track the sun will suffer from great reductions in flux output when clouds or haze obscure the sun's disc. The flux intensity can change by several orders of magnitude in a matter of seconds as a cloud moves in front of the sun. Accordingly, the overall lighting system in the building must be designed to respond to such changes on the time scale at which they occur. Trackers can be designed to collect light from a larger solid angle of the sky than the narrow image of the sun's disc. However, the concentration ratio possible with large-angle trackers is directly limited by the radiance theorem.

Three alternatives to active tracking optical systems have been discussed. The first would use fixed optical elements arrayed so that at various times of the day the sun's image is properly introduced into the optical transmission system. These systems trade off the simplicity of no moving parts for poorer optical performance. In general, they would require larger apertures to introduce the same average amounts of light compared to a tracking system. However, for noncritical lighting situations such as circulation areas or other non-task areas, lack of precise optical control may not be a serious drawback.

The second option is the use of holographic coatings to collect light from different portions of the sky as the sun moves and introduce it into an interior space. While it can be shown that it is physically impossible for such a system to collect light from anywhere in the sky and introduce it to a single spot with good efficiency, it is possible to exert some angular control for limited wavelengths and redirect the light in ways that may be useful in the building. Several theoretical papers have discussed these possibilities and new experimental work is starting with support from the Department of Energy.

A third option is the use of fluorescent concentrators in which a fluorescent dye absorbs incident light and then readmits light within a narrow set of wavelengths. Much of the emitted light is totally internally reflected light within the fluorescent plate. The light collected over the area of the plate migrates to the edges where it may be introduced into a light guide system. Fluorescent concentrators have been extensively studied as energy concentrators for photovoltaic systems. The possible use of such systems as non-tracking daylight collectors and concentrators in buildings is under investigation at Lawrence Berkeley Laboratory.

While both holographic films and fluorescent concentrators show theoretical promise, neither has been convincingly demonstrated as a near-term practical option for daylight collection and concentration. However, both represent radical departures from the more conventional reflective and refractive optical systems. We suggest, however, that there may still be opportunities for combinations of refractive and reflective systems that can track the sun's image with a minimum of moving parts and effectively introduce the solar beam into a building. This is an area in which clever optical engineering, as distinct from some fundamentally new optical breakthrough, could provide the impetus for a practical and cost-effective system.

Light-Transmission Systems

Light guide systems are essential to transmit the light collected by any of the foregoing collection systems to the point of use in the building. As in the previous section, limited theoretical and experimental work has been conducted on a number of these systems but definitive performance results have not yet been generated. We describe four options here.

Hollow reflective light guides are perhaps the first to come to mind when describing conduits to transmit light into a building. These guides might have circular, rectangular, or square cross section, and would have a highly reflective coating on the interior surface. In the past, simulation results and measurements have suggested that typical reflective surfaces, with 80 to 90% reflectivity, do not yield very promising results for beams that are not highly collimated. However, new advances in thin-film coatings for mirror designs have resulted in surfaces with 95% reflectivity with the possibility that the reflectivity could be enhanced several percent more. At this level, light guides with a length-to-diameter ratio of 50:1 could transmit in excess of 50% of the incident light under many conditions. The actual transmission depends specifically on the degree of collimation of the incident beam or the angle which the collimated beam makes with the axis of the light guide. This is a case where relatively small improvements in surface reflectivity make a relatively large improvement in system performance.

Hollow dielectric light guides have recently been patented by Whitehead in Canada. The guide surface is a prismatic cross section which traps light by total internal reflection and redirects it back down the core of the light guide as long as the incident light remains within a cone of 26 ^{o} half angle. Optical losses are due only to imperfections in the prismatic wall surfaces. In practice, these amount to about 1% loss per foot of length for typical materials produced to date. However, when the guide is used as a light distribution conduit, the light lost from the sides may contribute to illumination in the space. This material is available as a commercial item for electric lighting use and a number of experiments are underway to investigate its feasibility with beamed sunlight.

Lens guide systems have been discussed for some time. Lenses and mirrors would be used to transmit and redirect the beam through an optical system. Each lens element introduces a source of optical losses which must be minimized to maintain high system efficiency. For systems with reasonably large guide cross sections, thin plastic fresnel optics would probably be used. Limited demonstrations of such systems have been completed but no practical systems have been fabricated or tested.

Solid light guides can also be used to transmit light. Fiber optic systems have the potential benefit of using flexible cables which can be routed as desired through the interstices of buildings. However, their small cross section requires highly concentrating optical systems to collect an adequate total flux and transmit it to the point of use. Solid guides of very large cross section, either of glass, plastic or even liquid-filled, seem impractical due to the weight and massive amount of material involved. In the fiber optics field, most materials have been optimized for transmission in the near infrared for communication purposes. However, both glass and plastic fibers have good transmission in the visible portion of the spectrum. This could no doubt be enhanced by further optimizing the composition of either the glass or plastic fibers for daylight transmission.

Several general issues recur in examining light guide systems. First, as stated previously, there is a relationship between guide selection and collection/concentration optics. For example, small diameter fiber optic systems would require concentrating collectors to introduce adequate amounts of luminous flux to a space through a small cross-sectional area. The intensity of incident sunlight (10,000 footcandles) is 200 times the required illuminance levels in a typical building. Therefore, in principle, a square foot of sunlight can light 200 ft^2 within a building. However, optical system losses will reduce this by a factor of 2, and the intensity of beamed sunlight varies considerably depending upon atmospheric path length, local atmospheric conditions, and cloud cover.

Thus, on the average much lower ratios between collection and use would be expected. This in turn sets limits on the fraction of floor area that must be devoted to light guide area. In some buildings, the light guide cross section may be introduced at the exterior of a building or in core areas that will not be otherwise used. However, in some cases the guides will usurp valuable rentable floor space, which may severely limit economic viability. The light guide cross section can always be made smaller at the expense of increasingly sophisticated concentration systems. At the point of collection, conversely, no concentration is needed and sunlight at its original intensity can be introduced if there are no limits on the guide cross-sectional area. At the present time, there is enough uncertainty both in the performance and the potential cost of both the concentration collection systems and the guide systems, so that no single option or combination of options is clearly preferable.

SUMMARY AND RECOMMENDATIONS

Daylighting design strategies can be conveniently categorized by their zone of influence in a building. Simple "perimeter zone" sidelighting and toplighting attempt only to introduce light a relatively short distance from the window or skylight source (less than 25 feet), and should be accomplished without extraordinary measures or techniques. Providing daylight in zones adjacent to perimeter zones (20 - 50 feet) requires improved designs and/or materials to properly transmit and distribute the light flux. Providing daylight more than 50 feet beyond an aperture will generally require specialized optical systems for light collection and transport.

Perimeter Zone

While a variety of solutions are workable in perimeter zones, there is a need to define, test, and standardize cost-effective solutions whose basic elements can be reproduced with minor modifications to suit case-specific requirements. For example, for an open landscaped office with west-facing window wall, ten-foot-high ceiling, and no exterior control devices, it should be possible to identify a series of workable standard fenestration/lighting control options whose features, cost, and performance may all vary. These might be presented in a case study book format showing real buildings incorporating these solutions. These standard designs would greatly facilitate the work of the average designer who lacks extensive experience in this area. Each proposed standard design should also meet some minimum criteria for lighting quality, etc. In the case of a simple skylighted building it should be possible to visually and quantitatively represent the effects of a variety of simple skylight/lightwell and roof monitor designs so that once again their relative performance (energy, cost, structure, etc.) could be readily compared. All case study books should stress design alternatives and their performance differences as opposed to recommending the "best" solution in a given circumstance.

Intermediate Zones

A similar compilation of designs would be useful for intermediate zones, but more basic research (illuminance modeling, new materials and devices, etc.) may be required to first generate workable solutions. For example, research oriented to refine and establish the performance potentials of light shelves is needed, as are studies to determine the effectiveness of sloped ceilings. Many of the somewhat speculative ideas mentioned in this section must be adequately researched to determine if they are indeed workable solutions. These include the active optical devices for projecting beam sunlight into spaces and systems to link fenestration and lighting control systems. There are opportunities to develop new products and/or new systems for incorporation into buildings. Once the performance analysis or product development work is completed, it will again be important to package detailed design and performance data on these systems so they may become standard options for consideration in many building designs.

Space Enclosure Systems

Atria, circulation malls, fabric structures, and other unique but well-defined spaces in nonresidential buildings provide special daylighting opportunities and problems. Atria are now widely used in buildings, with little technical basis for many of the designs, although energy efficiency is often cited as a rationale for them. Research and design studies into nearly all aspects of the lighting and thermal performance of these diverse elements will be necessary. Careful monitoring of these spaces in existing buildings would provide the complementary information and feedback needed to refine design studies. Two critical and potentially conflicting energy performance issues, daylight illuminance and solar-induced cooling loads, must be resolved through analysis and field measurement projects. Some space enclosure systems provide very large and often unmanaged glazing which may result in large cooling loads and thermal discomfort. At the other extreme many atrium spaces that penetrate deep within the structure of a building may look good to the people circulating in the space but may not provide adequate illuminance intensity for plant growth, thus requiring extensive supplementary electric lighting.

Advanced Optical Systems

Research on advanced materials and designs for daylighting deep within buildings is at an early stage. While a number of theoretical studies have been published, there is little systematic or extensive investigation of this field. In recent years several DOE-supported studies have been initiated but have not yet progressed to the point of producing definitive results. If successful solutions can be found these approaches do have the potential of increasing the impact of daylight utilization in some building types where it would otherwise be impractical. This would be particularly appropriate in densely built-up areas where the vertical surfaces of buildings have limited sky view but where there is access from the roof. Research is needed in four general areas.

- Optical systems analysis studies: Studies to identify the critical performance requirements for system components and elements and the cost targets that must be met if these systems are to be economically viable. This should also include the architectural and other building constraints imposed in the operation of such systems. A major element in this area is the problem of integrating electric lighting controls with the operation of these daylighting systems.

- Collection/concentration systems: Optical systems to collect and concentrate light for introduction into transmission systems. This would include engineering development of known systems as well as investigations into newer optical systems such as holographic or fluorescent concentrator systems.

- Transmission systems: Analysis of the materials issues, and the design and performance of alternative light guide systems for varying building applications.

- Distribution systems: Development of appropriate optical elements to effectively utilize the light delivered to the point of use by a light guide system. This may also involve integration with existing electric lighting systems.

Section 7
PERFORMANCE ISSUES: RESOURCE ASSESSMENT

INTRODUCTION

The availability of the daylight resource is critical to effective utilization of daylighting since it is a driving function for the daylighted space. Compared to other climatic data, the existing base of knowledge in this area is almost nonexistent. Although there are a number of meteorological stations that collect solar radiation data, there are no stations in the United States now collecting daylight availability data on a continuous routine and basis. The only such data now being collected is by several research groups, none of which are located in New York State. Calculation techniques are available to predict daylight illumination from first principles, and other techniques are available to convert radiation data into illumination data. But without a source of direct measurement for comparison, the accuracy and reliability of these techniques for any given location is still open to question. These techniques are discussed below.

Two aspects of daylight utilization make the determination of daylight availability more troublesome than an equivalent determination of solar radiation. Unlike solar radiation values for a building, which tend to be averaged over time because of thermal mass effects, daylight phenomena should more properly be viewed as a series of instantaneous events. Daylight values must always be averaged with caution because averages can lead to misleading conclusions. Second, many daylighting designs are driven by the diffuse light component rather than direct sunlight; there is much greater uncertainty in the magnitude of the diffuse component than in our understanding of beam radiation or the total radiation environment. Landscaping and other obstructions alter the local light environment, as will microclimatic atmospheric effects such as air pollution. These effects make highly accurate site-specific data impractical to obtain for any large number of areas.

As with other aspects of the daylighting field, there is a need for additional data and additional analytical methods to accurately predict daylight availability. However, given the limitation to absolute accuracy discussed previously, the data we now have from several sources are probably adequate for many uses. Information on daylight availability is thus not a critical limiting factor in design, but an area in which additional information would facilitate most design and may be necessary to help refine possible future designs that are more sophisticated. In addition, since daylighting availability data requires a cumulative record that can only be created over a number of years, it is important to start such measurements now so that the data base is available when future needs emerge.

DATA REQUIREMENTS

The term daylight availability refers to a number of different measurements of available illumination from the sun, sky, and ground. The type of data desired, its reliability, and level of detail required are all highly dependent on the intended use. The first need for availability data is for predesign analysis of building concepts. In this instance the requirement is for a limited data set that allows a designer to quickly and easily characterize the performance of an architectural design. Typical daily values may be useful, as well as annual curves or frequency of occurrence of a range of various exterior illuminance conditions.

To compare and evaluate alternative architectural strategies early in the design process requires standard design conditions or design events. These would include typical patterns of overcast sky, clear sky, and possibly partly cloudy conditions. These conditions would be expected to vary over the course of the year. At a minimum, horizontal illuminance values are required, and vertical illuminance values would be more helpful. These data are useful directly for analysis of the illuminance patterns in buildings. It may also be important to evaluate solar gain at the same time that illumination is considered under design conditions. For these purposes it would be necessary to have equivalent solar radiation values for the design conditions.

Energy calculations require a different level of availability data. In this case the interest is in performance over time, and techniques to average or sum performance are essential. One approach is to use numbers of clear, partly cloudy days to modify energy results obtained for typical daily sequences of conditions. Another similar approach is based on percent sunshine (rather than cloud cover), which is available in some locations. Limited data of both sorts are available for New York State locations. Availability data requirements for hour-by-hour energy analysis models differ from data needs for simplified energy models. The standard techniques now utilized in DOE-2.1B rely on either first-principle calculations within the program or conversion from radiation data. These are discussed in more detailed in the section on calculation models.

The final concern, although not as critical as those discussed above, is the variability of daylight over both short and long time scales. In designing time delays in lighting control systems, it is important to be able to estimate the probable range of daylight levels over very short time intervals. There are few or no data of this sort available at the present time. At the other extreme, long-term trends in daylight availability may also be important. Some suburban or rural locations may become more polluted and alter daylight availability levels over time as industry expands. On the other hand, areas with high existing industrial content may over time reduce air pollution emissions and thus increase the availability of daylight within the local microclimate.

DETERMINING ILLUMINANCE LEVELS OUTDOORS

Two approaches are now used for determining illuminance levels outdoors. The first is a calculation of illuminance based on the physics of atmospheric scattering, including an accounting for key microclimate parameters. The second approach assumes that an existing body of solar radiation data can be converted to an equivalent body of illuminance data. The strengths and weaknesses of each approach are described below.

Standard Sky Calculations

Standard sky conditions have been created by a number of different researchers, most noticeably by the Commission Internationale de l'Eclairage (CIE). Their definitions of standard overcast and clear sky conditions are widely accepted by both researchers and practitioners throughout the world. Their approach starts with a definition of a sky luminance distribution for overcast and clear conditions. Equations for these conditions are well-documented. The illuminance on any oriented surface is then calculated by direct integration of the sky luminance contribution as seen by that surface. The sky luminance distributions are given relative to zenith luminance values. Thus, the illuminance on an arbitrary surface is defined in terms of a zenith luminance value. The task remains to determine zenith luminance as a function of atmospheric parameters. A number of equations have been proposed for zenith luminance under both overcast and clear conditions, but none of these is universally accepted. In principal zenith luminance is dependent on atmospheric water vapor and turbidity. While atmospheric water vapor can be readily calculated from other available climatic data, the available data on turbidity are limited. For, example, in the DOE-2.1B simulation model turbidity data for typical values for several New York locations are given. From the calculations described above or from direct measurement, horizontal or vertical illuminance data can be described by a set of equations. Long-term measurements of these values are being made at four locations in the United States:

Lawrence Berkeley Laboratory, Solar Energy Research Institute, National Bureau of Standards, and the Florida Solar Energy Center. Various predictive equations, models, and data sets have been developed by each group. Work is under way to compare results from these measurements and those of research workers overseas. The output of these efforts will likely be several usable models for determining illuminance on vertical and horizontal surfaces, although it will probably be some time before universally accepted formulae are developed. A daylighting subcommittee of the IES Calculating Committee is publishing new recommendations for standard availability data. It seems likely that over the next year or two, the limited group working in this field will develop some concensus for improved availability models. It would be useful to add one or more sites in New York State to this network to extend the rather limited data base that is now being developed.

Determination of illuminance under partly cloudy conditions is more of an art than a science. There are no accepted procedures for determining these illuminance values, although the standard approach has been to average clear and overcast conditions. While this may give reasonable results under some conditions, it can produce large errors under other conditions. Another alternative is to divide all partly cloudy conditions into either clear sky or overcast depending on whether direct sun is visible. Even under complete overcast, the thickness of the cloud layers will tremendously influence the illuminance on vertical and horizontal surfaces. In the final analysis it may only be possible to predict illuminance under partly cloudy conditions on some statistical basis with the long-term average of the calculation agreeing with long-term measured averages.

Conversion from Radiation Data

Where measured or calculated solar radiation is available, it is possible to derive illuminance values by converting from radiation values. The approach works best if the available solar radiation includes direct beam and a measured diffuse component. If the measured value available is global horizontal radiation, the task of separating diffuse and direct introduces potentially large errors in determining the diffuse component. Most calculation methods dealing with the diffuse component assume an isotropic sky source, although this is known to be a poor assumption under both overcast and clear conditions. The luminous efficacy (lumens/watts) of solar radiation can then be determined separately for the beam component and the sky component.

There is a large body of data on the subject of efficacy, much of which is only marginally in agreement. Approximate efficacy values are 110 lumens/watt for overcast skies, 125 for clear sky conditions, and approximately 90 to 110 lumens/watt for direct beam radiation, depending on solar altitude. As a source of light, daylight has approximately the same efficacy as the most efficient electric light sources. Luminous efficacy may be altered by reflectance from special materials or by transmission through special glasses and coatings.

EFFECT OF LANDSCAPE AND OBSTRUCTIONS

The effect of the immediate area surrounding a building and adjacent obstructions on available daylight also is not well understood. Some common landscape materials have been characterized in terms of reflectance, but data on other materials are generally unavailable. In an urban environment the average reflectance of adjacent buildings becomes a critical issue. Reflective glass buildings may have a specular reflective contribution in addition to diffuse reflectance. In a more rural or suburban environment, particularly in northern climates, snow on the ground can tremendously effect daylight values. Reflection from snow may have a strong specular component, unlike many other landscape materials. The net result is that it is possible in some orientations, particularly north, to find the ground contributing more light to a space than the blue sky itself under clear conditions. For regions that are substantially snow-covered during many winter months when available sky illuminance is minimum, knowledge of these ground-reflected effects would be useful in enhancing the effectiveness of daylighting designs.

SUMMARY AND RECOMMENDATIONS

Additional data on daylight availability are required to assist in the design of efficient daylighted buildings. Although data are now available from a number of sources, they are not always available in the format that would be most useful at several different points of the design process. It would therefore be useful to develop a resource book that provides daylight availability data in several different formats that would be of use to designers. Since it is hoped that improved techniques for determining daylight availability will be emerging over the next few years, this source book could be compiled in a way as to allow it to be easily updated as better data are developed. It is important that much thought be given to the type of data necessary and the presentation format. In parallel with this short-term effort to produce immediately useful information, direct collection and evaluation of daylight availability data should also be initiated, preferably in several locations. From a practical point of view the locations should be chosen on some population-weighted basis. From a scientific point of view, it would be more useful to find several varying climate locations. Rather than developing this data collection capability at a new location, a more effective way would be to try to add daylight sensors to buildings that are already being monitored, or work with universities or other groups who have already embarked on solar radiation collection programs. Instrument maintenance and data reduction are extremely important issues if the measured data are to be used effectively. These projects should be linked to other ongoing national studies to maximize the potential for comparing data from different locations.

Section 8

PERFORMANCE ISSUES: THERMAL CONTROL

BACKGROUND

Although cooling is the predominant energy consumption factor in climate control of many commercial buildings, heating loads are still important issues and may represent the greatest source of energy consumption in small buildings and in buildings located in northern climates. The importance of heating is further reduced to some building owners because the fuel used is much cheaper than equivalent energy from an electric source. However, in all New York State climate regions heating loads are sufficiently important to be addressed.

Any aperture that penetrates an insulated envelope of a building creates the potential for heat loss. Windows and skylights have historically been viewed as the weak link in the envelope thermal integrity. The U-value (or heat transfer rate) of windows and skylights is generally 5 to 20 times higher than that of a well-insulated wall. So under peak heating conditions, windows contribute a disportionately large share to the building heat loss. However, the complete perspective on heating loads must account for building operating conditions and the useful solar gain that windows contribute. From a thermal perspective alone this introduces several new levels of complexity. Adding daylighting concerns to this picture further complicates an energy analysis study. Control of electric lights in response to daylight will mean that internal loads are reduced, thus increasing heating energy requirements relative to the identical building in which lights are not controlled. However, a nondaylighted building might also utilize different fenestration solutions that have inherently lower heat loss, so the alternatives that are to be compared are not obvious. We discuss below some of the key issues relating to control of thermal losses through fenestration and then describe existing and new fenestration solutions to control heat loss.

KEY ISSUES SURROUNDING CONTROL OF THERMAL LOSSES

Heat Loss Rates and Heating Fuel Requirements

The instantaneous heat transfer rate through a window is not necessarily a good indicator of the net heating fuel requirements. We can illustrate this point by reviewing several heating situations in a building. Assume a cold and cloudy winter day in which there is a net heat loss across the window element in the building. The net heat loss is calculated by determining the conductive transfer across the window (based on U-value) and subtracting from that any solar radiant gain that might occur even from an overcast sky. During night hours, of course, the conductive loss is the only significant heat transfer component, assuming air leakage is minimal. The building heating and cooling system, however, does not respond to the performance of the window alone but to the thermal requirements for each zone in the building. In the perimeter zone the net energy balance is determined by the windows, walls, roof and floor where appropriate, ventilation or air leakage loads, and internal gains. It is possible and even likely that during the year conductive losses through the skin of the building are more than offset by internal loads. This was particularly true when lighting loads ranged from 3 to 5 watts/ft^2. Thus, even though the fenestration at a given moment is losing thermal energy, the zone as a whole may show a net gain and may require cooling rather heating. Building heating and cooling systems must act to satisfy the net heating or cooling loads occurring in that zone.

The response of HVAC systems is highly dependent on the specific details of the system. Buildings that have simultaneous heating and cooling loads and primitive control systems tend to provide heated and cooled air to all parts of the buildings and meet loads by mixing appropriate quantities of heated and chilled air. This is an inefficient way to provide space conditioning, but represented standard practice in buildings until the 1970s. Most older buildings have perimeter systems that offset heat losses through the outer wall when cooling might be called for deeper within the zone. These systems were provided as much for thermal comfort as to control net heating loads. The temperature of single glazing in a building in a cold climate will be substantially lower than the interior air temperature, thus reducing the mean radiant temperature of the space and requiring raised air temperatures to provide equivalent thermal comfort. Perimeter heating systems located under the windows provided heat to offset these effects. One can see that the net heat loss at the window may not translate into a zone heating requirement, and conversely, even without a heat loss at the window, older buildings may require heating energy.

Once a demand for heating is generated, the HVAC system converts fuel input to delivered heat with different efficiency factors. First, with some loss of efficiency, the input fuel is converted to heat in a boiler, and then the distribution system that delivers steam, heated water, or air also engenders systematic losses. Pumps and fans represent further parasitic losses and add to the inefficiency of the heat delivery. By the time net heat is delivered to the occupied space, system heating efficiencies of 50 to 70% are not uncommon, and sometimes run even lower. Thus one unit of heat energy demand in an occupied space may require 1.5 to 2 units of heat as input fuel.

Building operation and control strategies also effect the translation of zone heating requirements into building fuel input requirements. Many older buildings ran 24 hours a day with lights on and temperatures maintained at constant levels throughout the work week, and occasionally over the weekends as well. Most office buildings and many other building types have more limited hours of occupancy. A standard office may be occupied less than 50 of a total possible 168 hours per week. New strategies to minimize energy consumption turn off the HVAC systems during unoccupied periods, letting temperatures float up in summer and down in winter to a point well outside the comfort range during occupancy. In the heating mode, this frequently results in a lower set point of 55^0 for unoccupied periods. The heating system may be turned on somewhat earlier in the morning in order to raise the air temperatures back to comfort level before people arrive in the building, but this strategy still generally saves energy relative to constant 24 hour temperatures. This means that apparent heat losses that occur at night (when the coldest outdoor temperatures are frequently experienced) do not necessarily result in net heating energy requirements in the building.

In summary, simple estimates of heating requirements based on U-values and degree days may not provide reliable estimates of the heating loads imposed on buildings or the load component contributed by fenestration. In addition, HVAC systems and building operational strategies can also substantially modify the translation of architectural heating loads into fuel input requirements. We discuss sample results based on hour-by-hour energy analysis in another section of this report.

PEAK LOADS

In Section 4 the impact of daylighting and fenestration on electrical peak loads is discussed. If heating energy is provided to the buildings through direct electric resistance heating or heat pump systems, heating requirements may contribute to a building peak in those areas that experience winter peaking electrical loads. Even in the case where electric peak demand is not an issue, peak heating loads may dictate the size of air distribution system, including fans and air ducts. Unlike chiller systems, the incremental costs of boilers is not large, but the direct and indirect costs of air distribution systems (as well as their operating costs) can be substantial. Increasing peak load without an increase in average load also means that the boiler systems will operate at a lower, part-load efficiency on the average. This too results in less efficient use of input fuel requirements.

DAYLIGHTING EFFECTS ON HEATING REQUIREMENTS

Electric lighting systems provide heat to occupied spaces, and in the heating season this energy is an important element in the thermal balance of the building. Reducing the energy input to the electric lighting system as part of a daylighting strategy (or for any other reason) alters the thermal balance in the space and may produce an increase in net heating energy requirements. Older buildings with very high installed lighting loads (3 to 5 watts/ft^2) generally have excess heat even on a cold winter day. Moderate reduction in the electric lighting usage in such a space would probably not drop the space from a cooling mode to a heating mode. Newer buildings, however, with 1.5 to 2.5 watts/ft^2, will operate closer to the switching point between net cooling and heating loads. Moderate reduction in these buildings based on daylighting strategies may be enough to move the building from a net cooling requirement to net heating.

Although the general trend described above is clearly definable, specific quantitative effects are more difficult to estimate. Not all the energy consumed by an electric lighting system is available to offset space heating loads, therefore not all the energy reduction due to daylighting will be translated into a higher heating load. The relationship between energy consumption in the electric lighting fixtures and impact on heating and cooling loads is a function of the electric lighting system, the HVAC system, and other thermal properties of the buildings. An example is a conventional office design with a nine-foot ceiling in the occupied areas, and recessed light fixtures in the lightweight ceiling, with a plenum space of approximately 3 feet above the fixtures. A fraction of the energy consumed by the lighting fixture is emitted by the lamps as visible and invisible radiation. Another fraction is lost as heat from the lamps and ballasts. All the radiant energy leaves the fixture, but some fraction of the convected and conducted energy warms the air in the plenum above. In buildings where the plenum space is used as a return air duct, this heat contribution will be transferred back into the return air stream. In situations where the return air is recovered through insulated ducts, this heat may warm the plenum space and indirectly the floor above, but will not be directly seen in the return air stream. Some designs utilize heat recovery fixtures in which the return air flows through the fixture, cooling the lamps and ballasts and improving lighting system operation. An alternative design, less used today, provides water cooling to each fixture to remove heat from the fixture that could be utilized elsewhere in the building. A typical value for the fraction of lighting energy that enters the space would be 60%. Thus, utilizing daylight to reduce electric lighting requirements by a given amount might increase the heating load up to 60% of that amount. These values are still the subject of some uncertainty and will be examined in a research project on lighting and HVAC interactions that is supported by the Electric Power Research Institute.

Although a number of writers have used this argument to minimize the savings from daylighting, it will almost always be more efficient and cheaper to provide the additional heating energy requirement through the building heating system than through the lighting system. The best strategy will generally be to use the most efficient lighting hardware feasible, get the greatest benefit from daylighting, and then make up whatever additional heat is required using the building heating system. Note that in office designs based on interior landscaping and task/ambient furniture-mounted systems, all the electrical consumption in the electrical lighting system will show up in the space energy balance.

ARCHITECTURAL SOLUTIONS FOR THERMAL CONTROL

We divide the range of possible architectural solutions to control thermal losses into three major categories: exterior devices, glazing systems, and interior devices. In each category we briefly review existing options, their impact on daylighting strategies, and new innovations in the field.

Exterior Devices

Exterior devices to close openings in buildings existed long before glass was invented. In the recent past in the United States, for cost as well esthetic reasons, exterior insulating devices such as movable panels or insulating shutters have not been very popular. We consider two general classes of devices, one that includes those devices that provide some insulating value but were designed for sun and glare control, and the second that includes devices specifically added to control thermal losses. In the first category are a variety of shading screens and operable exterior venetian blinds that provide modest reductions in building heat losses. This is accomplished because they act as a barrier to radiant losses and to the convective heat losses that tend to be wind-driven. To the extent that these devices provide still air pockets or at least reduce air velocities at and around the windows, these losses will be reduced. In general these approaches rarely justify more than R-1 to an existing window. This would generally not be sufficient to justify those devices for their insulating values only, but the effect is certainly welcome as an added benefit.

Hinged shutters, sliding shutters, and rolling shutters represent the second category. The hinged shutter has by far been most common in the United States, although these have been largely decorative and applied primarily to residences and small commercial constructions.

Rolling shutters have been extensively used in European buildings, so we have some basis on which to judge their performance. These devices perform a security function, provide sun control, and provide some insulating value, although they were not originally designed for that purpose. They normally consist of a series of extruded metal or plastic sections that retract into a roll at the top of the window opening. Newer versions are being manufactured with thicker cross sections, with insulating foam filling the hollow cross section, and with tighter seals between each element to improve thermal performance. Even with these improvements the added insulating value of the shutter system plus air space will generally not exceed R-2 to R-3. Added to single glazing, however, this will reduce the heat loss by as much as 75%; by perhaps 50% when added to double glazing. These devices are relatively expensive, but their costs can be justified because they provide multiple functions. In larger installations, the devices are frequently automated, but they can also be controlled from inside or outside the building, with a variety of cranks, straps, and ropes. Rolling shutters are also available with wooden slats. The thicker the slats, the more bulky the rolled device becomes at the top of the window. In general, it is more difficult to incorporate these devices as a retrofit than if they are planned into the design of the facade.

Exterior sliding shutters have been used primarily in a few residential buildings as a custom feature. A recent review of commercially available exterior insulating products suggests that such devices are not currently on the market. The advantage of a sliding insulating shutter is that thickness should not be a problem, and it should add R-10 to R-15 to the aperture with a device less than 3 inches thick. Incorporating such a sliding shutter into the exterior facade of the building represents difficult but not insurmountable problems. Sliding shutters with slats for sun control have been used. For discrete windows in the wall, shutters can slide from left to right. For continuous vision strips, shutters can be moved into place vertically. An optimally designed shutter might be partially translucent so that sunlight is admitted in the closed position. Rolling shutters have a loosely closed mode that transits several percent of the incident light. When tightly closed they become completely opaque. Like the rolling shutters, sliding shutters systems could provide privacy and security as well as some sun control, so their costs could be justified on more than thermal performance. However, any shutter system that has a very low light transmittance could not be used during the day without seriously reducing daylighting opportunities. If the systems are used during the nighttime only, their effective performance will be reduced if buildings are operated in a floating temperature mode at night. Optimal control strategies could be designed to tell when the thermal losses from windows during the day exceeded the daylighting benefits. This would imply that shutters might be closed on overcast days, but opened on partly cloudy cold days when the daylighting benefit would exceed the reduction in thermal loss. There is at this time no good technical guidance regarding optimal operating strategy for such a shutter system.

Glazing Systems

The primary control of thermal losses through fenestration has been relegated to the choice of glazing system. The old standard of single glazing has been largely replaced, both by building code and common sense, by double glazing and occasionally triple glazing. In addition there is emerging a new family of products based on the use of first- and second-generation films and coatings that will reduce winter heat losses. In addition, new materials science technologies suggests that in the future it may be possible to have thick insulating glass with the transmittance of conventional glass, but with the insulating value of a solid wall.

Although single glazing is not generally the choice in new commercial buildings in New York State, a large fraction of the existing building stock is only single-glazed. Besides completely replacing the glazing systems, there are two approaches to increasing the glazing insulating value. First, an additional sheet of glass or plastic can be added to the inside or outside of the window. The choice of glazing material depends on a number of economic, architectural, and esthetic details. The second approach involves gluing a coated plastic film to the existing glass area. These films were originally designed to provide a solar control function; however, most manufacturers also offer a version having a low-emittance surface that reduces heating load up to 40%. These first-generation films use an aluminized coating on polyester, which is then protected with a polypropylene overcoat. The polypropylene overcoat is transparent to longwave infrared, thus producing the low-emittance interior surface. The U-value of a single-glazed window can be reduced from 1.1 to approximately 0.8 under standard winter conditions, and as low as 0.68 under mild winter condition.

Newer versions of these films offer much higher light transmittance. Older products are highly reflective, providing only as much as 20% light transmission. Two new products extend this range to above 50% visible transmission while still providing some solar control. These differ from the transparent heat mirrors discussed in the following section largely because they are at least partly reflective in the solar spectrum. We can expect to see most of the major solar control manufacturers offer an increased selection of films that combine low-emittance surfaces to control heat loss with higher visible light transmittance. Clear guidelines on the best use of these products must be developed in order to optimize their use. The solar film industry has been the target of an investigation by the Federal Trade Commission because of confusing, if not misleading, advertising. The advent of additional film types will add to that confusion unless the new performance attributes are clearly identified.

Double- and triple-glazed windows reduce heat transmittance by virtue of the insulating value of the air space contained between the glazed layers. The glazing itself may be clear, tinted, or reflective, or various combinations. The heat loss rate is largely determined by the spacing between the glass layers and by the presence of metallic coatings on any of the glazing layers. Double- and triple-glazings can be made in two general ways. The multiple glass layers can be hermetically sealed with metal spacers separating the panes and organic sealants enclosing the glazed package at its edges. Desciccants are normally added to absorb moisture and other gases in the sealed air space to prevent fogging. Spaces are kept as small as possible to reduce the size of the unit and to increase the lifetime. This may result in a degradation in thermal performance because air spaces less than one-half inch in thickness begin to have a rising U-value. At a quarter-inch thickness, thermal performance of a double-glazed unit is degraded by about 20%. Multiple-glazed units can also be made with each glazing layer in its own sash and frame element. In these designs the spacing between the layers may be much larger and in some cases may incorporate a venetian blind or other sun control device.

Reflective coatings in the air space in multiple-glazed windows reduce the heat transfer rate below that of identical windows without the coatings. The metallic films provide a low-emittance surface that reduces radiative transfer in the same way as the coated plastic films for single-layer windows. These window systems are generally highly reflective, and the metal layer provides the solar reflectivity. These metals are frequently fairly fragile and are therefore enclosed in sealed glass units. Single-glazed reflective units utilize other coating systems that do not generally provide the same degree of longwave infrared reflectivity. The addition of a reflective metal coating to a double-glazed window reduces the heat transfer rate to the value of triple glazing. Note also that the visible transmittance of these systems is normally very low.

Approaches to reducing thermal losses from fenestration can be roughly divided into two broad categories: improving the thermal resistance of the glazing elements themselves, or adding exterior or interior devices to improve thermal performance. The advantage of the latter approach is that the same devices that provide thermal control may also provide solar control, privacy, or some other function. This spreads the cost of the device over a larger number of functions. On the other hand, these approaches tend to reduce light transmittance and may interfere with view. For this reason, there is much interest in improving the intrinsic thermal performance of glazing systems without degrading light transmission or any other desirable window feature. In this section we describe several new glazing systems that have been recently introduced or that look promising in research laboratories. The emphasis of this section is on intrinsic glazing solutions, but we include a short section on new approaches to interior and exterior thermal control devices.

If we take conventional double glazing as a base case, new thermal improvements will emerge from an examination of its thermal performance characteristics. Opportunities exist for reducing thermal losses on the inner and outer surfaces, in the glazing material itself, and in the air space between the glazings. Major modifications to the exterior surface of the glazing are difficult because this affects its appearance, and any solution must withstand direct sun, wind, rain, and other environmental assaults. Similarly, modifications to the interior surface will be subject to periodic cleaning, indoor air pollutants, fingerprints, and other factors that might degrade performance. Glass itself has a very high conductance but good mechanical strength, resistance to abrasion and corrosion, durability, high clarity, and low cost relative to other solutions. Although plastic has a lower conductance, in the thicknesses that are practical for window systems this has very little useful effect. Research on foam-like materials that have the clarity of glass but much better insulating values is discussed later. However, this material is relatively fragile and must be protected by glazing layers on either side. Thus, we turn our primary attention to opportunities for improving thermal performance by reducing heat transfer in the air space between double glazing.

Heat transfer in a double-glazed cavity occurs by radiation and by a combination of conduction and convection. Under typical winter conditions, approximately 60% of the heat transfer is due to radiation, with the remainder a conduction-convection effect. Radiation transfer occurs between the two inside surfaces of the sheet of glass, the glass itself being opaque to longwave radiation. Since the air in the gap is transparent to thermal infrared radiation, the radiation transfer is independent of gap size. On the other hand, conduction/convection processes are highly dependent on the gap dimension and to a lesser extent on the overall slot geometry. Most strategies for improving window thermal performance revolve around techniques to reduce or control longwave infrared transfer between the pane and/or conductive/convection transfer across the air gap. Since radiation is the dominant heat transfer mode, the most obvious strategies involve reducing radiative transfer. Reducing convective transfer without a change in radiative properties will not produce substantial improvements. In fact, if all convective/conductive transfer was eliminated using a vacuum between the panes of glass, heat loss would be reduced by only about 40%, bringing the performance of the double-glazed window to a level slightly better than that of triple glazing but not as good as quadruple glazing. We will discuss the pros and cons of several approaches to reducing heat transfer in the air gap between double glazing.

CONVECTION SUPPRESSION

When the gap spacing is very small, heat transfer occurs by conduction only. As the gap spacing is increased, heat transfer by conduction is reduced, but at the same time natural convection currents start in the air gap, thereby increasing heat transfer. The net result is that the heat transfer rate drops at first as the air space thickness increases, reaches a minimum at about 1/2 to 1 inch in thickness, then rises gently and levels off up to a width of several inches. Aside from evacuating the air space, strategies to reduce convective/conductive transfer involve replacement of air with a gas having lower conductance and/or less convective heat transfer, or strategies that divide the air space into a number of spaces which, taken together, increased thermal resistance.

The simplest example of the latter strategy is conventional multiple glazing. Adding additional layers of glass, each with an air space of 1/2 inch, increases the total resistance of the glazing unit. Each added air space provides an additional R-1 value to the glazing unit. The difficulty with this approach is two-fold. First, each additional layer reduces the solar gain through the window system by about 15%. Second, the size and weight of the window system become unacceptably large when more than three or four glass elements are used. In principle, it might be possible to use very thin glass as a third or fourth layer between two outer glazings of conventional glass. However, large sizes of such thin glass are not routinely manufactured, and the handling and installation of the unit might prove to be a problem. An alternative is to add inner glazing layers made of thin plastic films, typically 1 to 5 mils in thickness. The film of choice for clarity, cost, and weatherability is polyester terephthalate (PET). However, PET has a higher index of refraction than glass and, although its absorption is low, it transmits only about 85% of the solar spectrum due to the high surface reflectance losses. However, it is possible to treat the surface of PET to reduce those losses, resulting in a high-transmittance film that maintains the other desirable properties of the base polyester. A film of this type is manufactured by 3M Company and has been incorporated into commercially available systems. The antireflectance coating is made by steam oxidation of an aluminum film, resulting in an dendritric-film structure that acts as a graded index antireflection film. The film itself should be relatively durable but must be protected from mechanical damage by placement within the sealed glass unit. Note that while the thermal performance of this window system with equal air spaces is slightly worse than the equivalent all-glass structure, if the units are compared on the basis of total overall exterior dimension, the performance is about equal. This is because the thin plastic film takes up less of the air space and allows larger air gaps than in the case of conventional triple glazing. The transmittance of the entire assembly could be increased if low-iron glass was used for the inner and outer glazing layers. A quadruple-glazed unit with inner and outer glass layers and two intermediate plastic films will have U = 0.26 (R4) and a solar transmittance of 0.6.

An alternative approach to creating a series of parallel air spaces is to divide a larger air space into cells of sufficiently small size so that the air within each cell operates largely within a conduction regime, with minimum convective heat transfer. This can be accomplished by dividing a thick window into a series of stacked air spaces. Research results from Berlad et al. suggests that R-10 windows are possible if the air space dividers are themselves insulated slats with low-emittance surfaces. Interferometric studies reveal that the air space geometry achieved characteristic of conductance only. In the configurations studied, the slats are designed to be closed at night so that they overlap in the center of the window, providing additional insulation but eliminating the view. The study concluded that in the open mode small clearances between the slats and each glazing layer are permissible, without degrading thermal performance. A similar concept utilizes transparent polyester material to divide the air space into triangular and rectangular cross sections. Test results show that R-5 values can be obtained with some loss of visual clarity. The system is unlikely to be economically viable unless the assembly process can be simplified and automated.

There is much literature on the use of honeycomb systems in flat plate collector covers to reduce heat loss. If the requirements on view out of the window are relaxed, many different cellular or fibrous materials can be introduced between glazing layers to reduce heat loss. Normally, as the insulating value is improved, the visible transmittance decreases substantially.

The other major approach for reducing convective/conductive is to substitute a low-conductance gas for the air in conventional windows. By selecting gases with the proper conductivity and kinematic viscosity, heat loss can be reduced. Note that as the air space increases, air itself performs reasonably well. However, for small air spaces there are a number of gases such as argon, krypton, sulfur hexafluoride, freon, etc., that show improved performance. The only major application of this technology in the United States is the use of carbon dioxide in insulated glass units that have sealed glass edges and relatively small gaps. However, in Europe more than 100 manufacturers of insulated glass use gases such as argon, sulfur hexafluoride, and freon to improve the thermal performance of the units. Although the performance improvements are only modest, the incremental costs are small. Such a strategy assumes that the hermetically sealed units are able to contain the injected gas over long periods of time.

It should also be possible to combine the use of low-conductance gas with one of the physical barriers described above. For example, a double-glazed unit with two plastic inserts (and therefore three air gaps) could be constructed with a relatively small air gap and still have a lower U-value than conventional quad glazing if it contained a gas such as krypton.

RADIATION SUPPRESSION

Control of radiative heat transfer across the air space of a double-glazed window has been the subject of much research and commercial activity in the past six years. It has long been known that the use of a low-emittance film in an enclosed air space will significantly reduce the heat transfer rate. The highly reflective metallic films used for solar control purposes in sealed glass units show this effect. However, a more desirable product is a low-emittance film with relative high transparency to the solar spectrum or at least to the visible spectrum. These films have been termed "heat mirrors" because their primary function is one of trapping heat within a space by reflecting longwave infrared radiation. The low-emittance (low-E) film optimized for winter heating purposes would have low emittance, on the order of 0.1, and a high transparency to the full solar spectrum, preferably 70% or above. A low-E film useful in an office building, however, should provide a reduction in U value and some sun control but maximize visible light transmission. The coating properties would thus switch from being transparent to reflective at about 0.7 microns, which is the limit of the visible spectrum. In general, there is a tradeoff between minimizing the emittance of the film and maximizing solar transmittance. It is easier to provide a low-E film with low solar transmittance than it is to provide the same emittance with high solar transmittance. In the section that follows we refer to the film optimized for winter heating as a transparent low-E film, and to the film optimized for commercial building applications (e.g., daylight transmittance with some sun control) as a selective low-E film. The larger and more obvious market has been the transparent low-E films for use in residences in cold climates. However, in the last two years there has been increasing interest in the selective low-E films for daylighting applications.

Low-E films can be used in two ways in window systems. The film can be applied directly to a sheet of glass, which is then incorporated into a double-glazed unit. The films can also be deposited on thin plastic, typically PET, which can then be either glued to the window surface or suspended vertically in the air space as a third glazing layer. In typical applications, the addition of a low-E film in an air space is approximately equivalent to adding another layer of glass. A detailed discussion of the pros and cons of both types of film systems and window configurations is beyond the scope of this study. Both types, however, are under development by a variety of manufacturers. The first product to appear on the architectural market was a transparent low-E film on plastic produced by Southwall Corporation. This product was designed to be incorporated into sealed glass units as a suspended third layer. It has very good optical properties but is not sufficiently durable for an exposed application. A selective low-E film on plastic has been marketed by several films as an advanced solar control film with higher transparency than conventional films. The product has reduced overall transmission compared to a transparent low-E film but is selective for the visible wavelengths, thus providing relatively high transmittance in the visible spectrum. A number of manufacturers both in the United States and overseas are developing a variety of coated plastic films. The problem is less one of producing the ideal optical properties, than insuring that both the low-E film and the plastic substrate have sufficient durability under typical operating conditions. In addition the product must compete in cost, so both the material and the deposition process must be conducive to high production at low cost. The cost of producing the coated plastic film is only a small component in the ultimate cost to the building owner of the complete window system. At present low-E films on plastics that are sold by the film manufacturer at 50-75¢/ft^2 appear at the retail level at an incremental cost of \$3-5/ft^2.

High-transmission, low-E films on glass are beginning to be introduced to the architectural market. Selective low-E films have been available in the European market for some years, and have competed successfully with triple glazing. Glass manufacturers have pursued two approaches to the application of low-E films to glass. One approach is to apply the film with a vacuum deposition process. Due to the increase sophistication of transparent low-E films compared to conventional solar control films, this has required major new investments in new vacuum deposition systems. Over the past several years Airco, a major manufacturer of glass coating systems, has developed transparent low-E coatings that can be produced by glass manufacturers who purchase their deposition systems. These systems are operating in Sweden, Canada, and in several plants in the United States and have now been ordered by a number of other U.S. glass manufacturers. In 1983, glass manufacturers began to offer transparent or selective low-E films in the architectural market. Samples of such coated glass had been fabricated and used in experimental buildings over the past several years but were not yet commercially available. Research in these fields is now directed toward further improvements in coating properties, improvements in durability that would permit use in non-sealed windows, and techniques for producing even cheaper coatings using non-vacuum-deposition processes.

Once a low-E film is used in double-glazed windows the dominant heat transfer mode in the air gap becomes convection/conduction. Adding a low-conductance gas now provides a more substantial improvement than if the gas was added to a window without a low-E coating. The use of a low emittance coating and gas in double glazing can result in heat transfer rates in the range 0.25 - 0.3. The low-conductance gas can serve two purposes. It can provide the same thermal performance with what would otherwise have been a suboptimal gap, or it can reduce the conductance substantially below the equivalent air-filled window. In addition to the cautions described earlier in the discussion of low-conductance gases, one must be sure that there is no reaction between the gas fill and the low-E materials. These gases can additionally reduce heat loss rates if added to windows incorporating low-E on stretched plastic films.

We speculate for a moment on the minimum heat loss rates that could be obtained from windows that utilize a combination of low emittance films and low conductance gases. A double-glazed window with a heat mirror coating on the number 3 surface and a vacuum in the space would operate at R-20. There are no fundamental reasons why such a window could not be built using today's technology. But making sucn a system commercially available at a cost-effective price involves engineering and product design solutions that maintain the vacuum over long periods of time and create the spacing between the plates without seriously degrading vision through the glass. This approach has been investigated in the past and is being explored at the Solar Energy Research Institute using laser-fused glass-to-glass seals. The other alternatives involve use of one or more vertical plastic layers with low-emittance coatings in the air gap. With proper selection of gap spacing and gas, this approach can result in an R-10 window system. Adding a second vertical plastic film with a low E-coating improves the performance out to the R-12 range. One can see that it is technically possible to build relatively high-transparent window systems (40 to 60% solar transmittance and even higher visible transmittance) using materials and designs that either are available today or will be available shortly. One such window system, utilizing two layers of low-E coated plastic in a rather wide air space, is available in Switzerland in prototype units.

The opportunities and problems with low-conductance windows based on low-E films and gas fills revolve around several issues. First, it is clear that very low conductance window systems can be built. However, there remain uncertainties with the durability and lifetimes of these systems, both the low-emittance films themselves and the plastic substrate on which they may be deposited. Any hermetically sealed system depends in part on the lifetime of the edge seals. The sealed insulating glass industry is in the midst of a long-term study of the factors that contribute to premature failure of sealed glass units. The permeability of existing sealing technologies must be assessed if new gas fills are to be used. Second, although high R-values can be obtained, one quickly reaches a point of diminishing returns in all but the very coldest of climates. Beyond about R-5 and certainly beyond R-10, the incremental improvements in performance are minimal. If they can be obtained at little or no extra cost, they are desirable, but if a cost or performance penalty such as reduced visible transmittance is associated with them, the added performance will generally not prove desirable.

Identification of the proper mix of desirable, cost-effective properties as a function of orientation and climate is not well understood. As with other emerging technologies, the first few years after market introduction will be critical to the ultimate acceptance of these window systems. Major failures of one or more noticeable buildings could cripple market acceptance in all such products for some time. Furthermore, because optical and thermal properties are so variable, there is a large potential for confusion at the level of the architect and engineer.

Transparent Insulating Materials

The ideal device to place between double glazing would be a material that is optically clear, has a very high transparency, reduces convective/conductive and radiative heat transfer, is highly durable, and can be fabricated cheaply and simply. In this section we describe a material that may meet all tnese objectives. Transparent aerogels are materials having a high fraction of very small voids or air spaces. At a microscopic level the material looks like an open 3-D lattice structure. Ninety-five percent of the volume of the material is air. Because the particle sizes are very small, light scattering is minimized and the material is highly transparent and optically clear. It has a low index of refraction (approximately 1.01), so surface reflectance losses are minimal as well. The optical and thermal properties of aerogels made from silica have been recently investigated at Lawrence Berkeley Laboratory (LBL) and are promising candidates for transparent insulation. The material itself is relatively fragile, although it is reasonably strong in compression. Present techniques for fabricating the material involve supercritical drying of a silica gel, which must occur at high temperature and high pressure. Further investigation may be able to simplify this production process. Because of the very small pore size, the conductance of the material can be lower than that of still air. In addition the material acts as a radiation barrier to longwave infrared. Placing a slab of such material in the air gap of a double glazed window results in performance values of R7 per inch. One could further improve these values by substituting a low conductance gas in place of air, or possibly by utilizing a vacuum in the system. The material must be placed in a sealed environment to minimize water vapor absorption, which degrades its optical properties. Although it is too early to tell whether this will prove to be a useful architectural solution, it appears promising at this time. A DOE-supported research project is in progress at LBL to further explore this material.

If a diffusing glazing is acceptable an alternative approach is to use transparent insulating matrix material that maintains high transmittance in a diffuse mode while providing good insulating properties. Materials of this type have been extensively used as glazed wall and roof panels. They normally consist of fiberglass sheets bonded to an aluminum frame of varying thickness and filled with fibrous insulating material.

SUMMARY AND RECOMMENDATIONS

If the energy benefits from daylighting are to be maximized, thermal losses from building apertures that admit daylight must be controlled. The standard for most windows until recently has been single glazing; double glazing is now becoming more commonly accepted. At R-2, however, even the resistance of double glazing is far below what one would desire for good thermal control of the building envelope. This section has described a number of technical approaches to produce window systems ranging from R-4 to R-20. In addition to reduction in heat loss, each of the approaches has an impact on view from the window, solar transmission, visible transmission, appearance, and cost. To facilitate development and utilization of the next generation of thermally improved window systems, we suggest the following activities.

Window System Analysis

One of the primary problems confronting manufacturers who can produce improved window systems and the architects and engineers who will specify them is the question of what thermal performance level are justifiable in commercial buildings in climates characteristic of New York State. This question has an energy savings component and a cost component. If cost were not a problem, then the window system having the lowest U-value consistent with daylighting criteria would be the best choice. The practical problem, however, is to identify the point of diminishing returns where further improvements in window thermal performance are not worth the additional cost. The problem is complicated by the large number of parameters that influence optimal thermal control solutions. Studies should be undertaken to identify the cost-effectiveness of the various thermal control solutions. For existing window systems this will provide guidance for architects/engineers who must make product selections, and for researchers and manufacturers it will help identify desirable performance characteristics for new products they may be developing.

Demonstrations

Building demonstrations that provide documented results can be useful in accelerating the acceptance of emerging technologies. These demonstrations should be carefully planned and executed. They should be oriented toward validating the performance of generic products as much as possible rather than specific proprietary products. Selection of appropriate buildings and experimental plans is essential to successful completion of such a project.

Testing Standards

Existing standards to determine the U-value of glazing systems will be adequate for determining performance values of new glazing systems. However, for a variety of operable systems existing test methods are incomplete or inadequate. Test results are likely to be altered by test conditions, the size of the product, and mounting details. The coupling between the thermal and air leakage characteristics of the primary window and the insulating device is not well understood. Industry groups such as ASTM have initiated same efforts in this area but have not developed definitive recommendations. The test standards that ultimately emerge from such a process will be important not only to manufacturers but also to specifiers, designers, and utilities that might consider incentive programs to accelerate conservation investments (e.g., Southern California Edison).

Product Development

As described earlier, there is a relatively large amount of product development work supported by the private sector. However, there are always situations in which good ideas languish for lack of suitable support. The complete cycle of product development from R & D through market introduction generally is extremely costly. The best use of new research funds would be to cost-share with existing private sector research to leverage private sector capital or to act as a catalyst to generate other investments.

Glazing Systems Research

This topic includes work that is more fundamental than the product development discussed above. Because of its nature it will engender a higher risk than product development efforts and thus be less likely to attract private sector support. The relationship between the basic research and ultimate products should be investigated in detail early in the process.

Field Testing

Demonstration projects, if properly conducted, serve largely to build confidence in the performance characteristics of energy-efficient systems. However, it is frequently impossible in a whole building demonstration to carefully identify the specific window system contribution. Laboratory testing is more controlled but will not produce results that are necessarily indicative of performance in the building. Field tests of fenestration systems that combine a high level of technical accuracy with the impact of all climate parameters are extremely important to validate the computer programs and performance data on which architects base design decisions. Such studies will generally cover not only thermal performance but also net energy performance, including both daylighting and thermal efforts.

Section 9

PERFORMANCE ISSUES: SOLAR CONTROL

KEY ISSUES OF SOLAR CONTROLS

Designing a building to provide effective daylighting does not guarantee that overall building energy consumption will be reduced. Daylight will reduce requirements for electric lighting energy, but the glazing systems required to admit the daylight may introduce thermal loads that increase heating and cooling costs, which in some cases may exceed the electric lighting savings. It is thus critical that daylighting strategies include proper control of heating and cooling costs as well as peak electrical loads. In this section we discuss the problems and opportunities for providing sun control to minimize air-conditioning loads in conjunction with effective daylighting strategies.

Five key issues emerge in any discussion of solar control and daylight utilization in buildings. In each case one finds opportunities where daylighting and solar control requirements reinforce each other, thus improving cost-effectiveness, but there are also situations where these strategies conflict, requiring some sort of optimization. Many of these conflicts have non-energy components in addition to direct energy components. The five key issues are: 1) view from window, 2) thermal comfort, 3) visual comfort, 4) admittance of light, and 5) peak load versus energy use.

View from Windows

An important function of much of fenestration is to provide contact with the out-of-doors. Optimum orientation and window position for daylighting benefits may differ from view requirements, and both may differ from sun control requirements. Architects almost always attempt to utilize fenestration when spectacular views exist at a particular orientation, even if this choice creates the potential for large cooling loads. In this case extra care must be taken to control the cooling load impact.

The choice of architectural solutions and devices to control solar gain may obstruct view from a window. Some solar controls are more obstructive and more disturbing than others, and each obstructs view in different ways. For example, overhangs and fins limit the field of view, but within that field of view generally do not interfere with view. Reflective and tinted glass are optically clear and, although they reduce brightness, will not distort the scene in any noticeable way. View out of a tinted or reflective window depends on the balance of light within and without the building. Near sunset, as the exterior environment dims, an occupant in a brightly lit interior will see a reflection of the room in the windows and will lose the view outside. Privacy is a related concern; the same semitransparent mirror effect occurs during the day but from the opposite perspective. When it is bright outside, an outside viewer perceives a mirror image in reflective and some tinted glass and cannot see inside. This is often desirable, and there is some design flexibility provided by selection of specific types of reflective coatings. Diffusing materials such as drapes may provide light but no view at all, or may provide an obscure view where only approximate outlines of outdoor objects can be seen. Screen materials with varying percentages of openness may provide a granular view like a high-contrast television image, and the clarity of the view will depend in part on the brightness of the scene illuminated outdoors, as well as the color and texture of the screen material. Venetian blinds and other louver systems can be retracted to provide an unobstructed view, but when used they introduce a visually disruptive element across the field of view. Depending on the adjustment of movable devices like venetian or vertical blinds, view can be favored in a specific direction. With all these devices the view as observed from deep within a room and the view as observed by a person standing right at the window may differ.

Thermal Comfort

The object of any solar control system is not only to reduce energy consumption for air conditioning but also to improve thermal comfort. Uncontrolled solar gain is a potentially serious problem in terms of occupant thermal comfort and more so in recent years where the tendency is to set interior temperatures at the high end of the comfort spectrum. Thermal comfort can be affected by direct solar penetration, by indirect penetration, and by proximity to warm surfaces that have been heated by the sun (e.g., tinted glass). It is not uncommon to find building materials in proximity to office occupants heated to 110^{0} to 140^{0}F when the air temperature outdoors is warm and the building is illuminated by direct sunlight.

Visual Comfort

Architectural solutions and other devices used to control solar gain may also provide some relief from glare. However, one cannot assume that all good shading solutions are also good solar control solutions. Solar control solutions that work by absorption and reflection will tend not to affect glare in an adverse way. However, solar control solutions that have light-colored surfaces and tend to diffuse light may produce very bright surfaces in the field of view. These light-colored surfaces may be desirable for admitting daylight, so the simultaneous requirements for sun control, glare control, and daylight admission may present difficult tradeoffs.

Admittance of Light

Sun control is, in some sense, fundamentally opposed to the admittance of daylight in buildings. Understanding the source and nature of solar radiation allows one to admit sufficient daylight for interior lighting while controlling total solar gain. Daylight has approximately the same luminous efficiency as the best interior electric light sources [≈120 lumens/watt]. This implies that daylight used indoors can replace lighting with no adverse effect on cooling and perhaps with cooling benefits if it is utilized well. Since the efficacy of daylight is about 120 lumens/watt and since conventional fluorescent system are in the range of 60-90 lumens/watt, one frequently reads that using daylight to replace electric light saves much cooling energy. This is a potentially misleading statement for two reasons. First, although the efficacy of daylight is probably higher than the efficacy of most current light sources, efficacy alone is not a proper metric for comparison. One needs to include distribution effects within the room as well as time-dependent effects. For example, in a sidelit room, meeting the required footcandle level near the back of the room requires excess footcandles near the front of the room because it is difficult to get uniform light distribution from a unilateral window source. The higher light levels near the window may be desirable but will also contain additional energy that will add to the cooling load. Second, if one designs a daylighting system to meet a required illuminance level under average conditions, then for some fraction of the year when the outside lighting condition are higher than average the interior conditions will exceed required levels. Once again the extra light may be desired but the heat gain associated with it may wipe out any apparent cooling load savings. If one designs for peak conditions to minimize this problem, then the average daylight contribution over the year may be substantially reduced. The ideal daylighting system, which modulates light through the window perfectly throughout the year and distributes it perfectly throughout the room, would not have these difficulties. However, at the moment, real architectural solutions suffer to varying degrees from both these problems. In the absence of more specific information on the efficacy of the electric lighting, the fairest statement would be that daylight has the same net effective efficacy in a space as electric light and will thus not enormously impact cooling loads either positively or negatively. This assumes, of course, that the daylighting strategy is effective.

The second major aspect of the fallacy is to compare a room having windows and electric light but no lighting controls to a daylight space that is identical except that electric lighting controls have been added. In this case, clearly the daylighted room has reduced cooling loads because the rooms are identical other than that electric light is not utilized in the daylighted case. However, this is a falacious comparison because there is no reason to expect that a room that does not utilize daylight needs to have the same fenestration system as the room that provides daylight. Thus a proper comparison might be a high-transmission window with lighting controls as the daylighted case and a similar room with tinted or reflective windows or perhaps smaller windows as the nondaylighted case. The relative performance of each will vary depending on the design details as well as orientation and climate. Even if the daylighted case provides better annual energy consumption for cooling loads, one still needs to worry about the peak contribution. This is discussed later.

The source of radiant gain in a space varies considerably both spatially and spectrally. Direct sun is a major contributor to cooling loads and can be a contributor to effective daylighting designs, although the primary source for daylight utilization has been diffuse light from the ground and sun. Sun control schemes, however, generally do not respond to the sky and ground as a source. As we strive to assert more sophisticated control over the energy flows in buildings, it will be increasingly important to utilize control systems that control the diffuse sky and ground sources as well as the direct sun source. On a peak basis the diffuse sources generally are not major factors; however, on an annual or seasonal average they may be major contributors to cooling loads.

Peak Load Versus Energy Use

Solar gain impacts building design, energy cost, and economic costs in two ways. In designing a solution that accommodates sun control throughout the cooling season, the cooling energy consumption and therefore annual cooling costs are affected. But solar gain also plays an important role in determining peak electrical loads in many buildings. Since commercial building owners are charged electric demand rates in addition to energy rates, control of peak electrical loads can be an important factor in controlling costs. In addition, peak cooling loads dictate the size of chillers, air distribution systems, and other design elements. Larger chillers operate less efficiently at a low fraction of rated capacity, and larger fans require higher electrical consumption over every operating hour during the year, not just under the peak condition. Thus peak design constraints impact annual energy use as well as peak demand conditions. Due to the variable nature of the daylight resource, operable strategies are frequently preferable to solutions. However, even automated operable systems provide more uncertainty than do fixed solutions in terms of response to peak load conditions. The conservative approach is to provide a solution and size critical building components around that solution. The better performance alternative may be to utilize a more sophisticated operable system; however, one must be able to count on this system operating properly to manage peak loads. This is an important area that will be discussed in greater depth later.

BASIC PRINCIPLES OF SOLAR CONTROL

Before discussing the pros and cons of various approaches to light and sun control in buildings, we review a few basic principles of the control of radiation through building apertures. Sunlight impinges upon a building from three sources: the sun, sky, and adjacent surfaces including both the ground and other obstructions. Radiation arriving at a window or skylight enters the building in three interrelated modes. Some sunlight will be directly transmitted through the opening without obstruction by any element or device. Some sunlight will be indirectly transferred into the building by reflection off of one or more surfaces in the fenestration system. Finally, energy from the sun can also be admitted to the building by being absorbed in one or more elements and then convected and reradiated into the building. The percentage of absorbed energy that goes into the building or to the outdoor environment varies tremendously depending on the properties of the absorbing element and its placement relative to other elements in the window system. For example, an opaque black screen located outside the window would absorb most of the incident radiation and then reradiate and convect most of that absorbed radiation to the outdoor environment, thus admitting little of the energy indoors. However, the identical device mounted behind a window would absorb the same fraction of energy, but most of the absorbed energy would be convected and reradiated into the building. Conversely, very light-colored reflective louvers mounted outside a window may diffuse the incident sunlight, a large fraction of which may be bounced indoors to contribute to the cooling load. The same white louvers mounted indoors, if properly tilted, would bounce and diffuse much of the light back outdoors. Thus the apparent reflectivity or absorptivity of a device alone does not determine its impact on cooling loads through fenestration.

The professional engineering societies have developed several standard terms to characterize the ability of a fenestration system to control solar heat gain. Solar transmittance refers to the sunlight either directly or indirectly transmitted through a window system as shortwave radiant energy. In some cases the directional properties are identified. For example, a sheet of glass will have one transmittance value for direct sunlight passing perpendicularly through the windowpane, and a slightly lower transmittance for diffuse sky light incident from all directions. Visible transmittance refers to the transmitted portion of sunlight as seen by the human eye. Many glazing systems and materials have different solar transmittance and visible transmittance values, so that it is important to specify which of the two one is referring to. Standard, clear one-eighth-inch, double-strength float glass has a normal solar transmittance of about 85% and a normal visible transmittance of about 91%. The difference between the two is due to absorption in the near infrared, which reduces the solar transmittance but does not affect the visible transmittance.

Shading coefficient is the standard metric for comparing solar heat gain of fenestration systems. The shading coefficient is defined as the ratio of total solar heat gain of a specific fenestration system (including directly and indirectly transmitted, as well as absorbed and reradiated, components) compared to the solar gain through one-eighth- inch, double-strength, clear glass under the same conditions. By definition it is not dependent on temperature or the intensity of the incident energy. Numerical values of shading coefficient range from 0 to 1.0. It is possible to get slightly higher values than 1.0 with low-iron glass that has a higher transmittance than normal float glass, but for practical purposes shading coefficients range from 0 to 1.0. Thus a device having a shading coefficient of 0.5 would transmit 50% of the energy that one-eighth-inch, double-strength clear glass would under the same conditions. Two common points of confusion need to be noted. First, shading coefficient is not synonymous with the visible properties of glazing materials. Two devices with two different shading coefficients will not necessarily have the same ratio of visible transmittance. Second, shading coefficient is relatively constant under differing sun conditions for homogeneous materials such as clear, tinted, and reflective glass, but becomes highly sensitive to angular effects for devices like venetian blinds. To properly characterize geometrically complex devices one needs to specify the solar angles under which the shading coefficient were measured or calculated.

The majority of buildings erected in the past 20 years take fairly conventional and not always effective approaches to sun control. This statement is supported by observing that the retrofit market for solar control window films is a huge and ever-expanding activity. This suggests that there are large numbers of buildings that do not satisfactorily control solar gain. Good building design should reflect the fact that the solar conditions on each of the four major orientations are substantially different, and one would expect the architectural response would be different. However, even a cursory view of existing building stock suggests that the vast majority of buildings do not recognize these orientation-based distinctions. With the exception of interior shading devices, conventional approaches to solar control tend to rely largely on static solutions. We review these solutions in the sections that follow.

Architectural Solutions

This term describes exterior elements that can be seen as part of the architectural design of the building rather than devices attached to the windows and skylights.

The most common shading element in this category is a window setback, which is equivalent to using an overhang plus side fins. In new buildings, the shading potential is limited since wall thickness is held to a minimum to maximize interior space. Lease agreements typically specify floor area calculated to the glass line, so there is a strong economic incentive to place the glazing at the outermost edge of the building.

Traditional fins and overhangs have been part of some architectural styles, but run counter to "modern" trends that emphasize smooth-surfaced buildings. A number of recently completed office buildings in California utilizle a variety of articulated skins, but these are not representative of standard practice.

Building elements can be utilized to shade other portions of the building, although this would not normally be the primary reason for determining a building footprint. Several buildings utilize sloped exteriors in which the upper stories project beyond the lower floors, providing some sun control. The effectiveness of these strategies obviously depends partly on orientation and climate.

Exterior Sun Control Devices

This category includes a variety of devices that are attached to the exterior of windows or skylights. They include plastic films, woven fabric, woven metal, punched and perforated screens, awings, and various types of louver systems. The devices vary widely in cost, durability, appearance, and performance.

Products such as woven fabric generally attenuate the incident light but do not distinguish between direct sunlight, diffuse sky, or ground-reflected light. The density of the weave and the color of the material control the transmittance. Darker materials control solar gain by absorption, whereas lighter materials reflect the greater percentage but also generally transmit slightly more. For an exterior device, the majority of absorbed energy is convected and radiated to the out-of-doors, so the distinction between absorption and reflection is not critical. Shading coefficients for these systems fall in the range of 0.1 to 0.5. Fabrics are typically mounted in frames, which in turn are mounted to the window system. Clearance is provided between the screen and the window so that heated air can flow easily around and over the screen to be dissipated outdoors. These screens also provide some protection against flying objects and will reduce heat loss by a small amount.

Two varieties of metal screens are available: punched and woven. Punched screens are generally fabricated from aluminum and have small tilted fins that provide some angular control of incident sun light. Woven metal screens consist of small louvers that are woven into place at a particular angle and cut off all but very low-angle sun. For both of these products, ground-reflected light enters somewhat more easily than sky diffuse, and both have a shading coefficient that varies with angle of incidence. Altering the color of these devices will affect the transmitted energy because of their louver-like construction. In this case the darker the device the better it will perform as an exterior shading system.

Large louver systems come in fixed and operable units for vertical, sloped, and horizontal configurations. Materials are usually sheet metal, aluminum, or plastic, some filled with insulation. Operable units can control daylighting, nighttime temperature, security, and noise. Again, costs, scale, appearance, durability, and performance vary widely. Shielded systems, such as those between two glass walls, have proven effective in several new commercial buildings. Louvers are typically light in color, maximizing the daylight reflected into interiors. Shading coefficients depend on angle of incidence for fixed systems, but on operating strategies for operable systems.

Smaller louvers or heavy-duty venetian blinds, long popular in Europe, are not commonly applied in the U.S., although their popularity is increasing. These units can be automatically or manually operated from inside. Concerns include aesthetics, view, and durability. Snow, wind, or rain may require the blind be automatically retracted in order to prevent system damage. These blinds have traditionally been under the control of building users affected by them. Automatic controls that optimize their performance must be carefully considered before selection.

Rolling blinds typically use finely woven fabrics. Their type, color, and openness of material affects performance. Different strategies would be applied for different climates and building orientations. Weather durability is a concern for these blinds, although they have been used in Europe for years. Rolling shutters, which also provide sun control functions, were discussed in Section 8.

Awnings have traditionally been used in residential construction, but are finding increased application to low- and mid-size non-residential buildings. Awnings come in a variety of colors, sizes, shapes, and materials (primarily fabrics), and may be permanent, seasonally installed, or operable (manually or motorized).

All exterior shading systems require careful selection and operation in order to optimize their sun control benefits. Operable systems have the greatest potential benefits but the least user experience. To date there is little guidance available for daily or seasonal adjustments by climate, building type, orientation, or indoor activity. For operable units which move slowly, as the sun moves, there are fewer complaints than for systems which respond quickly or have controls out-of-reach from building users. The interactions of fenestration controls with HVAC and lighting controls are not yet adequately understood.

Glazing Controls

A wide variety of glazing materials is available for control of solar gain. In addition to clear glazing there are two general classes of glazing that provide solar control. Tinted glass utilizes absorbing materials dispersed throughout the glass itself. Reflective glazings utilize a surface coating that may be deposited any number of ways to reflect and absorb incident energy. Each type of glass can be combined into multiple-glazed units, and the reflective coatings can also be deposited directly on the tinted or heat-absorbing glass. Heat-absorbing glass is available in three major varieties: grey, bronze, and blue-green. The total absorptance is a function of the thickness of the glass, with thicker glass providing greater absorption and less transmission. Grey glass has approximately neutral transmission and will transmit approximately the same percentage of visible light as total solar radiation. Bronze glass, because it uses different absorbing materials, generally transmits more solar radiation than visible light. Blue-green glass acts in the opposite way, with a much higher light transmittance than total solar transmittance. This is possible because only about 50% of the solar spectrum is visible light, the remainder being shortwave infrared.

Reflective coatings can be deposited on either clear glass or tinted substrates. The properties are highly dependent on the materials used for the coatings and the process by which they are deposited. These in turn vary widely depending on whether the coating must survive in an exposed environment or whether it will be protected in the air space of a double- or triple-glazed unit. The higher performance coatings generally are metallic films and require some protection within a sealed glass unit. These and other films can be used to make a multilayer structure that has a selective transmittance. Several glazings that have higher daylight transmittance than overall solar transmittance are commercially available in Europe. In general these selective coatings are more desirable than the nonselective coatings, although they will frequently be less durable and more expensive.

Clear glass can be converted to tinted or reflective glass by gluing plastic solar control films to it. This is viewed primarily as a retrofit strategy, although it can be used in new construction. Plastic solar control films come in tinted or reflective varieties. They are applied to the inner surface of the window in retrofits, but might be applied to the number two or three surface in a double-glazed unit in a new window. Newer versions of these films are also selective in their transmittance and will provide higher daylight transmittance than total solar transmittance. In addition, some of the films also have a low-emittance surface that reduces radiative heat loss. These are discussed in more detail in the section on thermal control (Section 8).

Sun control may also be provided using glazing materials other than glass. For skylights, various rigid plastics are traditional alternatives. Double-walled ribbed plastics are available in tinted and clear forms. Translucent fiberglass panels are also used as glazing materials and have tinted versions that provide some sun control. Glass blocks, which enjoyed widespread use in an earlier era, are making somewhat of a comeback after being abandoned almost entirely by the end of the 70s. Each block consists of modules four inches square up to about a foot square and typically two to four inches thick. They generally have a diffusing middle layer or ribbed surfaces on the two glass elements. This can provide a general light diffusion or can redirect the light in a specific direction. These glass blocks have only moderate sun control capability, with shading coefficients that range from 0.3 to 0.8.

Interior Shading Systems

Interior shading systems include the familiar array of blinds, shades, and drapes, as well as a few newer products. These devices are generally operable in one form or another and are designed to provide privacy as well as to control light and solar gain transmission. In addition, since they are seen by office occupants, their esthetic appearance is usually a major factor in their selection.

Two trends are emerging in the newer interior shading products. First, products incorporating more highly reflective surfaces are becoming available, thus reducing the attainable shading coefficients. Unlike exterior devices, most of the energy absorbed in interior devices remains in the space, so reflectivity is a desirable feature. Pleated blinds, venetian blinds, roller shades, vertical blinds, and draperies having various reflecting surfaces have become commercially available during the past few years. A second trend is the increased interest in automatic controls for window shading systems. These may be used to store or deploy a simple device or to adjust a device (e.g., venetian blind) to provide better solar control. Once one has an automatically controlled system, it should be possible to link fenestration control, lighting control, and other building functions to a microprocessor that determines the optimal operation of each controlled building element. However, we know of no buildings in which such systems are operating.

New Sun Control Options

The energy simulation results in Section 4 point to the importance of balancing daylighting benefits against cooling loads resulting from excessive solar gain. We described at length a number of solar gain control options available to designers. We also noted a trend toward using operable controls to provide maximum flexibility in controlling timing and magnitude of solar heat gain through windows. We now describe research directed toward the next generation of glazing materials that can provide the same type of solar gain control using different physical mechanisms. Here our interest is in glazing materials whose intrinsic optical properties either can be altered to provide directional selectivity in transmitting incident solar energy, or can modulate the incident sunlight in response to climatic conditions or building controls. Both private and public sector research is underway in each of these areas. Although each carries substantial technical risks, the potential payoffs are large if such materials can be successfully developed.

Directional Selectivity. Since the sun follows a predetermined path across the sky, which varies with hour and season, solar gain coming from a given position in the sky has specific seasonal patterns. It is thus possible to reduce solar heat gain at some orientations by controlling direct sunlight from specific angles. In this section we discuss glazing materials having fixed optical control properties: once those properties are defined, the glazing rejects incident solar heat gain each time specific geometrical relationships occur. For example, west-facing glazing could be designed to admit light from the lower southeast quadrant (which would be characteristic of late winter afternoon conditions), and reject sunlight from higher solar altitudes in the west and from solar positions characteristic of late summer afternoon sun in the northwest. If the angle-dependent transmissivity glazing could be fine-tuned for each building application and orientation, useful solar control could be achieved. Such an approach fails to distinguish between overcast and sunny days, and would have benefits primarily for solar gain control rather than glare control. Such glazings are used in the tinted upper section of automobile windshields to reduce higher altitude sunlight, and in some sunglasses to produce similar optical control. On a uniform overcast day, such a window might produce strange optical effects, and occupant response to such materials is unclear. Also, energy simulation analysis is required to quantify potential benefits from such glazing materials.

The technology for producing these glazing materials is speculative. Two approaches might be feasible. First would be holographic films in which the diffractive structure is tuned provide the desired optical performance. Some DOE-sponsored research on holographic films is in progress. The second approach would be to produce an oriented fine structure, having angle-dependent properties, within the window. Such an approach is not likely to yield the detailed optical control mentioned in the example above, but might provide simpler, yet useful, optical control. An example has been developed at Corning Glass. A light-sensitive glass substrate is exposed through an optical mask to intense light at a specific incident angle. Processing of the glass creates opaque louver elements within the glass matrix itself at an angle determined by the mask geometry and the incident exposing light. The overall effect is similar to miniature venetian blinds imbedded within the glass substrates. Other manufacturers have previously produced microlouver systems embedded within plastic substrates. These approaches appear to provide useful optical control but have not been proven in the glazing market.

Optical Switching Films. A second class of materials will provide time-dependent control of solar heat gain by modulating the transmissivity of glazing materials in response to given environmental parameters or control signals. While many physical phenomenon can change the transmissivity of an optical substrate, the three most plausible mechanisms are photochromic, thermochromic, and electrochromic materials. Basic research on these materials has been undertaken by the Department of Energy in the past several years. We will review the status of research in each area.

Photochromic coatings are well known because they provide the basis for sunglasses. The coatings change transmissivity in response to light intensity. Experimental work incorporating photochromic materials into plastics and thin film coatings has been done. The spectral- and intensity-dependent optical responses and temperature-dependent effects have been investigated. Since the switching phenomenon depends primarily on light intensity, such a device would behave in the same way in the summer as in winter when the intensities were equal. Thus seasonal selectivity desirable for thermal control would be unattainable. However, glare control would require similar performance in all seasons; thus the primary benefit of photochromic coatings would be to improve visual comfort. It should also be possible to use them as shading devices or in other ways. Analysis is underway with DOE support to determine the potential of these materials.

Thermochromic materials change transmissivity as a function of temperature. Liquid crystal temperature indicators are common examples of materials whose optical properties change when heated. Basic research is needed to better understand switching mechanisms and then create doped materials that will switch within the thermal range of interest for aperture applications. Limited DOE-supported research to develop thin-film solid-state devices meeting this criterion is underway. Other approaches based on non-solid-state materials, such as liquids or gels, have been demonstrated in limited applications. These typically switch from transparent when cool to a white, reflective/diffusing state when heated. While probably inappropriate for most primary-view glazing, such materials should be useful for roof apertures. The packaging and long-term durability of such materials represent significant development problems. Note that thermochromic materials can be made photochromic with neutral density absorbers that convert incident radiation to heat in the glazing material. In addition, the temperature balance of a switching layer can be controlled by whether its placement is inside or outside the insulated building envelope. A thermochromic switching layer used as an outer glazing on double glass would be sensitive to outside temperature conditions; the same material used as the inside glazing layer would behave differently. Once again additional energy simulation work is required to determine the behavior and potential energy control benefits from such materials.

Electrochromic materials are multilayer films whose optical properties can be controlled using an applied voltage. In principle these have the greatest versatility since their transmissivity can be controlled at any instant based not only on outside temperature and sunlight conditions, but also on interior thermal and visual requirements. However, these materials tend to be multilayer systems that are potentially more complex and difficult to fabricate, and more expensive than simple, single-layer photochromic or thermochromic systems. In addition they must be linked electronically to sensors or building automation systems. Electrochromic materials are well known in the display industry and have been investigated extensively for applications such as flat display panels and digital watch displays. Their use for building apertures with other performance requirements is the subject of DOE-supported study. Investigations include basic explorations to create new electrochromic materials as well as research on device configurations in which various multilayer designs are explored. Durable long-life coatings have yet to be demonstrated at laboratory scale; scaling up to architectural sizes might prove a significant problem. However, the ability to control the transmissivity of such materials for privacy, visual comfort, thermal comfort, peak load management, and other building functions suggests that they are an inviting and high-payoff target for advanced research. Research underway in Japan and several European countries indicates that this perception of potential benefits is widely shared. Again, detailed simulation studies are required to fully understand the ideal operating characteristics and potential benefits of electrochromic materials.

Advanced research to develop these solar control options shows promise in several directions. The research is at an early stage and the outcome is not yet certain. However, if such a class of materials can be successfully developed they should provide a new set of desirable and very beneficial capabilities to control daylight and sunlight in buildings.

SUMMARY AND RECOMMENDATIONS

As indicated by the energy analysis results in Section 4, control of solar gain is essential to effective daylight utilization. Some solar gain is a necessary adjunct to daylight admittance--however, uncontrolled solar gain will quickly erase the benefits of lighting energy savings. The following activities are suggested to acccelerate more effective development and use of sun control systems.

Fenestration System Analysis

Desirable sun control properties must be specified within the context of optimizing overall building energy performance. Since this process involves complex tradeoffs between energy savings and peak load performance, and among heating, cooling, and lighting loads, the optimum solutions for each climate, building type, and orientation are not generally known. Building energy simulation studies of the type presented in Section 4 could be used to develop such data.

Characterization of Sun Control Properties

Energy simulation studies of the type recommended above requires data on the solar optical properties of sun control products. Traditional sources provide limited data on shading coefficients. These are inadequate for many of the (optically) more complex and better performing systems. Performance data are required on solar heat gain from the sun at any incident angle, for ground-reflected radiation, and for sky diffuse radiation. These data might then be transformed into seasonal or annual performance indices. Test methods and/or calculation procedures should be developed to determine solar heat gain data.

Materials and Product Research and Development

More research is needed to establish the technical viability of advanced materials concepts such as optical shutters and angle-selective transmitters, and then move the research to the point where industry's interest is generated. As with insulating materials (discussed earlier), there may also be opportunities to assist manufacturers in development of improved sun control systems. The best projects would be those in which initial support leverages substantial additional support. Another role is to work with firms that have developed prototype products and provide assistance with market introduction. One element is the demonstration building, discussed below.

Demonstrations and Field Testing

Carefully documented demonstration programs can assist market introduction of novel products or systems and increase acceptance of existing designs that are not currently widely utilized. These must be carefully planned and carried out if they are to provide the desired data and have an appropriate impact. Field test studies might be more technically oriented than a demonstration project and would be designed to gather basic performance data from which products could be improved or redesigned, or which would form the basis for validating predictive design tools. Studies to determine the impact on load management and peak savings would be particularly useful.

Section 10
PERFORMANCE ISSUES: GLARE

INTRODUCTION

Major reductions in lighting consumption can be made using strategies that slash lighting use without regard for productivity, health, and safety. Our operating assumption, however, is that all recommended daylighting and lighting energy conservation strategies maintain or improve lighting quality and associated worker productivity, health, and safety. One advantage of more efficient lighting strategies is that they frequently produce more comfortable, pleasant, and productive working environments. These features will sometimes help sell these strategies to skeptical building owners if the energy savings alone are not sufficient.

DISABILITY GLARE

One of the critical concerns in effective daylight utilization is the problem of glare from windows and skylights. The lighting community defines two types of glare. The first, called disability glare, results from light sources that reduce the contrast of visual tasks due to the relative positions of the task, observer, and light source. The "veiling reflections" produced by these glare sources reduce the contrast between visual information and the background, making it more difficult to perform a visual task. A simple test to determine if veiling reflections will be a problem is to place a mirror at the task location with the occupant seated normally. Viewing the mirror as one would view the task, any electric or daylight sources that can be seen directly in the mirror represent potentially serious sources of disability glare. Disability glare will often reduce productivity, and thus has serious economic consequences.

Design Solutions

In electric lighting design, the basic approach to minimizing disability glare is to control the brightness of electric sources in the "offending zone" and to position the worker and task so as to minimize sources that fall in the offending zone. Although this requires some skill, once the light fixtures, occupant, and task locations are all fixed, a solution should be effective over time. The Illuminating Engineering Society has developed a number of quantitative metrics that allow one to determine the seriousness of veiling reflections and their visual effects. Although it is difficult to infer an absolute impact on performance, these quantitative values are useful for comparing alternative designs.

The same basic principles are operative in a daylighted environment. In general, one wants to minimize the brightness of sources in the offending zone and position occupants and tasks in a manner that minimizes visual effects. While the location of windows and skylights is generally fixed, the intensity of those sources is highly variable. A major difficulty is that control of source luminance to minimize veiling reflections will also reduce the availability of daylignt for providing illuminance. These issues are discussed in more detail in the next section. The major requirement for minimizing veiling reflections is to optimize the geometric relationship between occupant, task and building apertures. Part of this optimization is not only to minimize veiling reflections, but also to take advantage of the beneficial aspects of lighting quality. Just as light emanating from the offending zone in a room reduces contrast, and thus visual performance, light arriving at a visual task at low angles from the side enhances contrast relative to typical overhead sources and will thus improve visual performance. Studies done many years ago confirm that properly controlled sidelighting from windows will provide performance equivalent to much higher levels of illuminance from overhead sources.

These studies have resulted in simple rules of thumb for designers in terms of occupant placement relative to windows. Ideally, occupants should sit facing parallel to the window so that the light comes to the task from their left or right. Facing away from the window produces a body shadow on the task; facing towards the window creates a direct source of veiling reflections. In single-occupant offices it is frequently possible to orient task locations in such a way as to follow these guidelines. However, in larger spaces with multiple occupants and in open landscape spaces it may not always be practical to provide ideal orientations. Concerns for occupant placement relative to windows must also recognize that the view and visual relief provided by the windows is a desirable quality and may represent another set of constraints on occupant location. Finally, several new trends in office design may further modify conventional practice regarding occupant location relative to windows. The advent of extensive open landscape design may mean that although an occupant is in relative proximity to the windows, five- or six-foot high partitions may block direct view of the windows. This will minimize veiling reflections; however, it may interfere with effective daylight contribution to illuminance as well as removing a direct view of the out-of-doors.

The increasing prevalence of visual display terminals is another major factor in the design of electric lighting in daylighting systems for new office buildings.

Reflections of bright sources off these surfaces can seriously degrade visual performance. Once again, if the terminal screen is imagined to be a mirror, any object seen in the "mirror" that is brighter than the screen will produce the equivalent of veiling reflections and wash out the visual information. This is a serious problem in new offices that have large numbers of visual display terminals and also need to pack in large numbers of occupants. Given the increasing cost of land, and therefore building area, in an urban environment one can expect office densities to increase, making the problem even worse.

DISCOMFORT GLARE

The second type of glare from windows and skylights is discomfort glare. A source of discomfort glare is generally a source that is much brighter than the visual task being performed. A person reading a paper under normal illuminance levels will look up from the task to see a very bright source of light. The eyes may accommodate to the new brightness level, but then when the head is turned back to the task, the eyes must readjust to this much lower level. If the source is very bright, this adjustment will produce discomfort, most noticeably indicated by a squinting response. A related effect is that a bright source in a peripheral point in the field of view may be a distraction that draws the eye away from a less bright but more important task.

Discomfort glare is a problem for the electric lighting community, but the sources of discomfort glare in electric lighting design are typically much smaller than with fenestration. Discomfort glare formulae that account for the glare effect from electric source have been modified for use in daylighting design. The most commonly accepted formula is the Hopkinson-Cornell formula, in which a glare index is calculated based on brightness and size of the luminance source, its position relative to the observer, the luminance of the surroundings, and task locations. One standard approach to reduce discomfort glare is thus to raise the illumination of the task and surroundings with higher electric light levels. This, of course, will result in increased electric energy consumption. It is widely agreed that additional work is needed to upgrade and improve our understanding of discomfort glare. The formula was developed based on experiments with trained observers in England; and the possibility exists that there is an explicit cultural bias in the results. A recent review of similar studies in England, Belgium, and France concluded that the primary variable in determining glare index is source luminance. New studies in these areas are in progress at the University of Washington with support from NSF.

Design Solutions

Source luminance can be controlled in three ways. First, light can be admitted so that there is no direct view of the sky or sun. Architectural strategies for introducing light through multiple reflections off building surfaces are generally well known but not well understood. The second approach is to permanently reduce the luminance of the outdoor view using tinted or reflective glass. This has a secondary effect of reducing the available illuminance in the space. The third approach is to use operable light control mechanisms to control glare only when a glare source is present. We will discuss each approach in more detail.

A number of architects have defined the architectural design process as one of manipulating form to admit light into buildings. Masters of this tradition apply well-developed intuitive skills to admit light to a building with minimum glare problems. The basic approach is to redirect, filter, and otherwise diffuse light entering the building by reflection off of a number of surfaces, so that no surface seen by an occupant is excessively bright. In rooflighted buildings, control of lightwell geometry and shape can effectively diffuse light entering the building. In the Kimball Art Museum in Dallas, Texas, interior diffusing devices were placed under a light slot in the top of a barrel vault to diffuse the light. Diffusing the light from the source that admits it reduces the contrast between bright and dark areas in the interior space, thus minimizing glare. But a diffusing surface may itself become a glare source if its luminance is too high. In sidelit buildings, light-colored walls located adjacent to windows serve as a diffusing source, and splayed details in walls also act to smooth the transition from the bright view outside to the darker walls inside. Exterior devices such as slotted overhangs or other types of fin and louver devices also break and diffuse incoming light.

The magnitude of the control problem can be seen if one estimates the brightness range that must be controlled. A hazy overcast sky or a light-colored surface in direct sunlight can have a luminance of 6000 to 8000 footlamberts; a relatively dark overcast sky may have a luminance of 500 footlamberts. Indoor surfaces will typically have a luminance of 50 footlamberts. Thus the range between indoor and outdoor luminance varies from 1:10 to 1:100. Proper use of landscape design, building design, fenestration design, and interior design, as well as task placement and orientation, can all work to minimize discomfort glare.

In addition to the new architectural strategies, or as a subset thereof, choice of glazing materials and associated fenestration devices can control discomfort glare. The use of tinted or reflective glass or other types of screening materials will reduce the luminance of the outdoor sky and surroundings. These approaches are fixed solutions that reduce the luminance of the outdoors under all sun and sky conditions by an approximately equal amount. In addition, these solutions reduce the transmitted light by approximately the same percentage, thus reducing the daylight available for interior illuminance. Tinted glass moderately reduces visible transmittance, reflective glass and glue-on films or attached screens can reduce transmittance to as low as 5%. At these extremes, the glazing is functioning to provide view only, since it contributes little illuminance to the space. Where view is important and luminance must be controlled while still providing sufficient total luminous flux, one solution is to separate those portions of the fenestration that provide view from those that provide daylight. A standard approach might be to use a tinted or reflective lower view window approximately at eye level and then an upper window with higher transparency and a device such as a light shelf to protect occupants from direct view of sky glare. While the general approaches for these solutions are well understood, we do not yet have standard, well-developed architectural designs that successfully optimize the complex tradeoffs involved.

Since the nature of the daylight and sunlight resource is one of high variability over time, the third approach is based on use of operable systems to control glare and sunlight. These systems are also discussed at length in Section 9, Solar Control. The requirements for solar control and glare control are similar but not identical. For solar control, reductions as great as 80 to 90% of transmitted radiation will frequently be desirable. For glare control, it will generally be sufficient to reduce transmittance by a maximum of 50 to 75%. A large array of interior window management devices such as shades, blinds, and drapes has traditionally been used for glare control as well as sun control. Although a wide range of products exists, there are few guidelines that help architects choose among the alternatives for glare control, sun control, and related window management functions. New products, such as silvered venetian blinds designed to enhance daylighting contributions, may also worsen glare problem if the blinds are not properly adjusted. One approach to the dual control of glare and sun is to use a fixed device with only moderate attenuation to control glare during most of the year and then have an additional operable device primarily design for sun control that also can provide glare control during peak brightness conditions.

Discomfort glare and disability glare are both critical factors in good daylighting design. Buildings that provide proper daylight footcandles but do not successfully control both types of glare do not represent successful, cost-effective solutions. We view this problem at two levels. There is an existing body of knowledge that can provide good guidance and control of both discomfort and disability glare, but it is not widely diffused throughout the profession. The average building designer, however, is frequently confronted with crude and overly simplistic guidelines that may be misleading. Our first recommendation is that the existing information on control of discomfort and disability glare be reformulated to provide effective guidance for building designers. This should include basic principles as well as many examples and case studies. The case-study documentation should emphasize basic principles and general rules of thumb, but should also point out where good design suggests departures from standard rules of thumb.

At the same time, our understanding of occupant response to discomfort and disability glare is incomplete. Basic studies on discomfort glare are necessary to update and refine work completed 20 to 30 years ago, which is acknowledged to be in need of improvement. Metrics for determining visual performance in electric lighting design are undergoing substantive discussion and change. As this work evolves it should be extended to daylighted spaces so that electric lighting and daylighting strategies can be fairly compared in terms of visual effectiveness. At present it is possible to calculate and compare equivalent sphere illumination (ESI) for daylighted and electrically lighted spaces. However, the interpretation of ESI results is the subject of great debate, which suggests that use of ESI is not presently warranted for daylighting designs. New measurement tools to quantify luminance distribution in daylighted and electrically lighted spaces would help in developing new metrics to assess lighting quality.

Section 11
PERFORMANCE ISSUES: LIGHTING CONTROLS

INTRODUCTION

All buildings having windows or skylights can be said to be daylighted, but only those that have an effective means to control electric light will save energy and moderate peak load. Lighting controls are thus a necessary but not sufficient condition to ensure that potential electric savings are realized. As with other aspects of daylighting designs, controls appear to be a simple and straightforward issue. However, the art or science of designing cost-effective control systems that maximize daylighting consistent with occupant comfort is not well developed. In this section we discuss state-of-the-art lighting controls for daylighted buildings, and conclude with recommendations and suggestions for further research.

Lighting controls serve multiple functions in most buildings, so daylighting may not be the only reason controls are specified. In pre-energy-crisis days, it was common to minimize first cost by placing lighting controls in a central circuit-breaker panel. The entire area covered by a single lighting circuit would be switched at one time, and the zoning of these circuits was based more on the desire to minimize drafting and wiring costs than on any concern for function in the lighted space. Most buildings were lit to a single uniform level, that level representing the high end of the spectrum of visual needs. Lights would be switched on in the morning prior to the arrival of the first workers, and switched off late at night after cleaning crews had departed. In some buildings nighttime heating was provided by keeping the lights burning all night long. In the glorious days when building owners were paying less than 1 cent per kWhr, but materials and labor costs were high, it was common to burn lights 24 hours per day in the mistaken belief that this saved money relative to switching.

CONTROL STRATEGIES

The increased cost of electricity has had a substantial impact on electric lighting design. More care and thought are now given to visual performance requirements and their lighting solutions. Switching and control strategies, of which daylighting is one, play an increasingly important role. These strategies include 1) occupancy scheduling, 2) lumen maintenance, 3) fine-tuning, and 4) load shedding. Each has a set of different but overlapping hardware requirements, which suggests that a hardware investment may be paid back by more than one strategy. For this reason we describe strategy briefly before beginning the major description of lighting controls for daylighting purposes.

Occupancy Scheduling

In this strategy lights are turned off or dimmed to lower levels during periods when a space is unoccupied or occupied with tasks of a non-visually critical nature. A number of hardware systems are available. Control hardware can be classified as follows:

- Manual wall switches,
- Mechanical or electronic time clocks,
- Microprocessor based systems, or
- Personnel sensors.

Wall switches are inexpensive, but experience suggests that in areas occupied by more than one individual, manual switching is often used only at the beginning and end of the day.

Mechanical time clocks are frequently noisy, and unless a stop is installed on the switch, lighting hours may be excessive. Recently, programmable timeclocks became available with costs of ~$100/control point. These are appropriate for smaller buildings.

The operation of blocks of lights in a larger building can be automatically scheduled using a microprocessor-based system. These systems are appropriate in buildings where the arrival and especially departure times of the building personnel are relatively predictable. Microprocessor-based systems are preferable to manual wall switches or mechanical time clocks because they can control appropriate blocks of lights according to different schedules. As with any system that controls lighting according to a pre-programmed time schedule, override functions must be provided and must be accessible to occupants so that workers who need to work during a preprogrammed "off" time can obtain lighting in their local area. Virtually all commercially available microprocessor-based systems are relay-based switching systems, where each relay controls some large block of lighting. Exactly how many lights are controlled by each relay is a design consideration which depends on the anticipated needs in the space. The potential for saving energy by scheduling increases with decreasing switching zone size. However, the cost of the controls increases linearly with the number of control points, suggesting that an optimum switching zone size can be calculated if the occupant distribution can be calculated or estimated.

The most economical way of scheduling the lighting using a microprocessor-based switching system is to program only the "off" times and permit occupants to use overrides to switch their lights on.

Personnel sensors are the obvious choice in situations where tight scheduling of the lighting is desirable and where the occupant distribution patterns cannot be determined ahead of time. Appropriate locations would be one- and two-person enclosed offices, conference rooms, retail store supply rooms, and infrequently used areas in industrial settings. Areas occupied frequently by more than two people cannot usually be economically controlled by a personnel sensor because the overlapping patterns will greatly reduce potential energy savings.

Lumen Maintenance

The light levels in a newly installed lighting system are typically 20 to 40% higher than the design level because the light output of lamps, fixtures, and associated hardware tends to decrease with age. Thus new systems put out approximately 30% more light than designed for, and just before cleaning or replacement the nominal illuminance level would drop to the design level. Lumen maintenance systems are designed to sense the actual illuminance level in the space and reduce lighting system output so that only the desired footcandle level is maintained. When the systems are new this would result in savings on the order of 30%; for older systems the savings will drop to 0%. The savings from lumen maintenance systems can be estimated on an annual average basis of 30-50% of initial savings since the light output drops more rapidly in the first hours of operation. The real savings from this systems depend strongly on lighting maintenance procedures and decisions regarding group relamping or cleaning. In general, these systems would not be expected to save more than about 15% per year, and thus make more sense in combination with other strategies. A lumen maintenance system coupled with an energy monitor would provide a powerful economic inventive to relamp when appropriate, since energy use will be at a maximum when the lamps are old. Lumen maintenance can only be implemented with dimming hardware.

Fine Tuning

This strategy refers to tailoring the illuminance level spatially to the requirements at that location. In speculative office buildings it is common to design the complete lighting system without ever knowing the visual needs of the future occupants. Even in buildings in which lighting design has been matched to occupant needs, frequent changes in occupancy or in visual tasks may necessitate changes in lighting system output, which can be expensive if not planned for properly. The common response is to design for the worse case so as not to incur these costly changes later. The ability to carefully control the output fixture by fixture either with multilevel switching or dimming capabilities allows one to install a lighting system capable of providing worse-case illuminance but then adjusting the system so that its output in each spatial location matches the needs. A number of the newer dimmable systems come equipped with ballast adjustments to raise or lower the output of each set of lamps in response to local needs. In a more sophisticated system these changes could be made electronically based on input to a central controller. The resolution of such a system could vary from individual fixtures to a grouping of fixtures to an entire lighting zone. Depending on needs, this fine-tuning strategy could range from continuous dimming systems to on/off systems.

Load Shedding

Since commercial customers pay for peak demand as well as for electricity consumed, strategies that moderate peak load will have economic value. Since lighting loads represent 30 to 60% of the electric load at any given time, they likely represent approximately the same fraction of the peak load. The ability to shed load may be beneficial to large customers who have special rate agreements with the utilities, and may be financially beneficial to all customers since peak demand charges will be reduced. In some cities experiments have been undertaken where building owners "sell back" peak demand to the utility under critical load conditions. Ideally, some load shedding can be done in a manner that does not impact occupant productivity or perception, for example, by minimal dimming of lighting fixtures. In other cases, multilevel switching or switching off lighting systems in areas where they contribute to the aesthetics but not function might be acceptable. Specific solutions in any given building will depend greatly on the details of design and operation.

ELECTRIC LIGHTING CONTROLS FOR DAYLIGHTING

In order to save electricity or moderate peak load, daylighting strategies require effective lighting control strategies. As seen from the brief discussion above, a number of strategies will also work as daylighting controls.

Properly designed lighting controls are essential components of any successful daylighting strategy. The design and specification of a lighting control system must meet three stringent criteria. First, the operation of the controls must be consistent with the visual performance requirements and the perceived needs of building occupants. Controls that regulate illuminance without concern for the response of office occupants will rarely be successful. Second, the control system design and specification must be appropriate for the lighting hardware and overall lighting strategy. On/off controls used with high-intensity discharge lamps that require 5 to 10 minutes before they can be restruck make little sense in most building applications. The important issues regarding the relationship between task illuminance and ambient lighting systems must be addressed as well. Finally, the lighting control systems must save energy in a cost-effective manner. An additional desired feature is that they provide the flexibility for some load management when daylight is available. Cost-effectiveness is an implicit requirement since the systems will never be specified unless they meet some minimum cost-recovery criteria.

Before discussing typical lighting control systems for various lighting strategies, we discuss generic issues related to the operation of all photoelectrically controlled lighting systems.

Control System Components

Control systems can be described as having a minimum of three interrelated elements. The first is a light sensor or detector, necessary to sense ambient light levels in the space. The second is a control logic that compares the instantaneous measured value to some pre-set desired criteria. The third is a control device such as an electronics package or relay that controls light output based on signals from the control unit. In any given system one or more of these elements may be combined, but the functional requirements will be present in all systems. Note that in the case of an office occupant turning a light switch off when there is sufficient daylight, the sensing and control functions occur in the eye and the brain of the individual.

Spatial Control

Control systems can be configured in various ways to cover anywhere from a single task area or room to an entire building. In some cases the systems are modular and additive; in other cases the three key elements described previously are linked throughout the building. In the first case, a dimmable ballast with built-in sensor controlling a single fixture is a unit that can be repeated throughout a room, a zone, or the entire building. At the other extreme are systems using a central control system, distributed sensors, and on/off or dimmable controls throughout a number of rooms and zones, all of which are linked to the central control unit. Because the daylight contribution from most windows and skylights has a strong spatial dependence, zoning decisions have an important impact on both the acceptability of the final system and the cost and effectiveness. In cases where a group of fixtures or lamps are controlled by a single sensor, it is essential that different regions in the zone be illuminated in a similar way by the window system. For example, a 15-ft-deep, 50-ft-wide zone, with identical window treatment across the width of the zone, will have an illuminance gradient moving from window to the interior depth but should not have much variation longitudinally along the 50-foot dimension. In this instance a single sensor properly located with respect to zone depth should provide adequate control over the entire 50-ft-wide zone. However, if the same zone was divided into five 10-foot offices, each with their own operable shades or blinds, a single sensor located in one office might produce very misleading control signals. Imagine a case where the drapes in the office containing the sensor remained open on a sunny day, whereas the other four offices had closed drapes or shades. Use of multiple sensors in a zone to average a signal from several offices provides some improvement, but still leaves the possibility that the automatic lighting control system would respond inappropriately under some conditions. These examples also assume that the visual task requirements are uniform across the zone. If some tasks require more illumination than others, the appropriate solution would be to provide additional task illuminance. However, if this is not possible or desirable for other reasons, then the entire zone would have to be controlled in a way that satisfies the most demanding task. An advantage of fixture-by-fixture controls is that each fixture can be responsive to the visual requirements in that sub-area of the zone.

The appropriate location of a sensor that controls a single zone is the subject of continuing research. One option is to place the sensor outside the zone, for example on a vertical or horizontal surface outside the building. Then one develops a relationship between interior levels and simultaneous exterior levels. This approach has been used with some success, but seems unlikely to be a consistently good solution because the relationship between interior and outdoor illuminance levels is not necessarily constant. If signals from a number of outdoor sensors were read and integrated into the control logic, it might be possible to obtain better correlations. However, correlations based on single sensor readings are unlikely to produce satisfactory results. Sensors placed inside a room could be placed on a variety of surfaces. A sensor at the task location would read illuminance on the task on a dynamic basis. The signals read by sensors mounted on the walls or ceiling depend on the field of view of the active element in the sensor. A ceiling-mounted sensor, for example, mounted over a task location would effectively read the luminance of the task area with a narrow field of view, or could read the luminance of a much larger piece of the room including walls and window if its field of view was sufficiently large. Results to date suggest that a limited field of view that avoids direct view of the window is the preferred design. However, task locations in offices change, so some reasonable breadth of sensor view is useful so that relatively minor changes can be made without substantially affecting the relationship between sensor location and control system logic. In practice, the sensor acts somewhat as an integrator by looking at a moderate to large section of the room floor.

A further possibility is to locate a sensor in a scale model of the room that is being controlled. The sensor location in the scale model would approximate the task location, and the model would be mounted just behind the office glazing, interior to any operable shading system. This appears to provide solutions to several of the problems mentioned above, but remains to be tested to determine its practicality and effectiveness.

The time response of the sensor is also a matter of concern. A system having an instantaneous response may produce a "hunting" behavior between two adjacent sensors whose field of view may overlap. At the other extreme a long time response may not produce acceptable performance on a partly cloudy day, where the interior daylight level may change dramatically in a relatively short time. In practice a time response on the order of 30 seconds seems sufficiently long to damp out any feedback problem between adjacent sensors and sufficiently short to respond to most variations in daylight levels. An asymmetric response is best--fast response in reductions to available light, with slow response to increasing daylight.

Most existing systems that are ceiling-mounted respond indirectly to changes in horizontal illuminance in the space. However, an occupant's perception of the illumination quality and quantity is based on wall luminance and the perceived brightness of other objects in the space. This can produce a situation where the desired illuminance value is in fact maintained on a horizontal work plane, while at the same time producing relatively large changes in the illuminance distribution around the space. Furthermore, horizontal illuminance is known to be a poor indicator of visual performance. The spatial distribution of that illuminance and the resulting task contrast as perceived by the occupant are important issues. In principle it should be possible to develop sophisticated sensor systems that drive electric lighting systems so that equivalent visibility is maintained at all times. Such systems have not been demonstrated, and it is uncertain that the improved performance would justify the increase in cost and complexity.

As mentioned earlier, the human eye and brain can be considered a sensor-logic system for manually operated lighting. The advantage of manual operation is that the lights can be switched or dimmed at precisely the time that the desired visual performance requirements are met. On the other hand, humans are fallible and most will not spend their working time worrying about whether lights should be turned on or off. Thus it seems likely that the average savings from manual systems would be less than those from automatically operated systems. A major advantage of manual systems is that in principle there is no additional cost beyond the switch or dimmer already provided. However, the uncertainty in manual operation makes it unclear what kind of credits can be taken on the load portion of energy analysis calculations. In general, manual systems are plausible candidates for one- or two-person offices where the controlled lighting is for a personal task area. They might also be good candidates for use in intermittantly used spaces such as conference rooms, library or reading areas, etc., as long as users are conscientious in their use. In the case of a larger, open landscaped office, manual controls are unlikely to work well since they may be under the influence of a large number of people with differing needs and perceptions as to what constitutes adequate illuminance. However, it is important to realize that human satisfaction with the quality and quantity of the lighting is the ultimate goal. Even automatically controlled systems will be manually operated—that is, circumvented—if their operation is inconsistent with occupant needs. It is relatively simple to tape an opaque element over a ceiling-mounted sensor so that the sensor thinks that it sees darkness all the time and therefore keeps the lights on at all times. The most detailed studies to date of manually operated daylight-responsive lighting systems have been published by the Building Research Station in England.

Control System Logic

The signals from lighting sensors must be processed prior to actuating a lighting control. There are two major types of controls: distributed and centralized. In the case of distributed controls, the signal received from the lighting sensor is generally compared to a pre-set value representing the desired level. One sensor can be linked to one logic unit, or the output of a single sensor can be sent to a series of logic units in different fixtures. In the latter case all the fixtures might be driven uniformly, or differentially if the set-point varied among the fixtures. This latter situation might be desirable in the case of fixtures that step back from the window, but link to a single sensor at one location in the space. It would be possible to develop an approximate correlation between each fixture and the single sensor and use that correlation as the basis to drive the output of each fixture. The signals between sensors and logic units are typically low-voltage, primarily to reduce installation costs.

The simplest logic systems compare an input signal to one pre-set level and send an on/off control signal to the lighting hardware. The most obvious choice of photosensor is a photo-relay facing outside the building. Since photo-relays are typically thermal relays, thermal inertia tends to reduce the frequency of hunting or cycling when the daylight level is near the switching set-point. In addition, one can introduce a "dead-band" so that the lighting will be switched off when the daylight illuminance on the photosensor exceeds 300 lux, but will be restored until the daylight drops below 1500 lux. Limited data from some operating buildings suggests that even for relatively large deadbands (2:1), the lighting would still cycle under some daylight conditions. This suggests that both an adjustable deadband and an adjustable time response should be incorporated in one electronic package. At present there are few manufacturers of such hardware.

In principle, a lighting system could be switched by a photosensor located inside the controlled space and sensitive to the light from the controlled luminaires. This is rarely done because, in addition to the above problems, the lighting system will almost inevitably cycle on and off due to the sensitivity of the photosensor to the light from the fixtures it switches.

The second type of requirement is in a dimming or multi-step control system where the sensor input actuates more than one control or selects an intermediate position within a range of light output. For example, it is becoming more common to find two three-lamp fixtures wired in tandem so that three light levels are possible. Based on input from a sensor, a simple logic device might then determine whether 3, 2, or 1 ballast/lamp sets would be actuated. In the case of a dimming system, the sensor would drive some form of proportional controller to produce the desired output. In the case of the new electronic ballasts, these control logic functions are integrated into the power control circuitry of the ballast. In some cases the ballasts and lamps dim to 20 or 30% of output but do not go below those values in order to maintain lamp life. Additional logic could be provided so that the systems turned off completely if daylight levels continued to increase beyond those required to drop the system to its minimum set-point. One of the difficulties with this approach is that when the system turns on again it would move back up the curve, beginning at 20 or 30% light output and eventually reach 100% light output in a dark room. However, for electronic and lamp life reasons a number of these systems turn on to full power and then dim down to the required level in a span of 30 to 60 seconds. This might prove to be annoying to office occupants.

There are several hardware-dependent reasons for not allowing lamps to dim below a certain level. For example, current limiters installed on an entire branch circuit do not dim below ~50% for two reasons: 1) below 50% light output the differences in manufacturing tolerances between lighting system components results in non-uniform dimming, and 2) lamp life may be severely shortened due to reduced cathode heating voltage. Systems using dimming ballasts can dim to almost 0% light output but become extremely inefficient at the low end due to the necessity of providing constant filament power.

Central control systems receive input signals from a variety of sensors and can control lighting within a zone and among all zones in a building. In principle these systems have great flexibility, and their response can be fine-tuned or reprogrammed to meet changing requirements. At the same time it is important to provide local control and overrides so that the systems are sufficiently responsive case by case. An advantage of these systems is that many can be driven by a number of inputs, for example, daylighting, occupancy, and time. Thus if a space was partially daylit but the control system also knew that the space was unoccupied, the lights could be turned fully off rather than just dimmed in response to the daylight.

These systems require that all sensors be linked to a central controller and that the central controller in turn be linked to all the lighting hardware. This is generally done by using either low-voltage control wiring or high-frequency signals carried over power lines. The relative merit of each approach depends on the case under study.

Lighting Control Hardware

This last generic element in any control system refers to the devices that control power to lamps and ballasts. These can be divided into three general categories. The first and simplest are relay systems that simply turn ballasts or circuits on and off. Proper wiring of conventional relays to a series of ballasts and fixtures can provide a good degree of multilevel control with state-of-the-art hardware. At the other end of the spectrum are lighting control circuits built into the new generation of electronic ballasts. In this case the circuitry that controls the power output from ballast to lamp is integrated with the control logic that interprets signals received from the sensors or equivalent low-voltage signals received from the central control system. The distinguishing characteristic here is that the actuating device and the ballast or lamp control are part of the same device. The third category consists of auxiliary devices that are added to lamp/ballast systems to provide additional control. A number of fluorescent dimming systems originally designed as retrofit devices fall into this category. These can be wired into a system in front of the ballasts to provide the desired dimming control. In some cases devices are not as efficient as integral dimming controls, although in others they are because the parasitic losses are distributed over a large area. Their specific impact on the ballast and lamp system is highly dependent on the means by which they provide the dimming control.

A number of the logic and control systems described above either require power to operate or reduce the inherent efficiency of the full light output from the lighting system. These parasitic power losses and inefficiencies can reduce the real savings from a system compared to the system that runs more efficiently at full light output, in particular if daylighting savings are small. For example, a daylighting system that saved 30% of net energy but whose parasitic power losses were 15% higher than a non-dimming system would provide a net savings of only 15%, which might not justify the investment in the equipment.

Energy Savings

Part of the decision to invest in lighting controls is based on energy savings. It is thus important to be able to estimate the probable and realistic savings achievable using various control systems and strategies. As always, it would be best to base these conclusions on extensive measured data from buildings. However, the existing database in this area is extremely limited, and it is difficult to draw detailed conclusions at this point. In other sections we present two perspectives on the problem. In Section 4 we show results from a series of computer modeling studies where daylight savings have been estimated for several lighting control strategies. In Appendix B we review the data collected to date in a number of buildings where lighting energy savings due to daylighting have been measured or estimated. It is important to note that the difference in energy savings between lighting control systems is not simply a function of the characteristics of the lighting control hardware and system design but also a function of architectural parameters such as window size, glass transmittance, and interior room parameters. In Section 4 we also provide some additional comments on the effect of lighting controls on peak electrical loads.

SUMMARY AND RECOMMENDATIONS

Effective lighting controls are essential to realizing daylighting savings. The options are diverse, and there is little accumulated experience to guide decision making. Dimming will almost always be more expensive than switching. Some strategies require dimming capability, especially lumen maintenance and, to a lesser extent, daylighting, load shedding, and tuning. Scheduling can be easily accomplished with only switching hardware. In regard to presently available hardware, there is a fairly clear distinction between centralized microprocessor-based systems for scheduling and distributed lighting control hardware for the other strategies. At the present level of technology, a hybrid approach where all the lighting is scheduled by a microprocessor but daylighting, tuning, and lumen maintenance are implemented with dimming hardware in selected zones may be the most cost-effective.

Several critical research areas require additional attention.

Analysis of Control System Performance

Energy savings and load management opportunities are critically dependent on the interaction of control system type with the key variables such as glass area and transmittance, design illuminance level, etc. Simulation results are presented in Section 4 of this report, but this is an area that requires additional study. New work should also examine the interaction of lighting controls with HVAC controls and with operable fenestration controls. Control logic to optimize total building energy consumption might be quite different from approaches that minimize lighting energy consumption.

Lighting Control Hardware

Analysis of the type recommended above can reveal useful information about the performance of existing lighting control hardware, but can also provide insights into requirements for new control hardware. For example, such studies have shown the need for better design of the photometric sensor in daylighted spaces. Some work on development of improved elements in control systems is currently underway. Other control hardware elements might emerge from analytical studies or from observations in buildings.

Building Monitoring and Demonstration

Data collection in occupied buildings serves several useful purposes. First it can be used to validate or build confidence in predictions from the analytical studies. Second, these studies can identify critical performance issues that impact savings but may not be accounted for in computer simulations (e.g., occupant response issues). Third, successful demonstrations build confidence in the conservation technologies, and help accelerate acceptance and utilization of the approaches.

Handbooks and Design Guides

To have maximum impact, the useful information distilled from technical efforts described above should be assembled into a package that can assist building designers in specifying effective design solutions. These manuals should include not only the technical results but critical design guidance on non-energy aspects of the design of lighting controls.

Section 12

IMPLEMENTATION

INTRODUCTION

The earlier sections in this report described the potential energy benefits of daylighting buildings and some of the technical obstacles that must be overcome to achieve those benefits. They also indicate that successful technical solutions are a necessary but not sufficient condition to ensure that daylighting practices are widely implemented in nonresidential buildings. This section explores some of the real-world constraints and incentives that operate within the building design and construction process. These can either act to reduce potentially beneficial effects or to accelerate the implementation of strategies that otherwise might not appear economically justifiable. At a minimum, the forces that influence design in the building sector must be understood; a more aggressive stance is to attempt to create a climate in which building owners and designers are encouraged to incorporate daylighting strategies that reduce energy consumption and improve the habitability and productivity in commercial building environments.

INCENTIVES AND CONSTRAINTS IN THE BUILDING PROCESS

There are three sets of potential incentives and constraints that might influence, positively or negatively, the implementation of daylighting practices in the United States. The first is the impact of new codes and standards for nonresidential buildings; the second is the impact of zoning ordinances; and the third is incentive programs, primarily those developed by utilities.

Codes and Standards

While building codes and standards have historically been based on requirements for health and safety, beginning in the mid-1970s this mandate was extended to include energy effects as well. ASHRAE Standard 90-75, which was implemented in the wake of the oil crisis, was widely incorporated into state building codes as a basis for controlling the energy-related design of buildings. This standard, and several subsequent updates, have been widely discussed and debated in the building community. It is probably fair to say that while the standard may not necessarily encourage optimum design, in many cases it reduces the probability of allowing energy "hogs" to be built. Most design professionals acknowledge that initial design is only one element in establishing real energy consumption in buildings, and that operation, maintenance, and occupancy can have effects large enough to overcome those based on design alone. Despite this, many of the relatively simple and cost-effective practices required by the standard have saved energy compared to previous design, without inconvenience or significant costs to building owners. In fact, a number of building surveys suggest that current thermal and lighting design in buildings exceeds the minimum standards imposed by the ASHRAE standards.

The ASHRAE 90 standard addresses the envelope of a building only in terms of conductive loss and solar heat gain. In setting criteria for envelope design, there is no way to consider the potential benefits of using fenestration to reduce lighting energy requirements. Neither is there an option in the lighting section to quantitatively account for benefits from the use of daylight. The only option available to a designer wishing to get credit for a daylighted building, which may require more glass than the code allows, is to do a complete analysis of the proposed building, comparing it to a design that meets the standard and showing, using recognized simulation techniques, that the proposed building would have a lower energy consumption. Only a small fraction of designers choose this route since it involves additional engineering and design work. Because justifying a daylighted design requires this additional compliance work, we can say that the current standards inhibit daylight utilization.

A major study is under way under the auspices of ASHRAE and related professional organizations to upgrade the commercial building standard. The technical basis for these upgrades are studies supported by the Department of Energy and coordinated through a number of contractual activities managed by Pacific Northwest Laboratories. This process has produced a proposal for a revised building standard which is now undergoing public review. Both the envelope and lighting sections of this proposed revised standard have significant changes directly addressing daylighting. The relative energy consumption of the building envelope is calculated with daylighting as an explicit option. Additional benefits accrue to a design that incorporates daylighting. The manner in which these benefits are allocated to the envelope or lighting section is a matter of ongoing discussion. However, in one form or another, it is clear that the final version of this code will incorporate explicit references to daylighting in a way that should make it easier for building designers to incorporate daylighting. The process of updating this standard is a slow one, but in the long run these efforts should influence revisions made by each of the states that model their building codes and standards after the national ASHRAE standard. In addition, it is likely that results of this work would first be applied to government buildings, and that this application would provide some feedback on the success of these measures.

Several states have not waited for the ASHRAE revision process and have developed their own new nonresidential building standards. Recent changes in California standards are another example of how these activities influence daylighting design in commercial buildings. The proposed California standard is based on an overall building energy budget that is determined for each major nonresidential building type in each of several climate zones within the state. Energy simulation programs were used to determine budget goals based on extensive input from advisory groups of building design professionals. The attempt has been to set the budgets at a level that is consistent with readily available and proven commercial practice, that is economically beneficial to building owners and operators, and that reduces energy consumption relative to current building design practice. Once again, developing these standards has been a slow process, as the basic research for the technical basis of the standard has been followed by extensive industry input and review.

In the case of California, a major emphasis has been on minimizing the cost and difficulty of complying with the provisions of the standards. One approach is to create a number of standard alternative designs, each with different features that have been shown to meet the required performance budgets for given climate zones. In each case one alternative is typically a building with lighting controls and adequate fenestration to provide significant daylighting benefits. By showing that prescriptive criteria have been met, the designer can comply with the provisions of the standard without extensive simulation or analysis. It is anticipated that a large fraction of buildings submitted for compliance will choose this prescriptive route. In some cases this approach should turn out to be even simpler and less costly than standards based on ASHRAE 90. More important from the perspective of daylight utilization, there is now a simple alternative that incorporates daylight which can be utilized with the same administrative ease and compliance effort as other nondaylighting alternatives. Since this may also provide the more extensive glazed areas that are often desirable in office buildings, it may prove a preferred option in many cases. The California standard will be phased into use over several years, so it is too early to determine its impact. However, those involved in the ASHRAE 90 updates are examining the California proposals carefully and seem inclined to incorporate some of the compliance features described.

We emphasize that neither of these codes or standards provides detailed design guidance to ensure that proper daylighting design principles are utilized. However, each makes it possible to use daylighting strategies without incurring additional extensive analysis to show compliance. By presenting a daylighted building as an explicit option, it seems certain that these approaches will increase interest in these options and that in the long run, a greater number of daylighted buildings will be designed and built. However, the success of these buildings as productive work environments and as energy savers will still depend on specific technical and design skills being successfully applied to each case.

Zoning

In the past five years there has been renewed interest in the impact of zoning ordinances as incentive or constraint to the preservation of solar access to public open space, including urban plazas, parks, streets, and adjacent highrise buildings.

Urban planners, architects, and researchers have taken several approaches within this legal format to address the critical issues of developing while acknowledging a "right to light". Several U.S. cities, including New York and San Francisco, recently have adopted zoning ordinances to assure a qualitative response to light in the urban context.

Planners speak of appropriate tradeoffs with highrise developers, who evaluate projects strictly for cost effectiveness, where placing a value on daylight can be an illusive exercise. Given this renewed daylight consciousness, in 1979, the City Planning Department of New York authorized a study to revise the existing regulations last legally addressed in 1961, when Floor Area Ratio (FAR) was introduced to control a building's bulk.

The 1916 New York Zoning Regulations prescribed wide avenues and uniform street walls, resulting in set-back buildings that were eventually criticized as being boring "wedding cakes"; these regulations were also examined for this new zoning study.

In the published report by Kwartler/Jones Architects and Davis, Brody & Associates, admission of light and air to the street was the primary zoning consideration, but it did not dictate building shape or form. This performance-based zoning proposal would assess future building projects by four criteria including daylighting, street wall length, and reflectivity. A developer would receive authorization by scoring at least 85 points on a 100-point evaluation. Street wall height and wall length were included as criteria to allow for a blending of new and old projects. Reflectivity was optional, but building designs were credited for using light-colored exterior materials.

Daylight was the central element in the proposed ordinance. Building designs would be evaluated by the amount of natural light that would reach the surrounding street, using a "daylighting performance test." This innovative Daylight Evaluation Chart is new to the field of U.S. zoning. It records, in a form of spherical perspective, the amount of sky dome blocked by a proposed building as perceived by a person in the street. A viewer's head turning a full 180 degrees across the building is described to chart what the pedestrian would see.

The performance point system allows the architect and developer to trade off between themselves in achieving overall performance. Because there were no geometric limits relating to building bulk, shape, or form, the design choices were left to the architect and developer, not dictated by the zoning ordinance. Finally, this daylight-oriented regulation would ensure a level of daylight reaching building facades that would encourage the use of daylighting for perimeter task lighting.

The New York Planning Commission, in responding to the final report, endorsed a two-level proposal: for a proposed project to receive zoning approval, it must fulfill the requirements of one, not both, of the approaches, which are both based on daylighting. The original performance approach received minor changes in scoring the four criteria. The prescriptive approach is similar to elements of the 1916 ordinance, requiring the use of "sky exposure curves," which define the allowable shape and bulk of proposed projects.

Similarly, in June 1984, San Francisco voters passed Proposition K, the "sunshine ordinance," the first voter-approved limited growth measure for the city. significant shadow on a city park or playground. Because the measure applied only to Recreation and Park Department property, many large projects will not be affected. This law is an amendment to the city charter, requiring any requests for exemptions to be placed before the voters. Developers will remain in a flexible situation until "significant" shadows can be defined and modified by the Planning and Recreation and Park commissions.

San Francisco planners were under pressure from both developers and environmentalists recently when a new downtown plan was proposed in August 1984. The new voluntary plan is in direct response to the 1972 Urban Design Plan, which is credited with allowing Manhattan-sized highrises to be built, cutting off sunlight from many streets and major public open spaces, either completely or for much of the year. Building industry professionals now realize that these 1972 guidelines created irreversible climatic change in this part of the city. Further, planners now realize that sunlight cannot be separated from related problems, such as urban temperature fluctuation and building-created wind currents that can affect a city's economic and social vitality.

Finally, as an example of the growing concern for the preservation of daylight, Tokyo chose a method of constraint to deal with a growing disregard of many ordinances adopted over the last decade to guarantee residents a minimum amount of sunshine each day in their urban houses and apartments. With increased highrise development, Tokyo citizens have fostered the notion that light and heat are a right and not a privilege. As a result, any developer or architect constructing a building that casts a shadow on adjacent buildings or residential neighborhoods can expect to receive a fine of $420 to $1260 for every hour of lost sunlight. Even with the judicial and political contradictions that such a ruling would engender, developers now recognize sunshine payments as part of the cost of projects. Proposed easing of government restrictions on the construction industry continues to be discussed, while courts deal with a growing number of "right-to-light" suits.

Many planning professionals believe that the debate at both the public and professional levels is becoming better defined, as metropolitan areas first acknowledge the qualitative and energy-conserving quantitative aspects of daylight, and then address some of the complex planning issues through ordinance changes and public referendums. The two examples discussed here point to the potential for developing a generic model for urban zoning. The New York performance approach is an example. Street-level daylight is an attractive value for every urban setting. A successfully developed daylighted environment will depend on coordination between the design and planning professions to insure productive working environments.

Incentives

As utilities across the country have recognized that various conservation options represent cost-effective alternatives to increasing generating capacity, they have developed programs to accelerate the acceptance and use of these conservation options. These utility programs include the residential and nonresidential sectors and retrofitting as well as new building activities. As utilities are increasingly able to predict the specific benefits that may accrue from each conservation option, they are broadening their programs from those that provide information only to offering low-interest loans and direct financial subsidies to encourage implementation of specific actions. It is important to note that these programs are structured to be beneficial economically to the building owners as well as to the utilities, a situation in which both come out winners.

A utility incentive program that pays building owners to implement retrofit or new measures might be structured as follows. First, one estimates the cost and potential savings in paybacks to the building owner for specific daylighting strategies. At the same time, one estimates the potential kilowatt and kilowatt-hour reductions for the owner and the utility. The utility can also estimate its probable cost for adding new generating capacity that would be required to provide the equivalent load displaced by the daylighting strategy. Depending on the sophistication of the analysis, this could include both average demand and peak demand effects. This can normally be translated into an annual cost per kilowatt hour (kWh) and/or per kilowatt, which can be converted to a one-time incentive bonus. In the case of several utilities that have planned or implemented such programs, the incentive is structured as a one-time payment, amounting to \$0.03 to \$0.05/kWh per year saved. In the case of a skylighted office building in which the daylighting strategy saves perhaps 4 kWh/ft^2/yr, this may translate into \$0.15 to \$0.25/ft^2 of floor area. This is a direct cash supplement in addition to the annual energy savings realized in the owners' utility bill. These incentive payments can be used to convert a design option that might appear to be marginally beneficial to one that is more convincingly beneficial or to convert one that is perceived as not beneficial to marginally beneficial. It also implies to the prospective owner or designer that a utility, which usually has a conservative reputation, believes that the technology is workable and cost effective. To further encourage implementation of these actions, some utilities share the cost of the analysis of the daylighting design. These incentive and design assistance programs are probably the most direct and powerful influence to date to convince both owners and designers of the value of incorporating daylighting designs into their buildings. Incentives are aimed at reaching beyond the top few percent of the design profession that will attempt to implement daylighting designs without such incentives. Since these programs are new, it remains to be seen what their impact will be. Furthermore, it places some pressure on the utilities to accurately estimate the magnitude of potential savings, to ensure that there are no adverse side effects, and to select the most appropriate specific daylighting technologies for which they wish to provide incentive programs. Such an approach always runs the risk of promoting technologies that are not workable or, conversely, of ignoring technologies that deserve to be promoted. In addition, the content and structure of such a program depend heavily on the perspective of each utility on matters of energy conservation and load management.

EDUCATION AND TECHNOLOGY TRANSFER

Introduction

There is a rapidly growing need for sharing information at many levels of daylighting research and application. This section explores the issue of communicating daylighting materials to professional architects and engineers, and suggests ways to reach these professionals in their business places, in government offices, or through educational institutions.

First, educational materials used to describe daylighting approaches and associated design procedures are likely to change over time. While the examples of good daylighted buildings may be timeless, specific technologies and procedures are not. Therefore, the information and tools translated from research must be flexible and updatable. Second, this kind of information must be versatile enough to be useful in the many contexts for which it is intended. In a university classroom it may be part of a larger curriculum unit; in a design office it may be the subject of a series of afternoon seminars. Flexibility is mandatory.

The greatest challenge is the most basic, communicating the substance of daylighting. Professionals often indicate that there are serious obstacles to communication between technical specialists and professional users of technical information in almost any field of design. The character of each group's thinking and expectations differs greatly from the other's.

Audience Types

The development of a series of audience profiles will help match the information provided to the professional need, in addition to assigning priorities for an array of information products. We will comment on five key professional audiences.

Building Industry Professionals. This audience is diverse in both its training and business approach to the building process. Yet the members of this group, which includes architects, engineers, building owners, construction managers, planners, and interior designers, must coordinate their professional efforts to make a successful building.

All of these professionals find themselves flooded with design information based on both technological and economic information and policy. Like other business ventures, the larger the firm, the more individuals are specialized according to interest and capabilities. Where in-house capacities are limited, consultants are used. Further, the greater the number of employees, the more information gathering and storage becomes systematized. Larger firms have extensive libraries and make use of technical data storage systems, microfiche files, and computer files.

Government Policy Makers. During the past five years, government policy makers at the local, state, and federal levels have responded to a variety of urban design and environmental issues with building codes, tax incentives, and legislation.

The design and planning issues involving daylighting, which include sun access, utility peak load, and building energy use, have been a vital part of this response to the growing concern for the economics of conservation of resources.

Policy makers at all levels often lack strong connections to information on current research or experimental applications that could help influence decision making.

Professional Societies. The professional societies that embrace the building industry, and specifically those that have targeted the issues of daylighting design and application, are varied in their membership profiles.

This variety of educational backgrounds, professional motivations, and building design approaches contributes to a sense of isolation in many instances, and enthusiastic collaboration in others. Based on some of these historical professional alliances, the challenges of daylighting design with an integrated energy approach have helped foster new motivation for working closely together and relying on shared expertise to solve problems.

Architects (American Institute of Architects/AIA) are working more closely with engineers (Illuminating Engineering Society/IES) to address the complex issues of electric lighting and controls as they interact with fenestration and sun control systems. Mechanical engineers are collaborating with energy analysis consultants to address building envelope design strategies.

Educational and Research Institutions. Integration of energy-related issues into architecture programs is entirely dependent on curriculum planning policies. In general, there seems to be a consensus among faculty that daylighting should not be treated as a separate discipline, except in a research seminar.

Perhaps even more than the practicing professional, the person who teaches energy-related courses wants to know the latest developments in the field. The students graduating from professional building curricula enter their given practices with theoretical background and practical tools that are often 10 years ahead of current application. Either they are given "energy specialist" status, or are expected to rise up in the ranks, often subverting this state-of-the-art knowhow.

Most research institutions in the energy-related fields are split between government and private funding. The source of support generally dictates research objectives. Research programs that receive government funding often must steer their objectives toward a broad-based audience of professionals, where privately funded research can be product-specific.

Building Users. This often-overlooked audience is receiving renewed interest by building professionals as building systems and materials grow in complexity.

During the 1970s, social and behavioral issues relating to the built environment received wide attention by the design professions, but as energy concerns became dominant, the building user was forgotten. Indoor air quality problems surfaced as HVAC system changes and increased use of synthetic building materials caused physical reactions among some building users. With the emergence of computerized building energy systems to control ventilation systems, electrical lighting, and a variety of interior and exterior sun control components, building users find themselves in an awkward position of not knowing what is happening to themselves in their environment and in many cases having little or no control over interior environmental conditions.

Users must be educated about these environmental issues and included in everything from the design process to building component and systems operation procedures and post-occupancy evaluations.

Within many of these audiences there is either an active, ongoing information dissemination component, planning and producing materials for their particular constituency, and/or specific programs already in place to address the need for daylighting design tools and information. There is a continuing need for educational and communication channels which cross traditional professional and disciplinary boundaries. The 1983 International Daylighting Conference was a major step in bringing participants from all segments of the design and construction community together with researchers to discuss and review critical daylighting issues. A second conference is planned for 1986.

DESIGN TOOLS

The potential benefits of daylighting can be listed easily. Daylighting can 1) enhance the quality of the indoor luminous environment, 2) improve visual performance, 3) reduce electric lighting energy consumption, 4) reduce heating and cooling loads, and 5) reduce peak electrical demand. However, not all daylighting strategies will necessarily achieve all five of these goals; in some circumstances achieving several of these benefits can only be accomplished at the cost of reducing others. To properly evaluate the successes and failures of a particular design, it is necessary to establish clearly defined goals and objectives that explicitly address the five issues mentioned above. Ideally, comparing what was achieved in a design to what was intended will provide feedback that will prove helpful in subsequent building design exercises.

One reason for clearly distinguishing which design decisions apply to lighting quality, lighting energy consumption, peak demand impact, etc., is that the design and evaluation tools may be quite different for each of these issues. Further, the requirement for design tools that will enable adequate analysis or evaluation of each of these issues will vary depending upon the stage in the design process. As one moves through the design process and then through construction and occupancy of a building, one's concerns differ, one's perspective changes, and the quality and quantity of information required change significantly. Failure to recognize this often results in applying an inappropriate design tool that may produce incorrect or misleading results even if it is properly applied. Worse yet, when appropriate design tools are not available, one may tend to let the design tool output dictate design direction.

We briefly review some of the design tools available to assist in designing pleasant, energy-efficient daylighted buildings. The discussion is not meant to be all-inclusive or definitive, but rather suggestive of the many issues faced by designers today and some of the options available to solve them.

Design tools may be complex because many factors may influence the determination of interior illuminance levels. Figure 12.1 provides a partial list of key variables.

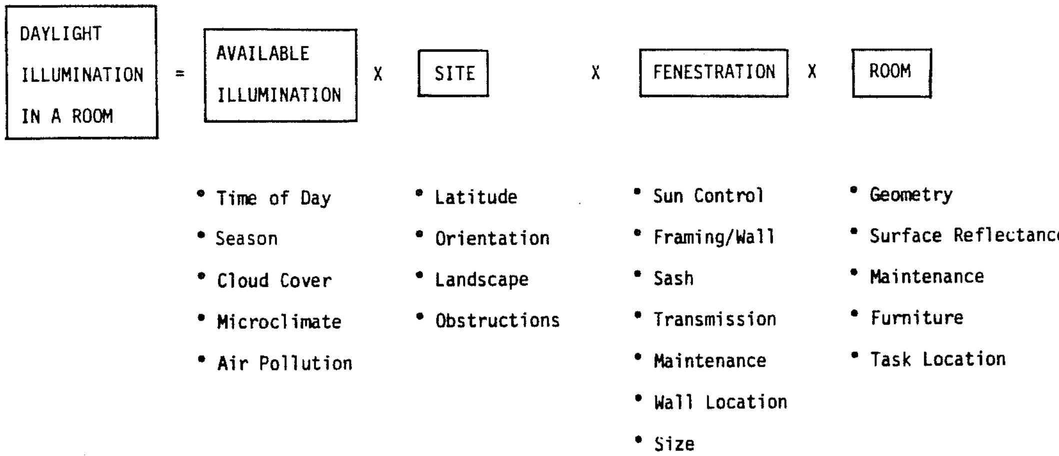

Fig. 12.1. Variables that influence determination of interior daylight illumination.

One of a designer's most difficult tasks may be not the use but rather the selection of a design tool. Selection implies a) that the designer has a choice, and b) that the criteria for choosing are understood. Some of these criteria are listed in Fig. 12.2. The first set of factors relates to the usefulness of the tool, while the second set relates to technical requirements for it.

DESIGN TOOL CHARACTERISTICS

- LEARNING CURVE
- EASE OF USE
- AVAILABILITY
- COST

- INPUT REQUIREMENTS
- LIMITS OF APPLICABILITY
- TRANSPARENCY
- SENSITIVITY
- STABILITY
- ACCURACY: ABSOLUTE/RELATIVE
- QUANTITY/QUALITY
- OUTPUT FORMAT

Fig. 12.2. Performance characteristics of daylighting design tools.

We a tend to lump daylighting tools into general categories such as calculation methods, tabular methods, or graphic methods. However, these categories describe the presentation format of the tool rather than the basis for its predictive capability. Fig. 12.3 shows a hierarchy of design tools based on the procedure by which they were developed. Understanding how a design tool was derived helps us understand its capabilities and limitations. Analytical approaches can be converted directly to calculation procedures for hand calculations or programmable calculators, or can be converted into computer programs. Design tools based on physical model measurements can be used directly for design purposes. They can also be used to develop a data base from which other types of design tools can be developed.

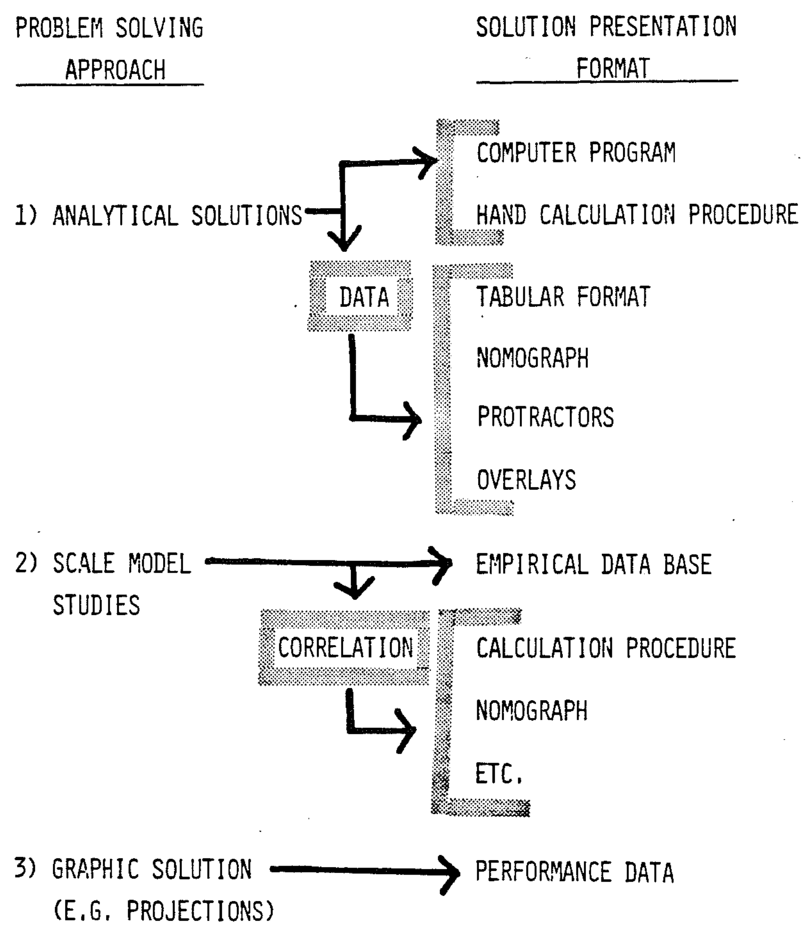

Fig. 12.3. Derivation of daylighting design tools.

Many examples of each type of tool shown in Fig. 12.3 exist, although their frequency of use and adequacy vary considerably. The largest future thrust will clearly be in the development of microcomputer-based tools, particularly those having enhanced graphic presentation capabilities.

A major problem for tool users will be to evaluate the technical quality of results emerging from these microcomputer programs. A set of measured benchmark data is under development at Lawrence Berkeley Laboratory to provide the basis for performance comparisons. Standardized procedures to test programs and interpret results of those tests and comparisons will be needed. A critical function of this approach is to indicate the limits of applicability of these programs, not just their numerical accuracy.

Appendix E provides a sampling of existing tools with daylighting modeling capability.

RECOMMENDATIONS

From the brief audience profiles, some general recommendations can be made:

1. Codes and Standards

   Continue to develop state and national building standards for new design (and retrofit) that encourage and promote effective daylight utilization. This should be accomplished by implementing standards and compliance procedures that are pragmatic and cost effective from the building owners' perspective and which do not impose unnecessary burdens on designers or code officials.

2. Incentives

   Encourage further development of utility incentive programs based on electric load management and energy savings potentials. Evaluate the effectiveness of these programs in reaching and influencing decision makers and develop techniques to determine the actual savings achieved by each incentive program element. (See comments elsewhere on building monitoring program.)

3. Education and Technology Transfer

   - One of the most effective ways to introduce a new concept to the architectural and engineering fields is through articles in professional journals. Emphasis should be placed on conveying general concepts and displaying case studies.

   - To learn more about a topic, practical design manuals and design tools are essential. They should stress rules of thumb and procedures to evaluate cost effectiveness of alternatives. It is important to indicate the limits of applicability for each tool and to provide a spectrum of tools to address the varying needs at each point in the design process.

   - An effective workshop or seminar on a topic is always useful. In order to be successful, its objectives and content must be clearly presented. The presentation(s) should contain graduated levels to accommodate individuals with more or less understanding of the topic.

   - Because of the large percentage of small firms, their needs should influence decisions regarding costs of materials and courses.

- Each of the particular audiences have produced information at a level tailored to their constituents' specific needs. The challenge remains for building industry professionals to continuously review and update these materials for content and effectiveness and then package and disseminate them in a number of different formats to a wider marketplace. This activity is essential for the continued successful dissemination of daylighting design information that is trusted and believable. A national network of educational institutions, the Daylighting Network of North America, has recently been organized. This review, evaluation, development, and dissemination function is a major objective of this Network.

4. Design Tools

Provide up-to-date information to design tool users on the availability and capabilities of various daylighting design tools. Develop methodologies and the technical data that will allow others to critically evaluate the comparative performance of alternative design tools for various daylighting design applications.

APPENDIX A
BIBLIOGRAPHY

This appendix lists most the publications on the subject of daylighting that appeared in journals, books, and conference proceedings over the past six years. A review of this work is instructive for several reasons. First, these articles form a prime source of information, which we reviewed in the course of this assessment study. Second, the number and timing of the articles indicates the generally increasing level of interest in daylighted buildings that occurred over that six-year period. During any equivalent period of time in the early 70s or late 60s, there are many fewer publications on the subject of daylighting. Finally, not only the number of publications but the content and themes of the material have changed over time, as one would expect from a field in which there is a continuously maturing view. A few things have not changed and that too provides valuable information. In 1984, as in 1977, there are still virtually no studies that provide measured results from daylighted buildings.

An initial version of this bibliography appeared in 1980 covering articles published between 1977 and 1980. For this assessment report we collected and reviewed the additional publications that appeared between 1980 and 1984 in the major architectural, engineering, and lighting design periodicals, as well as conference proceedings, books, and other published sources.

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OCTOBER 1984

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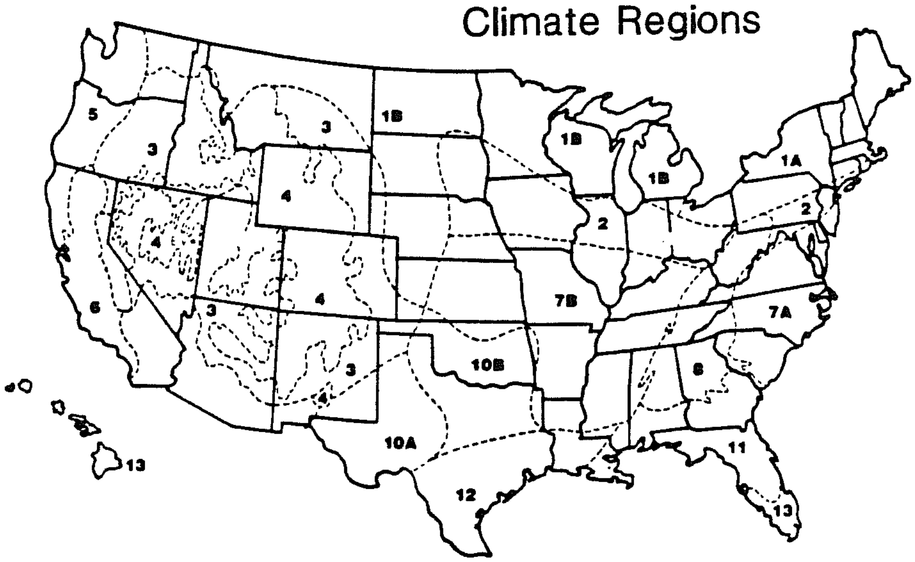
Climate Regions



†The 13 general climate regions have been developed from ongoing research at the AIA Research Corporation in conjunction with the National Climatic Center of NOAA. The regions have been based on heating and cooling needs, solar usefulness in a 50° to 65°F range, wind usefulness in a 75° to 85°F range, diurnal temperature impact, and low humidity impact for natural heating and cooling of homes. Further information is available in Technical Report No. 1, from the AIA/RC.

Appendix: B

Daylight Design Building Case Study Review

Climate 1A....................Niagara Falls, New York
Buffalo, New York

Climate 1B....................Spokane, Washington
St. Paul, Minnesota
Holland, Michigan

Climate 2.....................Sioux City, Iowa
Philadelphia, Pennsylvania

Climate 3.....................West Valley City, Utah

Climate 5.....................Mt. Angel, Oregon
Arcata, California

Climate 6.....................Sacramento, California
Palo Alto, California

Daylight Design Building Case Study Survey

CLIMATE ZONE	BUILDING	DESIGN ELEMENTS								GLAZING TYPES								DAYLIGHT & SUNLIGHT CONTROLS Interior									Exterior						
		side lighting	clerestories	skylights	roof monitors	atriums	light wells	beam sunlight	sun controls	single	double	triple	heat absorbing	heat reflecting	photochromic	glass block	plastic	between glass	glazing	films	screens	shades	blinds	drapes	shutters	vegetation	vegetation	overhang	fins	louvers	screens	shutters	light shelf/reflctr
1A	OFFICE Occidental Chemical Niagara Falls, NY	●							●	●	●							●								●				●			●
1A	OFFICE Liberty N'l Bank Buffalo, NY	●		●		●			●		●												●					●					●
1B	OFFICE Farm Credit Banks Spokane, WA	●							●		●												●					●					●
1B	SCHOOL UM/Eng'rg Building St. Paul, MN	●			●	●		●	●																		●	●					●
1B	FACTORY Herman Miller Plant Holland, MI	●	●	●		●																											
2	OFFICE Iowa Public Service Sioux City, IA	●		●		●										●																	
2	OFFICE Stock Exchg Bldg Philadelphia, PA			●		●					●			●												●							
3	OFFICE Johnson Control W. Vly City, UT	●	●	●	●				●			●														●	●						●
5	LIBRARY Benedictine College Mt. Angel, OR	●	●	●																										●			●
5	SCHOOL Humbolt St Sci Cplx Arcata, CA			●				●	●		●						●									●							
6	OFFICE Bateson Building Sacramento, CA		●	●	●	●			●																	●		●		●			
6	SCHOOL Stanford Eng'r Bldg Palo Alto, CA	●		●						●															●		●					●	

February 1985

Case Study Windows & Daylighting Group, Applied Science Division, Lawrence Berkeley Laboratory

Commercial/Office/Highrise	
Building Type CODE	3.1.2
New York/USA	
Geographical Location CODE	1A

43N ° latitude 79W ° longitude

Source(s): LD&A; P/A 9:81; Cannon Design Inc.

[ ] File [ ] Slides

Building: Hooker Chemical Office Building (Occidental Chemical Center)

Address

City Niagara Falls State NY Zip

Country USA

Architect: Mark Mendell

Firm Cannon Design, Inc.

Address 2170 Whitehaven Road

City Grand Island State NY Zip 14072

Country Phone 716/773-6800

Consultants: Daylighting

Electrical

Energy Analysis John Yellott

Mechanical

Structural Gillum Colaco

Landscape

- [ ] proposed
- [x] new
- [ ] retrofit
- [x] urban
- [ ] suburban
- [ ] rural
- [ ] bldg obstructions
- [ ] grnd reflectance

Square Footage 200,000 Completion Date 1982

Design Elements

- 1.1 [x] side lighting
- 1.2 [ ] clerestories
- 1.3 [ ] skylights
- 1.4 [ ] roof monitors
- 1.5 [ ] atriums
- 1.6 [ ] light wells
- 1.7 [ ] beam sunlight
- 1.8 [x] sun controls
- 1.9 [ ] ____________

Glazing Type

- 2.1 [x] single
- 2.2 [x] double
- 2.3 [ ] triple
- 2.4 [ ] heat absorbing
- 2.5 [ ] heat reflecting
- 2.6 [ ] photochromic
- 2.7 [ ] glass block
- 2.8 [ ] plastic
- 2.9 [ ] ____________

Daylight & Sunlight Controls

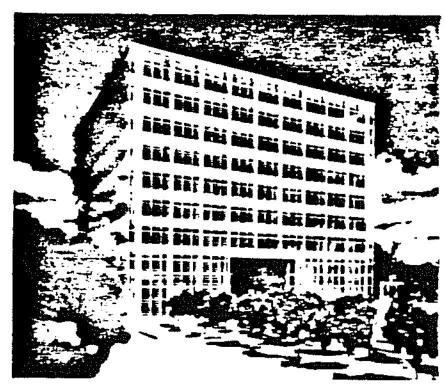
EXTERIOR

	* F	M	A	
3.1	[ ]	[ ]	[ ]	vegetation
3.2	[ ]	[ ]	[ ]	overhang
3.3	[ ]	[ ]	[ ]	fins
3.4	[ ]	[ ]	[x]	louvers
3.5	[ ]	[ ]	[ ]	screens
3.6	[ ]	[ ]	[ ]	shutters
3.7	[ ]	[ ]	[x]	light shelf/reflector
3.8	[ ]	[ ]	[ ]	____________

INTERIOR

	F	M	A	
4.1	[ ]	[ ]	[x]	between glass
4.2	[ ]	[ ]	[ ]	glazing
4.3	[ ]	[ ]	[ ]	films
4.4	[ ]	[ ]	[ ]	screens
4.5	[ ]	[ ]	[ ]	shades
4.6	[ ]	[ ]	[ ]	blinds
4.7	[ ]	[ ]	[ ]	drapes
4.8	[ ]	[ ]	[ ]	shutters
4.9	[x]	[ ]	[ ]	vegetation
4.10	[ ]	[ ]	[ ]	____________

* F: fixed
M: manual operation
A: automatic operation



Lighting Systems

Function/Location

Energy Use ______ Total Watts ______

Hrs Yrly Oper'n ______ Energy Yr KwH ______

Lighting Controls

- 5.1 [ ] on/off
- 5.2 [ ] step/dimming
- 5.3 [x] automatic
- 5.4 [ ] manual

4/83

Occidental Chemical Center

Niagara Falls, New York

"This 200,000 ft^2 square-plan building is probably the most energy-efficient office building in this climatic zone," said Mark Mendell, principal-in-charge of the project for Cannon Design, Inc., architects, engineers, and energy planners, Grand Island, NY.

The building's exterior consists of an inner glass wall and an outer one, 4 ft. apart. The double skin is designed to reduce significantly the impact of air infiltration.

Between the glazed walls are assembled airfoil-shaped louvers frequently used for HVAC applications. The louvers cover all glazed areas of the building skin except the recessed lobby entrance.

The double skin effect and louver assembly have been achieved without excessive costs, since they can be constructed with off-the-shelf components.

Each facade is controlled independently, powered by motorized screw-shaft rods, and activated by a light sensor. During the day when the building is occupied, the louvers on each face move simultaneously to track the sun, eliminating direct sun and its inherent heat gain, yet allowing diffuse light into the offices. At night when the building is empty, the louvers close completely, creating a fully insulated opaque shell.

"The louvers work like a giant, automatic set of venetian blinds," Mr. Mendell explains. "In the late afternoon on a clear day, when the sun is in the southwest, the louvers on the building's north and east face open completely, in horizontal alignment, to admit as much daylight as possible. The louvers on the south face turn down slightly, and those facing west turn down to a maximum angle, 45 degrees, to block the sun, while still permitting exterior views.

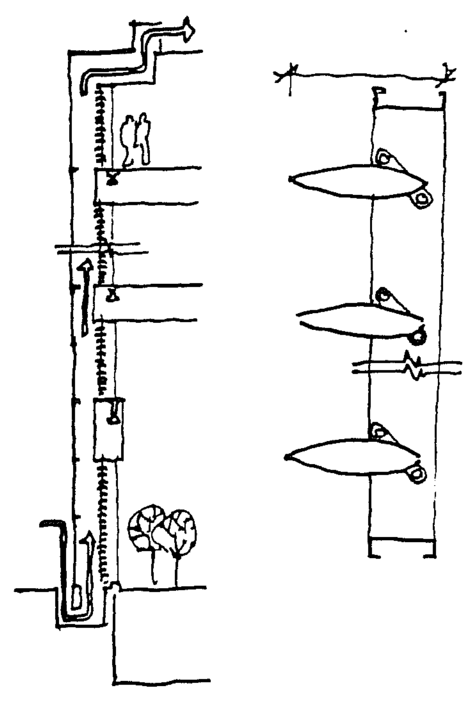
"The facades will look different depending on the weather, season and time of day," Mr. Mendell continues. "In the late afternoon on a sunny day, for instance, the north and east faces will be transparent, while the west side will be nearly opaque."

Immediately inside the interior wall is a 15-20 ft perimeter artifical lighting area with staged controls to complement daylighting. Offices on the rest of each floor will use task-ambient lighting.

"On cloudy days the artficial perimeter lights supplement sunlight in the offices," Mr. Mendell explains, "As the sun brightens, these artificial lights turn off automatically."

"The Hooker building's artificial lighting requirements will be less than 1 W/ft^2 when taking daylighting into account," he adds. "This is substantially less than the 2 W/ft^2 achieved by most buildings with efficient lighting systems."

A central computer controls the artificial perimeter lights as well as the alarm intercom security systems, HVAC dampers, environmental controls and other building functions.



Case Study

Windows & Daylighting Group
Applied Science Division
Lawrence Berkeley Laboratory

Commercial/Office/High-Rise		
Building Type	CODE	3.1.2
New York/USA		
Geographical Location	CODE	1A

Source(s): LD&A , 2:83, P. 10

[x] File [ ] Slides

Building: Liberty National Bank Headquarters (Norstar Building)

Address
City Buffalo State NY Zip
Country USA

43N ° latitude 79W ° longitude

Architect: Mark Mendell
Firm Cannon Design, Inc.
Address 2710 Whitehaven Road
City Grand Island State NY Zip 14072
Country Phone 716/ 773-6800

[ ] proposed [x] urban [ ] bldg obstructions
[x] new [ ] suburban [ ] grnd reflectance
[ ] retrofit [ ] rural

Consultants: Daylighting Alan M.H. Sloan
Electrical
Energy Analysis
Mechanical
Structural
Landscape

Square Footage 216,000 Completion Date 1982
Construction Cost $15,187,000

Design Elements

1.1 [x] side lighting
1.2 [ ] clerestories
1.3 [x] skylights
1.4 [ ] roof monitors
1.5 [x] atriums
1.6 [ ] light wells
1.7 [ ] beam sunlight
1.8 [x] sun controls
1.9 [ ] ____________

Glazing Type

2.1 [ ] single
2.2 [x] double
2.3 [ ] triple
2.4 [ ] heat absorbing
2.5 [ ] heat reflecting
2.6 [ ] photochromic
2.7 [ ] glass block
2.8 [ ] plastic
2.9 [ ] ____________

Daylight & Sunlight Controls

EXTERIOR

	* F	M	A	
3.1	[ ]	[ ]	[ ]	vegetation
3.2	[x]	[ ]	[ ]	overhang
3.3	[ ]	[ ]	[ ]	fins
3.4	[ ]	[ ]	[ ]	louvers
3.5	[ ]	[ ]	[ ]	screens
3.6	[ ]	[ ]	[ ]	shutters
3.7	[x]	[ ]	[ ]	light shelf/reflector
3.8	[ ]	[ ]	[ ]	____________

INTERIOR

	F	M	A	
4.1	[ ]	[ ]	[ ]	between glass
4.2	[ ]	[ ]	[ ]	glazing
4.3	[ ]	[ ]	[ ]	films
4.4	[ ]	[ ]	[ ]	screens
4.5	[ ]	[ ]	[ ]	shades
4.6	[ ]	[x]	[ ]	blinds
4.7	[ ]	[ ]	[ ]	drapes
4.8	[ ]	[ ]	[ ]	shutters
4.9	[ ]	[ ]	[ ]	vegetation
4.10	[ ]	[ ]	[ ]	____________

* F: fixed
M: manual operation
A: automatic operation

Lighting Systems

Function/Location

Energy Use Total Watts
Hrs Yrly Oper'n Energy Yr KwH

Lighting Controls

5.1 [ ] on/off 5.3 [x] automatic
5.2 [x] step/dimming 5.4 [ ] manual

4/83

The Norstar Building

Buffalo, New York

A major element of the building's energy-efficient design is the use of daylighting. According to the designer's extensive daylighting analysis, the combination of the building's siting and envelope design will provide natural daylighting to nearly two-thirds of the building's usable area.

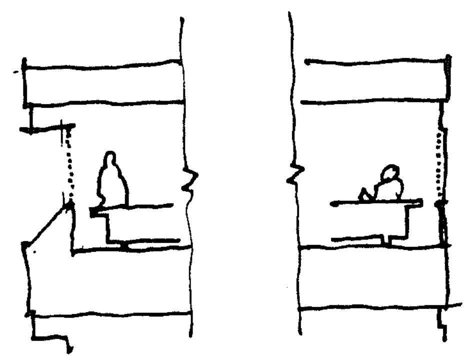
This proportion of daylit space is achieved by limiting the width of the 12-level building to 80 ft, since the daylighting benefits will extend to an interior-depth of 15 ft. The building's large perimeter also satisfies the owner's requirement to accommodate many private offices, each with window views, an especially desirable feature for the building's tenant rental floors.

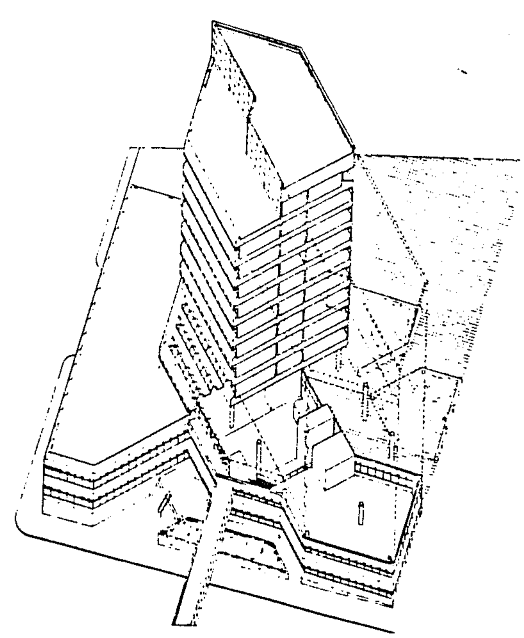
Additionally, the building's angled position on the site creates two long facades oriented to the northeast and southwest, respectively. This orientation guarantees permanent solar access--since no future building can obstruct its daylight--and, according to wind tunnel testing, also provides outstanding wind protection on the plaza created by the building.

The design encompasses two slightly different building facades to maximize the benefits of solar daylighting while minimzing heat gain. On the wall facing northeast, double-glazed windows are flush with the building profile to allow direct lighting. Approximately 25 percent of the glass (along the upper section of each window area) is clear. The remaining window area is tinted to provide interior daylighting with minimal solar heat gain.

On the southwest facade, the tinted glass area is recessed, creating a combination sun shade/light shelf to broadcast light deep into the interior and provide additional protection from direct heat gain in summer months. The remaining 25 percent of clear glass surface is flush to the building profile. This combination of recessed and flush facades maximizes the effect of daylighting, providing varying amounts of light to nearly two-thirds of the building's work areas.

The primary artificial lighting system--high efficiency, parabolic fluorescent fixtures--uses fiber optic sensors to adjust to daylighting conditions. These sensors, controlling the fixtures in the exterior offices, automatically adjust the overhead lighting to maintain at least 60 fc illumination levels throughout the day. The total artificial lighting load in the building is estimated to be 1.3 W/ft^2, a low figure for a commercial office structure.





Case Study Windows & Daylighting Group
Applied Science Division
Lawrence Berkeley Laboratory

Commercial/Office/Highrise		
Building Type	CODE	3.1.2

Washington/USA		
Geographical Location	CODE	1B

Source(s): WMFL; FCB; OFC/ LD&A 1:82

[x] File [x] Slides

Building: Farm Credit Banks Building

Address W. 601 First Avenue
City Spokane State WA Zip 99204
Country USA

47.5N ° latitude 117.5W ° longitude

Architect: Bruce Walker
Firm WMFL
Address West 224 Main Avenue
City Spokane State WA Zip 99201
Country USA Phone 509 /838-8681

Consultants: Daylighting Harvey Bryan
Electrical Flack & Kurtz
Energy Analysis Vladimir Bazjanac
Mechanical Flack & Kurtz
Structural KKBNA Inc.
Landscape

[ ] proposed [x] urban [x] bldg obstructions
[x] new [ ] suburban [x] grnd reflectance
[ ] retrofit [ ] rural

Square Footage 252,000 Completion Date 1982

Design Elements

1.1 [x] side lighting
1.2 [ ] clerestories
1.3 [ ] skylights
1.4 [ ] roof monitors
1.5 [ ] atriums
1.6 [ ] light wells
1.7 [ ] beam sunlight
1.8 [x] sun controls
1.9 [ ] ______

Glazing Type

2.1 [ ] single
2.2 [x] double
2.3 [ ] triple
2.4 [ ] heat absorbing
2.5 [ ] heat reflecting
2.6 [ ] photochromic
2.7 [ ] glass block
2.8 [ ] plastic
2.9 [ ] ______

Daylight & Sunlight Controls

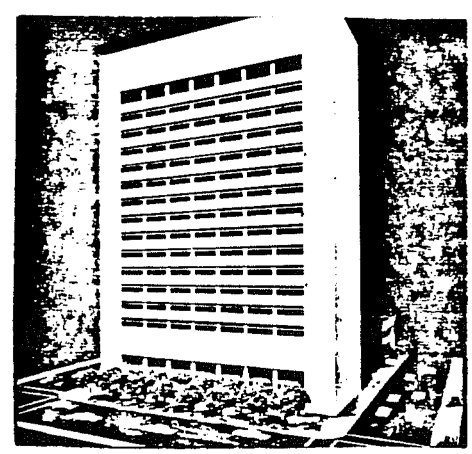
EXTERIOR

	* F	M	A	
3.1	[ ]	[ ]	[ ]	vegetation
3.2	[ ]	[ ]	[ ]	overhang
3.3	[ ]	[ ]	[ ]	fins
3.4	[ ]	[ ]	[ ]	louvers
3.5	[ ]	[ ]	[ ]	screens
3.6	[ ]	[ ]	[ ]	shutters
3.7	[x]	[ ]	[ ]	light shelf/reflector
3.8	[ ]	[ ]	[ ]	______

INTERIOR

	F	M	A	
4.1	[ ]	[ ]	[ ]	between glass
4.2	[ ]	[ ]	[ ]	glazing
4.3	[ ]	[ ]	[ ]	films
4.4	[ ]	[ ]	[ ]	screens
4.5	[ ]	[ ]	[ ]	shades
4.6	[ ]	[x]	[ ]	blinds
4.7	[ ]	[ ]	[ ]	drapes
4.8	[ ]	[ ]	[ ]	shutters
4.9	[ ]	[ ]	[ ]	vegetation
4.10	[ ]	[ ]	[ ]	______

* F: fixed
M: manual operation
A: automatic operation



Lighting Systems

Function/Location ______

Energy Use ______ Total Watts ______

Hrs Yrly Oper'n ______ Energy Yr KwH ______

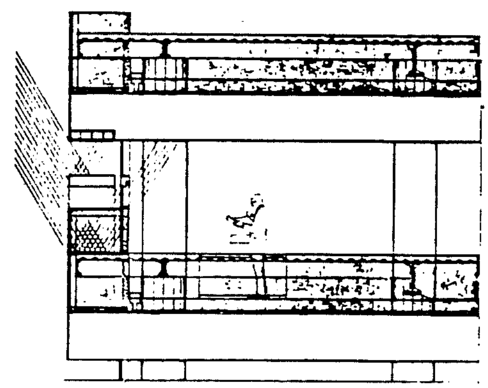
Lighting Controls

5.1 [ ] on/off 5.3 [x] automatic
5.2 [x] step/dimming 5.4 [ ] manual

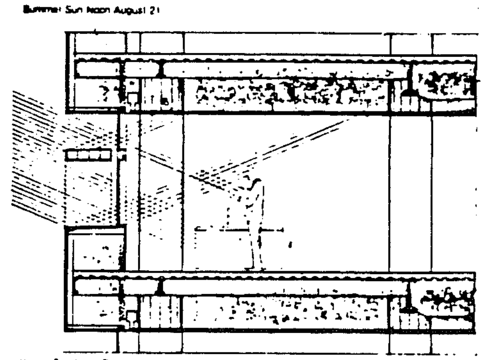
4/83

Farm Credit Banks Building Spokane, Washington

The project's major energy savings are attributed to natural lighting of interiors, energy conservation was the key to developing the building's configuration. Relatively narrow tower floors (65 ft interior dimension) minimize middle zones that cannot be lit naturally. Orientation of window walls (north-south) and open offices will reduce the need for artificial light during daytime hours up to 15 ft or more from window. The reduction in energy consumption can amount to 50 to 60 percent, the architects report. Including mechanical and electrical systems, the building has an anticipated annual energy consumption of 40,000 Btu/sq ft/yr.



Summer Sun Noon August 21



Winter Sun Noon December 21

Direct and Reflected Daylight

The glass is shaded with exterior horizontal and vertical surfaces, the outside edges being positioned three ft in front of the clear glazing on the south facade. Two horizontal surfaces, one at sill height (32 in.), and another seven ft above each floor reflect natural light deep inside. The floor-to-ceiling height on office floors is nine ft. Vertical shades occur every 20 ft along the window wall. The total shading prevents exposure to sunlight from April to September; during winter months, it allows limited solar gain to supplement building heating.

Glare will be controlled by the upper sun shelf and interior roller-mounted vinyl solar shades that can be manually operated by occupants.

Average artificial lighting energy consumption is projected at 1.4 watts/sq ft/yr, with standard parabalume overhead fluorescent lighting fixtures controlled by photocell dimmers that respond to daylighting conditions.

Lighting levels in task areas are projected at 71 footcandles; corridors and lobbies will attain 30 footcandles.

Case Study Windows & Daylighting Group
Applied Science Division
Lawrence Berkeley Laboratory

Educational/College-Univ.	
Building Type CODE	2.3
Minnesota/USA	
Geographical Location CODE	1B

Source(s): LD&A, AIA J, 1:83,p.64

[ ] File [ ] Slides

Building: Civil/Mineral Engineering Building

Address Univ. of Minnesota
City St. Paul State MN Zip
Country USA

45N ° latitude 73W ° longitude

Architect: David J. Bennett
Firm BRW Architects
Address 2829 University Ave. S.E.
City Minneapolis State MN Zip 55414
Country Phone 612/ 379-7878

[ ] proposed [x] urban [ ] bldg obstructions
[x] new [ ] suburban [x] grnd reflectance
[ ] retrofit [ ] rural

Consultants: Daylighting BRW Architects
Electrical OLB & Assoc.
Energy Analysis
Mechanical OLB & Assoc.
Structural MBJ Inc.
Landscape

Square Footage 142,500 Completion Date 1983
Construction Cost $11,115,000

Design Elements

- 1.1 [x] side lighting
- 1.2 [ ] clerestories
- 1.3 [ ] skylights
- 1.4 [x] roof monitors
- 1.5 [x] atriums
- 1.6 [ ] light wells
- 1.7 [x] beam sunlight
- 1.8 [x] sun controls
- 1.9 [ ] ____

Glazing Type

- 2.1 [ ] single
- 2.2 [ ] double
- 2.3 [ ] triple
- 2.4 [ ] heat absorbing
- 2.5 [ ] heat reflecting
- 2.6 [ ] photochromic
- 2.7 [ ] glass block
- 2.8 [ ] plastic
- 2.9 [ ] ____

Daylight & Sunlight Controls

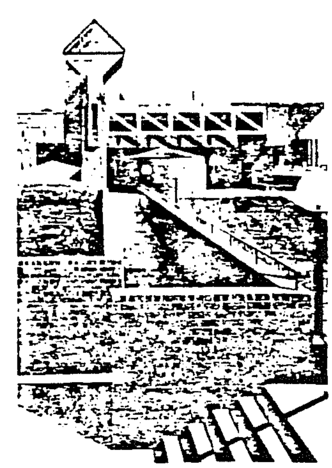
EXTERIOR

	* F	M	A	
3.1	[x]	[ ]	[ ]	vegetation
3.2	[x]	[ ]	[ ]	overhang
3.3	[ ]	[ ]	[ ]	fins
3.4	[ ]	[ ]	[ ]	louvers
3.5	[ ]	[ ]	[ ]	screens
3.6	[ ]	[ ]	[ ]	shutters
3.7	[x]	[ ]	[ ]	light shelf/reflector
3.8	[ ]	[ ]	[ ]	____

INTERIOR

	F	M	A	
4.1	[ ]	[ ]	[ ]	between glass
4.2	[ ]	[ ]	[ ]	glazing
4.3	[ ]	[ ]	[ ]	films
4.4	[ ]	[ ]	[ ]	screens
4.5	[ ]	[ ]	[ ]	shades
4.6	[ ]	[ ]	[ ]	blinds
4.7	[ ]	[ ]	[ ]	drapes
4.8	[ ]	[ ]	[ ]	shutters
4.9	[ ]	[ ]	[ ]	vegetation
4.10	[ ]	[ ]	[ ]	____

* F: fixed
M: manual operation
A: automatic operation



Lighting Systems

Function/Location ____

Energy Use ____ Total Watts ____

Hrs Yrly Oper'n ____ Energy Yr KwH ____

Lighting Controls

- 5.1 [ ] on/off
- 5.2 [ ] step/dimming
- 5.3 [ ] automatic
- 5.4 [ ] manual

4/83

Civil/Mineral Engineering Building
University of Minnesota

St. Paul, Minnesota

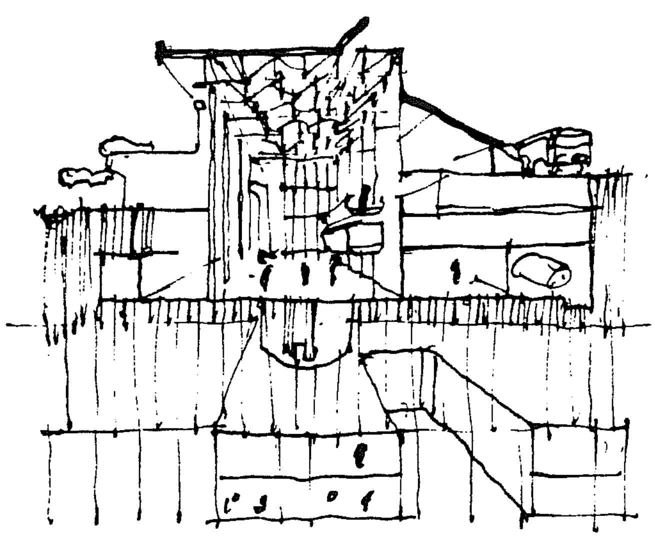
The design of the Engineering Building at the University of Minnesota combines relatively common energy-efficient surface building practices with both earth-sheltered techniques already proven on the University campus and innovative deep-earth sheltering. Additionally, high technology solar optic daylighting systems will be used for the first time in any public building.

The bulk of interior lighting needs, however, are met with a combination of metal halide and high efficiency fluorescent systems with some incandescent accent system fixtures. Despite the necessity for external electric lighting in the earth-sheltered design, the total connected lighting load is estimated to be a low 1.59 W/ft^2, with lighting levels varying from 30 to 60 fc in hallways and general rooms to 100 fc task lighting in laboratories. This load also includes the high pressure sodium lighting surrounding the building exterior.

The three levels immediately below grade are designed with no opening on the northeast face. Openings are concentrated on the southwest face to expose the central roofed areas to daylighting and direct solar gain. Internal space is laid out correspondingly; laboratories and classroom requiring precise lighting control are beneath the sheltered area, while offices are located on the sun-exposed side, which also is steeped down into a sunken courtyard to maximize solar benefits.

Also, the use of landscaping is an integral part of the Engineering Building design. This involves the use of draping deciduous vines to provide solar shading of the southwest facing exterior in the summer months. During the winter, the ivy sheds its leaves to allow solar heat gain. This technique of landscape microclimatology has proven effective in reducing solar heat gain by 50 to 75 percent.

Another innovation is the use of a remote view optical system to create an illusion of above grade construction in the 110 ft space deep based on the principle of the periscope, the system will transmit a realistic, three-dimensional view, looking west from the site to the mined space reception area.



Case Study

Windows & Daylighting Group
Applied Science Division
Lawrence Berkeley Laboratory

Industrial (Warehouse & Factory)
Building Type CODE 4.

Michigan/USA
Geographical Location CODE 1B

43N ° latitude 86W ° longitude

Source(s): PA 2:82, p.110

[ ] File [ ] Slides

Building: Herman Miller Plant

Address
City Holland State MI Zip
Country USA

Architect: Paul Kennon, Principal
Firm Caudill, Rowlett, Scott, Inc.
Address 1111 West Loop South
City Houston State TX Zip 77027
Country Phone 713/ 621-9600

Consultants: Daylighting Caudill, Rowlett, Scott
Electrical B.J. Kemper & Assoc.
Energy Analysis
Mechanical Engineered Systems
Structural Caudill, Rowlett, Scott
Landscape

[ ] proposed [x] new [ ] retrofit
[ ] urban [x] suburban [ ] rural
[ ] bldg obstructions [x] grnd reflectance

Square Footage 202,600

Design Elements

1.1 [x] side lighting
1.2 [x] clerestories
1.3 [x] skylights
1.4 [ ] roof monitors
1.5 [ ] atriums
1.6 [ ] light wells
1.7 [ ] beam sunlight
1.8 [ ] sun controls
1.9 [ ] ____________

Glazing Type

2.1 [ ] single
2.2 [ ] double
2.3 [ ] triple
2.4 [ ] heat absorbing
2.5 [ ] heat reflecting
2.6 [ ] photochromic
2.7 [ ] glass block
2.8 [ ] plastic
2.9 [ ] ____________

Daylight & Sunlight Controls

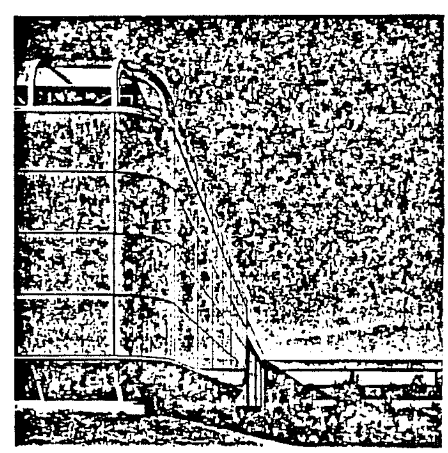
EXTERIOR

	* F	M	A	
3.1	[ ]	[ ]	[ ]	vegetation
3.2	[ ]	[ ]	[ ]	overhang
3.3	[ ]	[ ]	[ ]	fins
3.4	[ ]	[ ]	[ ]	louvers
3.5	[ ]	[ ]	[ ]	screens
3.6	[ ]	[ ]	[ ]	shutters
3.7	[ ]	[ ]	[ ]	light shelf/reflector
3.8	[ ]	[ ]	[ ]	____________

INTERIOR

4.1	[ ]	[ ]	[ ]	between glass
4.2	[ ]	[ ]	[ ]	glazing
4.3	[ ]	[ ]	[ ]	films
4.4	[ ]	[ ]	[ ]	screens
4.5	[ ]	[ ]	[ ]	shades
4.6	[ ]	[ ]	[ ]	blinds
4.7	[ ]	[ ]	[ ]	drapes
4.8	[ ]	[ ]	[ ]	shutters
4.9	[ ]	[ ]	[ ]	vegetation
4.10	[ ]	[ ]	[ ]	____________

* F: fixed
M: manual operation
A: automatic operation



Lighting Systems

Function/Location ____________

Energy Use ______ Total Watts ______
Hrs Yrly Oper'n ______ Energy Yr KwH ______

Lighting Controls

5.1 [ ] on/off
5.2 [ ] step/dimming
5.3 [ ] automatic
5.4 [ ] manual

4/83

Herman Miller Plant

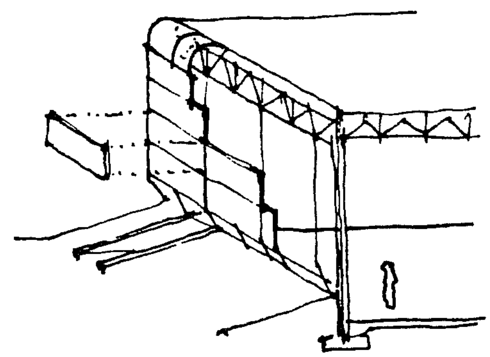
Holland, MI

For the new seating plant in Holland, MI, the Miller organization chose CRS of Houst, long known for its front end collaboration design process, or "squatters" sessions. From these early meetings came design input from the plant workers and managers, not just from upper management. The intent then was, to quote Paul Kennon, CRS president and design principal for the job, to "combine high morale with high technology.....". In its final form, the Holland facility will comprise two more comparable plant segments, since this is only the first of three planned.

An expression of technology, the buildings are termed long, slick, extrusion-like elements on the exterior, while the simple wide flange columns and open web trusses and joists are the interior aesthetic. Except for one thing. The building skin is stainless steel outside, painted steel inside, and insulation between. Pulled outside the column line, the panels stop short at the op and bottom, the form completed by glazing. The entire cornice is vaulted acrylic skylight, and the "base" is inward-slanting fixed and sliding windows.

Exceptions to these conditions occur at the entry, which awaits the completion of the "people place", a skylighted pavilion to serve as entry, break or lunch area, seminar space, and other uses. This missing piece accounts for the angled slices terminating the steel skin on the southeast and northeast facades near the present entry.

Because of the continuous top and bottom glazing and additional skylights, the interior requires less electric lighting. The inner surfaces of the perimeter walls fairly glow on bright days, and workers are provided both optional ventilation and eye-level views through the lower glazing. There is one problem with the cornice vaults--an overabundance of insolation in some areas in warm weather which is being studied; it would seem that some form of optional shading or shuttering should be installed. Trial panels of more opaque acrylic have shown a distinct dampening effect on the building's expression and it is to be hoped, will not be seen as the solution.



Case Study Windows & Daylighting Group
Applied Science Division
Lawrence Berkeley Laboratory

Comm. Office Low-Rise		
Building Type	CODE	1.1.1
Iowa/USA		
Geographical Location	CODE	2

Source(s): PA 4:82, p.146

[ ] File [ ] Slides

Building: Iowa Public Services Building Headquarters

Address 401 Douglas
City Sioux City State IA Zip 51102
Country USA

42N ° latitude 96W ° longitude

Architect(s) (1) Rossetti Associates
(2) Foss, Engelstad, Heil Assoc.
Address
City State Zip
Country (1) Phone 313/ 964-3240
(2) 712/252-3889

Consultants: Daylighting
Electrical Foss, Engelstad, Heil
Energy Analysis
Mechanical Foss, Englestad, Heil
Structural
Landscape

[ ] proposed [x] urban [ ] bldg obstructions
[x] new [ ] suburban [ ] grnd reflectance
[ ] retrofit [ ] rural

Square Footage 167,635

Construction Cost $14.35 million
(including interiors and site work)

Design Elements

1.1 [x] side lighting
1.2 [ ] clerestories
1.3 [x] skylights
1.4 [ ] roof monitors
1.5 [x] atriums
1.6 [ ] light wells
1.7 [ ] beam sunlight
1.8 [ ] sun controls
1.9 [ ] ____________

Glazing Type

2.1 [ ] single
2.2 [ ] double
2.3 [ ] triple
2.4 [ ] heat absorbing
2.5 [ ] heat reflecting
2.6 [ ] photochromic
2.7 [x] glass block
2.8 [ ] plastic
2.9 [x] TINTED

Daylight & Sunlight Controls

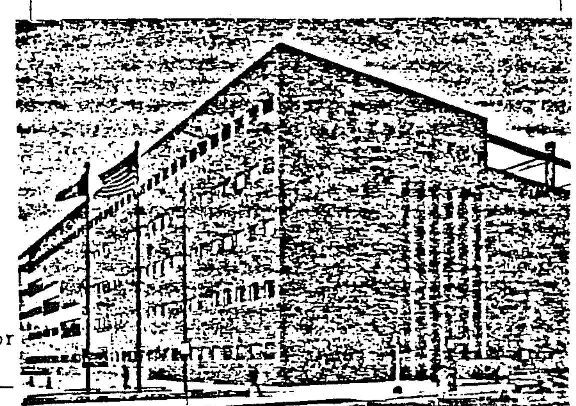
EXTERIOR

	* F	M	A	
3.1	[ ]	[ ]	[ ]	vegetation
3.2	[ ]	[ ]	[ ]	overhang
3.3	[ ]	[ ]	[ ]	fins
3.4	[ ]	[ ]	[ ]	louvers
3.5	[ ]	[ ]	[ ]	screens
3.6	[ ]	[ ]	[ ]	shutters
3.7	[ ]	[ ]	[ ]	light shelf/reflector
3.8	[ ]	[ ]	[ ]	____________

INTERIOR

	F	M	A	
4.1	[ ]	[ ]	[ ]	between glass
4.2	[ ]	[ ]	[ ]	glazing
4.3	[ ]	[ ]	[ ]	films
4.4	[ ]	[ ]	[ ]	screens
4.5	[ ]	[ ]	[ ]	shades
4.6	[ ]	[ ]	[ ]	blinds
4.7	[ ]	[ ]	[ ]	drapes
4.8	[ ]	[ ]	[ ]	shutters
4.9	[ ]	[ ]	[ ]	vegetation
4.10	[ ]	[ ]	[ ]	____________

* F: fixed
M: manual operation
A: automatic operation



Lighting Systems

Function/Location

Energy Use ________ Total Watts ________

Hrs Yrly Oper'n ________ Energy Yr KwH ________

Lighting Controls

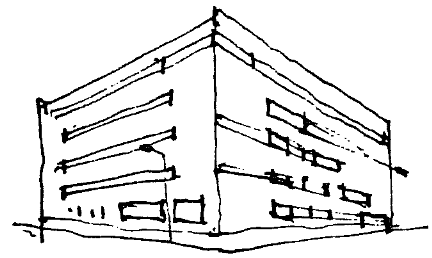
5.1 [ ] on/off 5.3 [ ] automatic
5.2 [ ] step/dimming 5.4 [ ] manual

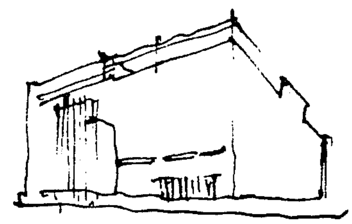
4/83

Iowa Public Service Bldg Headquarters

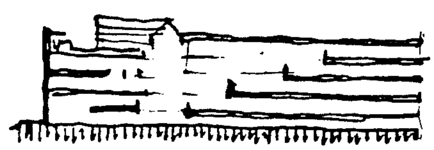
Sioux City, Iowa

Because it is not really a "public" building in the normal sense, the entry is restrained, and even though it is four stories high, it is studded with columns and somewhat ambiguous. For security reasons, the reception foyer is isolated, but visitors can just begin to get a hint of the atrium beyond the sloped glass wall. Behind the receptionist the atrium opens up and, away from the entry, escalators soar and bridges pass overhead under a huge L-shaped skylight.





On each successive floor, the west edge of the atrium steps one 36-ft bay farther west while the bridges shift in the same direction by 12 ft. As in the reception area, sloped interior glazing connects each bridge with a beam a floor above, creating transparent canopies. A viewer on a bridge can look down on another or up to the skylight, and the angle creates a periscope effect for viewers farther away to view the reflected sky.



On the office floors, daylighting is introduced in various ways. The fifth floor has glass block outer walls and clear glass on some corridor offices while the lower floors have many perimeter office walls of bronze glass on the exterior, glass block facing the circulation (atrium) side. Because these offices are located along the south wall of each floor above the first, light is transmitted through them to the secretarial and circulation spaces. Interior colors range from green and orange to shades of mauve and plum, in some areas perhaps threatening to get a bit out of hand when added to the rich materials palette of wood, metal, and ceramic tile. But in general the spaces are bright, warm, and cheerful, and it is easy for a visitor to feel the friendly interaction of the employees while touring the building.

Case Study — Windows & Daylighting Group, Applied Science Division, Lawrence Berkeley Laboratory

Comm. Office High-Rise	
Building Type	CODE 3.1.2
Pennsylvania/USA	
Geographical Location	CODE 2

Source(s): Glass Digest 4/83 p. 56; P/A 7:82

☐ File ☐ Slides

Building: Philadelphia Stock Exchange Building

Address 1900 Market St.

City Philadelphia State PA Zip

Country USA

40N ° latitude 75W ° longitude

Architect: Gerald Cope

Firm Cope Linder Associates

Address 1 North 12th Street

City Philadelphia State PA Zip 19107

Country Phone 215/ 925-6767

☐ proposed ☑ urban ☐ bldg obstructions

☑ new ☐ suburban ☐ grnd reflectance

☐ retrofit ☐ rural

Consultants: Daylighting Wheel Gerztaff

Electrical Cosentini Assoc.

Energy Analysis

Mechanical Cosentini Assoc.

Structural Cope Linder Assoc.

Landscape

Square Footage 500,000

Construction Cost $23.6 million

Design Elements

- 1.1 ☐ side lighting
- 1.2 ☐ clerestories
- 1.3 ☑ skylights
- 1.4 ☐ roof monitors
- 1.5 ☑ atriums
- 1.6 ☐ light wells
- 1.7 ☐ beam sunlight
- 1.8 ☐ sun controls
- 1.9 ☐

Glazing Type

- 2.1 ☐ single
- 2.2 ☑ double
- 2.3 ☐ triple
- 2.4 ☐ heat absorbing
- 2.5 ☑ heat reflecting
- 2.6 ☐ photochromic
- 2.7 ☐ glass block
- 2.8 ☐ plastic
- 2.9 ☑ LAMINATED

Daylight & Sunlight Controls

EXTERIOR

	* F	M	A	
3.1	☐	☐	☐	vegetation
3.2	☐	☐	☐	overhang
3.3	☐	☐	☐	fins
3.4	☐	☐	☐	louvers
3.5	☐	☐	☐	screens
3.6	☐	☐	☐	shutters
3.7	☐	☐	☐	light shelf/reflector
3.8	☐	☐	☐	

INTERIOR

	F	M	A	
4.1	☐	☐	☐	between glass
4.2	☐	☐	☐	glazing
4.3	☐	☐	☐	films
4.4	☐	☐	☐	screens
4.5	☐	☐	☐	shades
4.6	☐	☐	☐	blinds
4.7	☐	☐	☐	drapes
4.8	☐	☐	☐	shutters
4.9	☑	☐	☐	vegetation
4.10	☑	☐	☐	OVERHANGS

* F: fixed
M: manual operation
A: automatic operation

Lighting Systems

Function/Location

Energy Use ____ Total Watts ____

Hrs Yrly Oper'n ____ Energy Yr KwH ____

Lighting Controls

- 5.1 ☐ on/off
- 5.2 ☐ step/dimming
- 5.3 ☐ automatic
- 5.4 ☐ manual

4/83

Philadelphia Stock Exchange Building

Philadelphia, PA

In The Philadelphia Stock Exchange Building, a 15,000 square-foot ridge skylight caps a half-acre atrium containing pools, fountains, waterfalls, and lush greenery. Because of its desirability, the structure has been able to change a higher per square foot rent than the city's average downtown space.

The eight-story, $23.6 million building is almost a showcase for the ways that glass can be utilized in prestigious commercial construction. In addition to the dramatic skylight, the second through eighth floors of the interior encircling the atrium feature glass so that occupants can view the garden.

The structure was developed with the concept that tenants would rather have more attractive surroundings, at a higher cost, than a run-of-the-mill facility. The theory turned out to be correct. The building has been almost totally occupied from its opening, and the rents are $4 per square foot more than other structures in the same neighborhood.

The skylight is the key to the atrium. The framing design consists of an interlocking system of sloped rafters and horizontal purlins made tubular aluminum extrusions.

"The marvelous thing about the skylight," explains Gerald Cope, partner Cope Linder Associates, architects for the building, "is the sense that you're in a great garden. For those people in the offices looking into that garden, there's almost a constantly changing scene through Winter, Spring, Summer, and Fall."

The building has been designed to take advantage of the energy-saving benefits of daylight with the atrium. Artificial lighting normally accounts for more than 50 per cent of a commercial building's fuel budget. Taking advantage of free daylight through the large expanses of glass is an effective fuel-saving technique.

The skylight is not the only energy-saving technique utilized. About 42,000 square feet of bronze reflective insulating glass units were used on the building exterior on the second through eighth floors. The glass has a coating on the first, or outdoor, surface. About 12,000 square feet of clear insulating units were used on the exterior of the ground floor.

The bronze units consist of two pieces of 1/4 inch glass with a 1/2 inch air-space. The outdoor glass panel is bronze tinted, and the indoor one is clear. The units transmit about 19 per cent of the available daylight, according to the manufacturer's literature, and reflect about 36 per cent of outdoor daylight. The glass has a low shading coefficient and a low relative heat gain to help in saving fuel.

The building interior has about 31,000 square feet of 1/4 inch green-tinted glass on the second through eighth floors. The interior of the ground floor also is glass, with about 15,000 square feet of 1/4 inch clear units.

Case Study — Windows & Daylighting Group, Applied Science Division, Lawrence Berkeley Laboratory

Commercial/Office/Low-Rise	
Building Type	CODE 3.1.1
Utah/USA	
Geographical Location	CODE 3

41N ° latitude 112W ° longitude

Source(s): DOE

[x] File [ ] Slides

Building: Johnson Controls Office

Address 2255 Technology
City W. Valley City State UT Zip 84119
Country USA

Architect: Douglas Drake, Project Architect
Firm Johnson Facilities Design Group
Address 507 E. Michigan St.
City Milwaukee State WI Zip 53201
Country ______ Phone 414/ 276-4200

Consultants: Daylighting Donald Watson, Wm. Lam
Electrical ______
Energy Analysis Donald Watson
Mechanical Fred Dubin
Structural Brust Engineering Inc.
Landscape ______

[ ] proposed [ ] urban [ ] bldg obstructions
[x] new [ ] suburban [x] grnd reflectance
[ ] retrofit [x] rural

Square Footage 14,884 Completion Date 12/81
Construction Cost $848,654

Design Elements

1.1 [x] side lighting
1.2 [x] clerestories
1.3 [ ] skylights
1.4 [x] roof monitors
1.5 [ ] atriums
1.6 [ ] light wells
1.7 [ ] beam sunlight
1.8 [x] sun controls
1.9 [ ] ______

Glazing Type

2.1 [ ] single
2.2 [ ] double
2.3 [x] triple
2.4 [ ] heat absorbing
2.5 [ ] heat reflecting
2.6 [ ] photochromic
2.7 [ ] glass block
2.8 [ ] plastic
2.9 [ ] ______

Daylight & Sunlight Controls

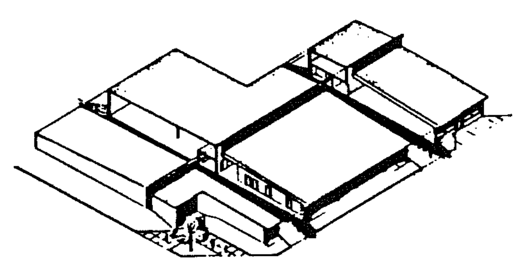
EXTERIOR

	* F	M	A	
3.1	[x]	[ ]	[ ]	vegetation
3.2	[x]	[ ]	[ ]	overhang
3.3	[ ]	[ ]	[ ]	fins
3.4	[ ]	[ ]	[ ]	louvers
3.5	[ ]	[ ]	[ ]	screens
3.6	[ ]	[ ]	[ ]	shutters
3.7	[x]	[ ]	[ ]	light shelf/reflector
3.8	[ ]	[ ]	[ ]	______

INTERIOR

	F	M	A	
4.1	[ ]	[ ]	[ ]	between glass
4.2	[ ]	[ ]	[ ]	glazing
4.3	[ ]	[ ]	[ ]	films
4.4	[ ]	[ ]	[ ]	screens
4.5	[ ]	[ ]	[ ]	shades
4.6	[ ]	[ ]	[ ]	blinds
4.7	[ ]	[ ]	[ ]	drapes
4.8	[ ]	[ ]	[ ]	shutters
4.9	[ ]	[ ]	[ ]	vegetation
4.10	[ ]	[x]	[x]	INSUL. CURTAIN

* F: fixed
M: manual operation
A: automatic operation



Lighting Systems

Function/Location ______

Energy Use ______ Total Watts ______
Hrs Yrly Oper'n ______ Energy Yr KwH ______

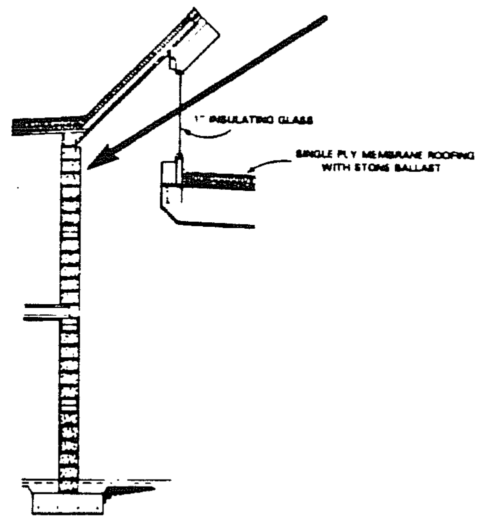
Lighting Controls

5.1 [ ] on/off
5.2 [x] step/dimming
5.3 [x] automatic
5.4 [ ] manual

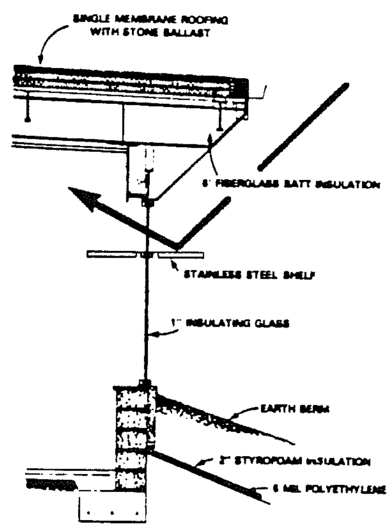
4/83

Johnson Controls Office West Valley City, UT

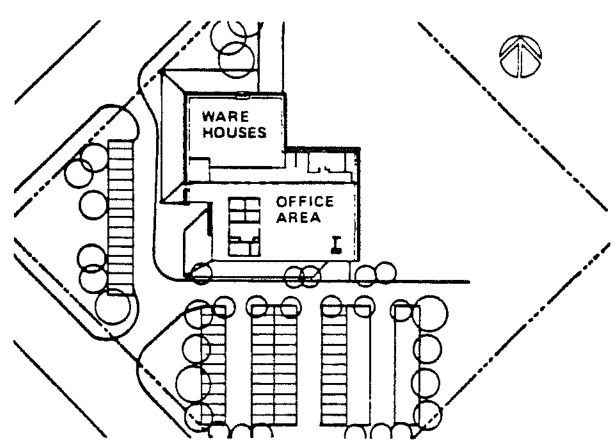
The cost-effective features of the design, according to Johnson officials, result from the use of daylight. Reliance on daylighting had an immediate effect on space, structural, and facade design concepts for the facility. In order to employ combined daylighting and passive solar heating to the extent desired, the office incorporate approximately twice as much glass as other Johnson offices; about 1,200 square feet of glass for 10,000 square feet of office/sales space.



The offices were placed on the south side of the one-story building for maximum daylight and solar heat gain. The warehouse space, where daylight and heat are less critical, is on the darker nother side of the building. Also, an °open-office' furniture approach was used to enhance daylight distribution.



Unlike most modern buildings, minimum ambient daylight levels were used to help determine the final shape of the building. Ambient light levels at the center of the office space can range from a low of 60 footcandles in June to a high of 270 footcandles in December, without any artificial lighting. Light levels will not, however, be uniform throughout the space. Light levels at the north and south walls of the office will be about three times higher than at the center throughout the year, ranging from 200 footcandles in June to about 850 footcandles in December. The daylight solution dictated a maximum allowable depth of 60 feet in each space.



In addition to increased glazing and open planning, the office also required higher ceilings than other Johnson offices, to facilitate distribution of daylight. The reflective sloped ceiling of the single-floor structure ranges from a height of 10'6" at the south wall to 13'6" at the interior edge of the clerestory spine.

Case Study — Windows & Daylighting Group, Applied Science Division, Lawrence Berkeley Laboratory

Educ. Univ. Facilities		
Building Type	CODE	2.3.2
Oregon/USA		
Geographical Location	CODE	5

45N ° latitude 123W ° longitude

Source(s): Mt. Angel brochure

[x] File [x] Slides

Building: Library, Mt. Angel Benedictine College

Address

City Mount Angel State OR Zip

Country USA

Architect: Alvar Aalto

Firm

Address

City Helsinki State Zip

Country Finland Phone /

Consultants: Daylighting

Electrical

Energy Analysis

Mechanical

Structural

Landscape

- [ ] proposed
- [x] new
- [ ] retrofit
- [ ] urban
- [ ] suburban
- [x] rural
- [ ] bldg obstructions
- [ ] grnd reflectance

Completion Date 1970

Construction Cost $1,272,000

Design Elements

- 1.1 [x] side lighting
- 1.2 [x] clerestories
- 1.3 [x] skylights
- 1.4 [x] roof monitors
- 1.5 [ ] atriums
- 1.6 [ ] light wells
- 1.7 [ ] beam sunlight
- 1.8 [ ] sun controls
- 1.9 [ ] ______

Glazing Type

- 2.1 [ ] single
- 2.2 [ ] double
- 2.3 [ ] triple
- 2.4 [ ] heat absorbing
- 2.5 [ ] heat reflecting
- 2.6 [ ] photochromic
- 2.7 [ ] glass block
- 2.8 [ ] plastic
- 2.9 [ ] ______

Daylight & Sunlight Controls

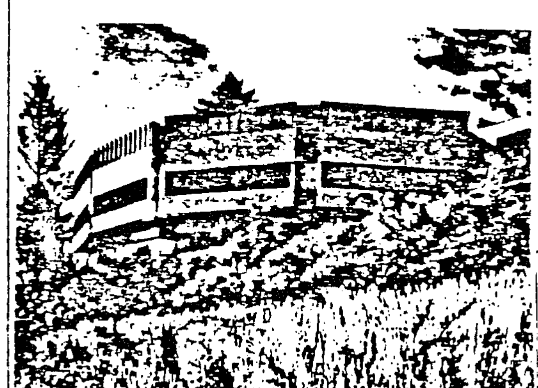
EXTERIOR

	* F	M	A	
3.1	[ ]	[ ]	[ ]	vegetation
3.2	[ ]	[ ]	[ ]	overhang
3.3	[ ]	[ ]	[ ]	fins
3.4	[x]	[ ]	[ ]	louvers
3.5	[ ]	[ ]	[ ]	screens
3.6	[ ]	[ ]	[ ]	shutters
3.7	[x]	[ ]	[ ]	light shelf/reflector
3.8	[ ]	[ ]	[ ]	______

INTERIOR

	F	M	A	
4.1	[ ]	[ ]	[ ]	between glass
4.2	[ ]	[ ]	[ ]	glazing
4.3	[ ]	[ ]	[ ]	films
4.4	[ ]	[ ]	[ ]	screens
4.5	[ ]	[ ]	[ ]	shades
4.6	[ ]	[ ]	[ ]	blinds
4.7	[ ]	[ ]	[ ]	drapes
4.8	[ ]	[ ]	[ ]	shutters
4.9	[ ]	[ ]	[ ]	vegetation
4.10	[ ]	[ ]	[ ]	______

* F: fixed
M: manual operation
A: automatic operation



Lighting Systems

Function/Location

Energy Use ______ Total Watts ______

Hrs Yrly Oper'n ______ Energy Yr KwH ______

Lighting Controls

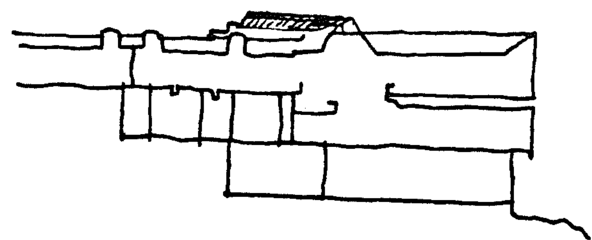
- 5.1 [ ] on/off
- 5.2 [ ] step/dimming
- 5.3 [ ] automatic
- 5.4 [ ] manual

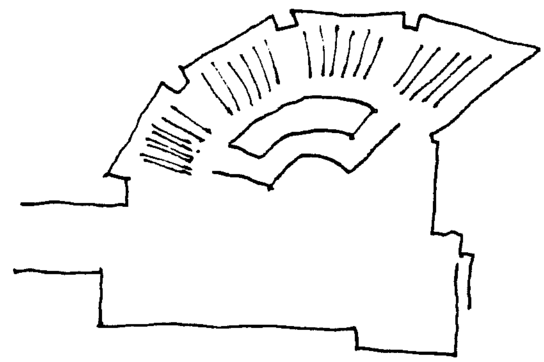
4/83

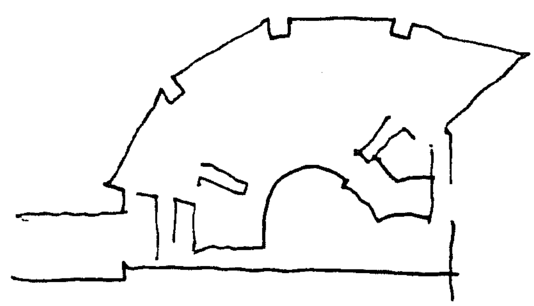
Library Benedictine College

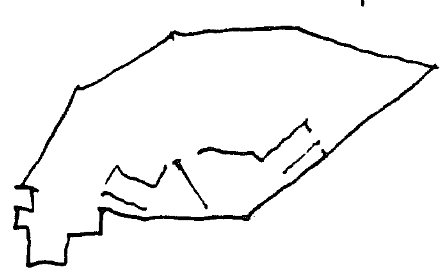
Mount Angel, Oregon

Workspaces occur at both levels of the library: open desks on the perimeter of the upper level without view but with high-level light, and below, carrels near exterior windows running from desk to ceiling and partially shaded by external vertical timber louvers. The outside finish wall materials are rough yellow brickwork, the basement cut into the hillside is dark painted concrete, and all window frames are dark hardwood. The roof is copper.









Case Study Windows & Daylighting Group, Applied Science Division, Lawrence Berkeley Laboratory

Educ. Univ. Facilities	
Building Type CODE	2.1.2

California/USA	
Geographical Location CODE	5

41N ° latitude 124W ° longitude

Source(s): Solar Age, Oct 81 p. 65

☐ File ☐ Slides

Building: Humboldt State University Science Complex
Address
City Arcata State CA Zip
Country USA

Architect: Richard Bartlett
Firm Ratcliff Architects
Address 3408 Grove St.
City Berkeley State CA Zip 94703
Country Phone 415/ 652-1972

Consultants: Daylighting
Electrical Buonaccorsi & Assoc.
Energy Analysis
Mechanical Buonaccorsi & Assoc.
Structural
Landscape

☐ proposed ☑ new ☐ retrofit
☐ urban ☑ suburban ☐ rural
☐ bldg obstructions ☐ grnd reflectance

Square Footage 50,000 Completion Date 1982
Construction Cost $4 million

Design Elements

- 1.1 ☐ side lighting
- 1.2 ☐ clerestories
- 1.3 ☑ skylights
- 1.4 ☐ roof monitors
- 1.5 ☐ atriums
- 1.6 ☐ light wells
- 1.7 ☐ beam sunlight
- 1.8 ☑ sun controls
- 1.9 ☐

Glazing Type

- 2.1 ☐ single
- 2.2 ☑ double
- 2.3 ☐ triple
- 2.4 ☐ heat absorbing
- 2.5 ☐ heat reflecting
- 2.6 ☐ photochromic
- 2.7 ☐ glass block
- 2.8 ☑ plastic
- 2.9 ☐

Daylight & Sunlight Controls

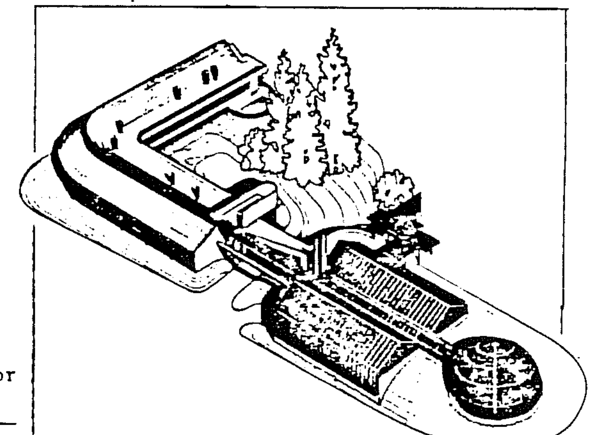
EXTERIOR

	* F	M	A	
3.1	☐	☐	☐	vegetation
3.2	☐	☐	☐	overhang
3.3	☐	☐	☐	fins
3.4	☐	☐	☐	louvers
3.5	☐	☐	☐	screens
3.6	☐	☐	☐	shutters
3.7	☐	☐	☐	light shelf/reflector
3.8	☑	☐	☐	GREENHOUSE

INTERIOR

	F	M	A	
4.1	☐	☐	☐	between glass
4.2	☐	☐	☐	glazing
4.3	☐	☐	☐	films
4.4	☐	☐	☐	screens
4.5	☐	☐	☐	shades
4.6	☐	☐	☐	blinds
4.7	☐	☐	☐	drapes
4.8	☐	☐	☐	shutters
4.9	☑	☐	☐	vegetation
4.10	☐	☑	☐	LOUVERS

* F: fixed
M: manual operation
A: automatic operation



Lighting Systems

Function/Location

Energy Use Total Watts
Hrs Yrly Oper'n Energy Yr KwH

Lighting Controls

- 5.1 ☐ on/off
- 5.2 ☐ step/dimming
- 5.3 ☐ automatic
- 5.4 ☑ manual

4/83

Science Complex Humboldt State University

Arcata, California

A two-story laboratory building in the shape of an "L" with rounded corners holds most of the complex's 50,000 square feet of floor space. A continuous skylight at the building's peak will provide some daylight to the second floor. The return air duct and the copper tubing of a domestic hot water preheat loop will fill 70 percent of the skylight aperture.

Like the band of glass that parallels it above, a continuous two-story glazed chamber forms the outer wall of the south and west sides of the laboratory building. The four-foot airspace between layers of glass will trap heat in a buffer zone and surround the supply-air duct with insulating air. Vents running the length of the chamber walls on both floors permit flexible ventilation control.

The double-glazed greenhouse is divided into rooms with controlled climates so that botanists can breed plant specimens with varying light, temperature, and humidity needs. Part of the south perimeter is a Trombe wall.

To the east of greenhouse will sit a Plexiglass dome for heat-loving subtropical plant specimens.

Case Study

Windows & Daylighting Group
Applied Science Division
Lawrence Berkeley Laboratory

Civic Office Low-Rise
Building Type — CODE 1.1.1

California/USA
Geographical Location — CODE 6

38N ° latitude 122W ° longitude

Source(s): Present Value, Constructing a Sustainable Future, p. 47, by G. Coe

[x] File [x] Slides

Building: Gregory E. Bateson Building (Site 1-A)
Address: Eighth & D Streets
City: Sacramento State: CA Zip:
Country: USA

Architect: Glen Hezmalhalch, Project Architect
Firm: Office of the State Architect
Address: 1500-5th St.
City: Sacramento State: CA Zip:
Country: Phone: 916/322-4932

Consultants: Daylighting (in-house)
Electrical
Energy Analysis
Mechanical
Structural
Landscape

[ ] proposed [x] urban [ ] bldg obstructions
[x] new [ ] suburban [x] grnd reflectance
[ ] retrofit [ ] rural

Square Footage 276,000 Completion Date 1980
Construction Cost $19.6 million

Design Elements

1.1 [ ] side lighting
1.2 [ ] clerestories
1.3 [x] skylights
1.4 [x] roof monitors
1.5 [x] atriums
1.6 [ ] light wells
1.7 [ ] beam sunlight
1.8 [x] sun controls
1.9 [ ] ______

Glazing Type

2.1 [ ] single
2.2 [ ] double
2.3 [ ] triple
2.4 [ ] heat absorbing
2.5 [ ] heat reflecting
2.6 [ ] photochromic
2.7 [ ] glass block
2.8 [ ] plastic
2.9 [ ] ______

Daylight & Sunlight Controls

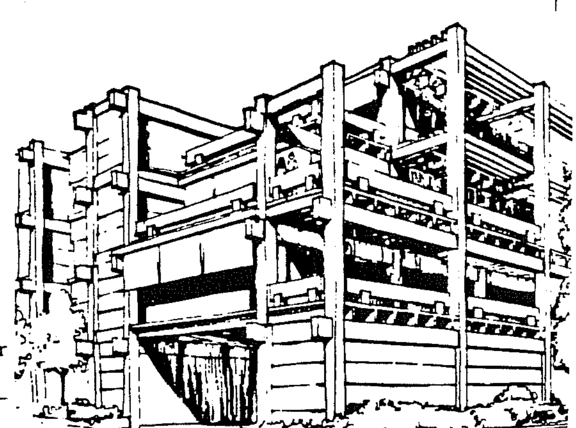
EXTERIOR

	* F	M	A	
3.1	[ ]	[ ]	[ ]	vegetation
3.2	[x]	[ ]	[ ]	overhang
3.3	[ ]	[ ]	[ ]	fins
3.4	[ ]	[ ]	[x]	louvers
3.5	[ ]	[ ]	[ ]	screens
3.6	[ ]	[ ]	[ ]	shutters
3.7	[ ]	[ ]	[ ]	light shelf/reflector
3.8	[ ]	[ ]	[x]	SHADES

INTERIOR

	F	M	A	
4.1	[ ]	[ ]	[ ]	between glass
4.2	[ ]	[ ]	[ ]	glazing
4.3	[ ]	[ ]	[ ]	films
4.4	[ ]	[ ]	[ ]	screens
4.5	[ ]	[ ]	[ ]	shades
4.6	[ ]	[ ]	[ ]	blinds
4.7	[ ]	[ ]	[ ]	drapes
4.8	[ ]	[ ]	[ ]	shutters
4.9	[x]	[ ]	[ ]	vegetation
4.10	[ ]	[ ]	[ ]	______

* F: fixed
M: manual operation
A: automatic operation



Lighting Systems

Function/Location ______

Energy Use ______ Total Watts ______
Hrs Yrly Oper'n ______ Energy Yr KwH ______

Lighting Controls

5.1 [ ] on/off 5.3 [ ] automatic
5.2 [ ] step/dimming 5.4 [ ] manual

4/83

Gregory E. Bateson Bldg

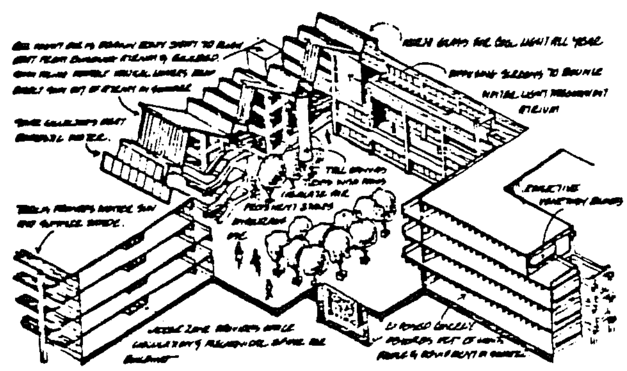
Sacramento, California

A striking feature of the 276,000 sq. ft. building is a central atrium or court. The landscaped court replaces corridors as the main passageways and includes areas where employees can meet for lunch and coffee breaks. In addition to improving the work environment with plants, light, and space, the court has a number of energy-related benefits. North- and south-facing skylights cover the court, providing light and air. Exhaust fans and louvers that shade the skylight will be computer-controlled to maintain a comfortable environment while using only a fraction of the energy that would ordinarily be required to heat or cool that much space.

During winter, the exterior shading louvers can be opened to allow direct solar gain to enter the court, thereby providing ample passive solar heating. In summer, the louvers will automatically block the sun's rays, while admitting indirect daylight. During the day, the court will remain cooler than the outside because the direct sun is blocked out.

Along the perimeter of the building, heat infiltration is regulated by the use of trellises on the south side and exterior shading on the east and west sides. The trellises act as an overhang, blocking summer sun but allowing the low winter rays to enter. Computer-controlled exterior shades on the east and west will lower the shade windows from direct sunlight and retract when the sun is off the window pane. Exterior shading prevents heat from entering, allowing for greater window area without adding to the cooling problem, and larger windows reduce the amount of artificial light needed in work areas.

Lighting in Site One will require half of the power required by a conventionally engineered office building, while providing better lighting conditions for office workers. Much of this savings is achieved by the use of individually controlled lighting for specific work areas. Where that type of lighting is not possible, in conference rooms for example, louvered fluorescent fixtures will be used.



Case Study — Windows & Daylighting Group, Applied Science Division, Lawrence Berkeley Laboratory

Educ. University Facilities		
Building Type	CODE	2.1.2
California USA		
Geographical Location	CODE	6

Source(s): Present Value, Constructing a Sustainable Future p. 29 by G.Coe
[x] File [x] Slides

Building: Terman Engineering Center

38N ° latitude 122W ° longitude

Address
City Stanford State CA Zip
Country USA

Architect: Harry Weese
Firm Harry Weese & Assoc.
Address 10 West Hubbard
City Chicago State IL Zip
Country Phone 312 467-7030

[ ] proposed [ ] urban [ ] bldg obstructions
[x] new [x] suburban [x] grnd reflectance
[ ] retrofit [ ] rural

Consultants: Daylighting Harry Weese & Assoc.
Electrical Kammisa & Wipf
Energy Analysis
Mechanical Kasin Guttman & Assoc.
Structural Nishkian Hammill & Assoc.
Landscape

Square Footage 152,000 Completion Date 1977
Construction Cost $7.5 million

Design Elements

- 1.1 [x] side lighting
- 1.2 [ ] clerestories
- 1.3 [x] skylights
- 1.4 [ ] roof monitors
- 1.5 [ ] atriums
- 1.6 [x] light wells
- 1.7 [ ] beam sunlight
- 1.8 [ ] sun controls
- 1.9 [ ] ____________

Glazing Type

- 2.1 [x] single
- 2.2 [ ] double
- 2.3 [ ] triple
- 2.4 [ ] heat absorbing
- 2.5 [ ] heat reflecting
- 2.6 [ ] photochromic
- 2.7 [ ] glass block
- 2.8 [ ] plastic
- 2.9 [ ] ____________

Daylight & Sunlight Controls

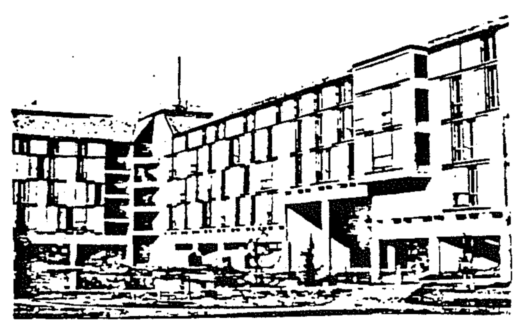
EXTERIOR

	* F	M	A	
3.1	[x]	[ ]	[ ]	vegetation
3.2	[ ]	[ ]	[ ]	overhang
3.3	[ ]	[ ]	[ ]	fins
3.4	[ ]	[ ]	[ ]	louvers
3.5	[ ]	[ ]	[ ]	screens
3.6	[ ]	[x]	[ ]	shutters
3.7	[ ]	[x]	[ ]	light shelf/reflector
3.8	[x]	[ ]	[ ]	POOL

INTERIOR

	F	M	A	
4.1	[ ]	[ ]	[ ]	between glass
4.2	[ ]	[ ]	[ ]	glazing
4.3	[ ]	[ ]	[ ]	films
4.4	[ ]	[ ]	[ ]	screens
4.5	[ ]	[ ]	[ ]	shades
4.6	[ ]	[ ]	[ ]	blinds
4.7	[ ]	[ ]	[ ]	drapes
4.8	[ ]	[x]	[ ]	shutters
4.9	[ ]	[ ]	[ ]	vegetation
4.10	[ ]	[ ]	[ ]	____________

* F: fixed
M: manual operation
A: automatic operation



Lighting Systems

Function/Location ____________

Energy Use ______ Total Watts ______
Hrs Yrly Oper'n ______ Energy Yr KwH ______

Lighting Controls

- 5.1 [ ] on/off
- 5.2 [ ] step/dimming
- 5.3 [ ] automatic
- 5.4 [ ] manual

4/83

Terman Engineering Center

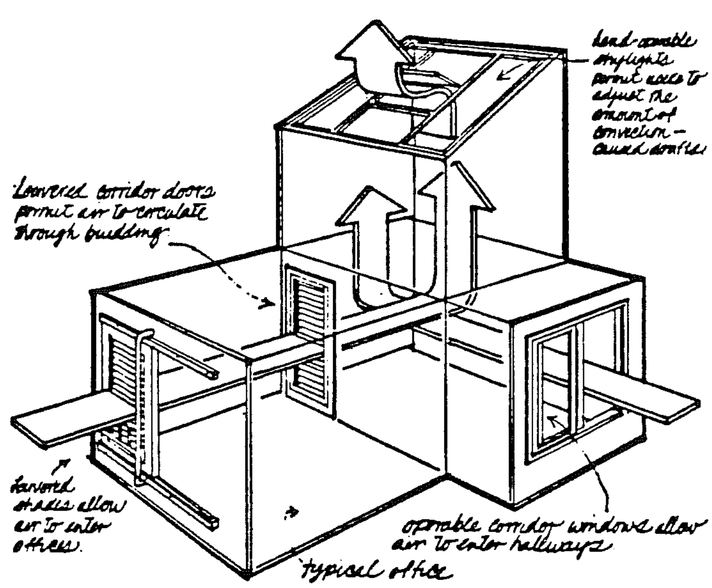
Palo Alto, California

The Terman Engineering Center is a seven-story, 150,000 sq. ft., L-shaped building with a pool on the south and a shaded sunken garden on the north. The first two floors are made of pre-cast concrete. The floors above the concrete base are framed in wood; laminated beams of fir and hemlock are bolted to fir columns. All of the building's service systems--sprinklers, water pipes, cable trays--are exposed, a feature that saves money and was considered desirable by the users.

All offices have floor-to-ceiling French windows with bronze-tinted glass. Outside the windows are hand-operated louvered shutters that slide closed on tracks. When closed, the shutters block out direct sunlight but allow soft filtered light and air flow through the rooms. The corridor doors are made with an insert which, when opened, allows air movement through a louvered door panel. This feature enables visual privacy while allowing for air circulation. Each room is equipped with baseboard hot water convectors for winter heating.

Vertical shafts in the corridors are topped with operable skylights. These induce circulation by exhausting hot air and simultaneously reflecting light down the shaft into the corridors, minimizing the need for corridor lighting.

The combination of daylighting and ventilation methods has been proven effective. Two summers have passed, and even advocated air-conditioning during the planning stage admit that the Terman Center is a pleasant place to work. One professor noted that the induced ventilation, due to the stack effect created by the open skylights, is so effective that he has trouble keeping messages tacked to his bulletin board. He also reported that, after working in the building two years, he has yet to turn on the heat.



APPENDIX C
INSTRUMENTATION

The use of scale models to assist in the development of daylighting strategies is one of the few areas of architectural design where direct physical measurements, in a simple building analog, provide useful data for design purposes. The only related simple use of models is to predict sun shading and sun penetration patterns in buildings. However, unlike the shadow evaluation, which normally requires only visual observation of the data "collection" element, daylight illuminance measurements require relatively sophisticated light measurement systems to provide useful data. Scale modeling is widely promoted in the architectural press as an alternative to the reliance on computer models for analysis of daylighting strategies. But, the average potential user faces two significant deficiencies: 1) access to adequate photometric instrumentation and 2) a sound understanding of the technical basis for light measurements, the procedures to be followed, and the limitations associated with those procedures. Educational and training materials can assist in removing the second obstacle, but access to instrumentation remains a critical limiting factor.

In 1981, we completed a review of photometric instrumentation that was available on the market (other systems can be custom-fabricated for research purposes). In this report we have updated the product data and price information to reflect cost and availability as of 1983. In general, we find that available photometric instrumentation does not meet an architect's (engineer's) or lighting designer's combined requirement for small size, accuracy, and low cost. Furthermore, a desirable package for architectural use would combine a number of sensors linked to a single readout and would provide some ability to store and manipulate the gathered data. While a few consulting groups and several research groups have put together special instrumentation packages having these factors, they are not commonly available as modular, commercial items.

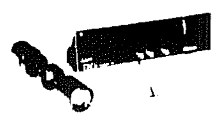
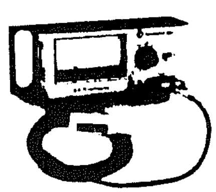
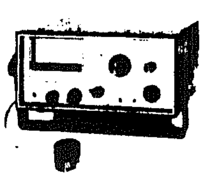
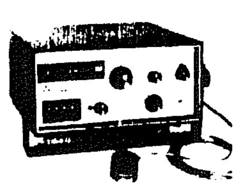
Two activities are suggested by this situation. First, it would be useful to develop a "low-cost, accurate, versatile" photometric system that fits the needs of design and engineering firms. This might involve limited "market research" to determine the needs of potential users. Second, utilities, universities, and other institutions could make instrumentation packages available to design firms on short-term loan. Similar equipment loan programs (e.g., wind data collection systems) have been successfully instituted by utilities in various parts of the U.S.

The data in the following table were last revised in mid-1983. The table contains a large number of manufacturers of relevant equipment; however, others not listed may offer similar equipment. Manufacturers should be consulted directly to determine current prices, performance, and availability. Inclusion in this table does not constitute a recommendation by the authors or sponsors of this report. illuminance

Survey of Light Measuring Instruments
Lawrence Berkeley Laboratory
University of California, Berkeley 94720

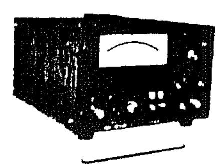
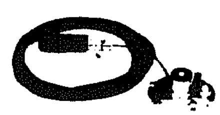
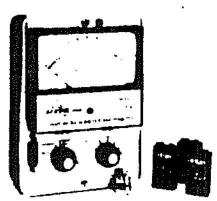
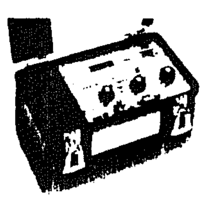
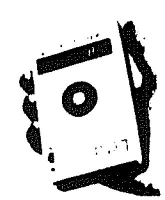
May 1983
Update

LBL-12897

MANUFACTURER	PHOTO	MODEL	SENSITIVITY RANGE	COSINE CORRECTION	CIE PHOTOPIC % DEVIATION	SENSOR SIZE	SILICON SENSOR	SELENIUM SENSOR	DIGITAL DISPLAY	ANALOG DISPLAY	LUMINANCE	ILLUMINANCE	METRIC	ENGLISH	SIZE	WEIGHT	PORTABLE	LENGTH OF CORD SENSOR TO READOUT	COST DATE	COMMENTS
EG&G ELECTRO-OPTICS 35 Congress St. Salem, MA 01970 (617) 745-3200		550-1 Radiometer/ Photometer	1.999×10^{-3}–1.999×10^{3} fc 19.99×10^{-3}–19.99×10^{3} fl	●	±1%	1 cm²	●		●		●	●	●	●	9" × 11" × 3"	7 lbs.		5'	$1900 5/83	Optional 550-2 Type B Silica Multiprobe $750; System Price: $2650.
GOSSEN Berkey Marketing Companies 25-20 Brooklyn-Queens Expressway West Woodside, NY 11377 (212) 932-4040		Gossen Panlux Electronic Foot-candle & Foot-lambert Meter	5×10^{-2}–1.2×10^{4} fc 1.5×10^{0} 3.6×10^{5} fl	●		2¼" diam.		●		●	●	●		●	4¼" × 3" × 1⅜"	13 oz.	●	1 m	$300 5/83	
INTERNATIONAL LIGHT, INC. Dexter Industrial Green Newburyport, MA 01950 (617) 465-5923		IL410 Photometer SC 110	3×10^{-1}–10^{3} fc 3×10^{0}–10^{4} fc	●	±2%		●			●		●			4.2" × 3.5" × 9.1"	2½ lbs.		7'	$458 5/83	Compact low profile probe available. Comes with probe below. High illumination probe.
		IL510A Research Photometer	10^{-2}–10^{4} fc		±2%	1½" × 1¾"	●			●		●			5.2" × 11.2" × 8.0"	7½ lbs.		7'	$1551 5/83	Programming switch reads currents in amps.
		IL710A Research Photometer	2×10^{-3}–5×10^{4} fc		±2%		●		●			●			11" × 5" × 9"	15 lbs.	●	7'	$1988 5/83	Research photometer range as low as 4×10^{-9} with photomultiplier

Survey of Light Measuring Instruments
Lawrence Berkeley Laboratory
University of California, Berkeley 94720

LBL-12897

MANUFACTURER	PHOTO	MODEL	SENSITIVITY RANGE	COSINE CORRECTION	CIE PHOTOPIC % DEVIATION	SENSOR SIZE	SILICON SENSOR	SELENIUM SENSOR	DIGITAL DISPLAY	ANALOG DISPLAY	LUMINANCE	ILLUMINANCE	METRIC	ENGLISH	SIZE	WEIGHT	PORTABLE	LENGTH OF CORD SENSOR TO READOUT	COST DATE	COMMENTS
KRATOS ANALYTICAL INSTRUMENTS 24 Booker St. Westwood, NJ 07675 (201) 664-7263		M 460 Photo-multiplier Photometer	100 microamps–100 pico-amps*		±2%		●	●		●					5½" × 8½" × 10"	10 lbs.	●		$1980 5/83	*Not calibrated in fc or fl; no direct conversion.
LI-COR, INC. 4421 Superior Street P.O. Box 4425 Lincoln, NE 68504 (402) 467-3576		LI-210SB Photometric Sensor		●		1" diam. × 1" height	●											5'	$ 265 5/83	2003S mounting fixture optional.
		LI-185B Quantum/Radiometer/Photometer	3×10^{1}–3×10^{5} lux							●		●	●		5" × 7" × 2.5"	2.44 lbs.	●		$ 495 5/83	Uses either batteries or AC adapter.
		LI-188B Integrating Quantum/Radiometer/Photometer	0–1.999×10^{5} lux						●			●	●		5.7" × 10" × 5.9"	4.25 lbs.	●		$ 990 5/83	Uses either batteries or AC adapter.
LICTMESSTECHNIK LMT GmbH Berlin u. Co., KG Helmholtzstr. 9 D-1000 Berlin 10 West Germany 030-393 40 28		Pocket-Lux Portable Illuminance Meter	10^{-1}–1.999×10^{5} lux	●	±1%	10mm diameter	●		●	with adapter		●	●		40mm × 80mm × 135mm	350 g	●		DM 1.490 3/81	Automatic ranging system. Storage of measured display. Special option—DM 1.790 with ext. photovoltaic cell and 3m connection cable. Uses either batteries or AC adapter.

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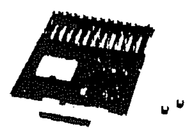
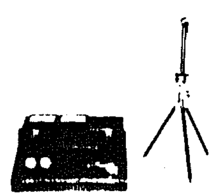
Lawrence Berkeley Laboratory
University of California, Berkeley 94720

LBL-12897

MANUFACTURER	PHOTO	MODEL	SENSITIVITY RANGE	COSINE CORRECTION	CIE PHOTOPIC % DEVIATION	SENSOR SIZE	SILICON SENSOR	SELENIUM SENSOR	DIGITAL DISPLAY	ANALOG DISPLAY	LUMINANCE	ILLUMINANCE	METRIC	ENGLISH	SIZE	WEIGHT	PORTABLE	LENGTH OF CORD SENSOR TO READOUT	COST	DATE	COMMENTS
MEGATRON LTD. 165 Marlborough Road Hornsey Road London N19 4NE England		Architectural Model Luxmeter	0–10^4 lux	●	2.98%	1.6 cm		●		●		●	●		13" × 13" × 4½"	7 lbs.	●	2 m	£650	3/81	12 individually operated photocells allow 12 simultaneous measurements ideal for model work.
		BRS Daylight Photometer	0–10^5 lux	●	2.98%	2.5 cm		●		●		●	●		13" × 8½" × 5"	7½ lbs.	●	5 m	£450	3/81	Reads daylight factor directly 0–5%, 1–10%, 0–20%.
		B.R.E. Cylindrical Illuminance Meter	0–10^4 lux	●	2.98%	2 cm × 4 cm		●		●		●	●		13" × 5" × 3"	3 lbs.	●	2 m	£265	3/81	Toggle switch to allow for cylindrical or planar measurement. Also potentiometer for zero drift correction.
		DA 5 Luxmeter	2.5×10^{-1}–2.5×10^{1} lux	●	2.98%	6.7 cm		●		●		●	●		10½" × 5" × 2½"	2 lbs.	●	2 m	£160	3/81	Low level illuminance meter. Portable, lightweight.
		Spatial Illumination Meter Mark 2	0–2.5×10^4 lux	●	2.98%	2.5 cm									6" × 13½" × 8"	13½ lbs.	●	10 m	£490	3/81	

Survey of Light Measuring Instruments
Lawrence Berkeley Laboratory
University of California, Berkeley 94720

LBL-12897

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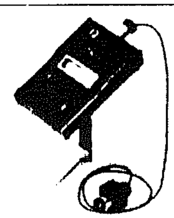
OPTRONIC LABORATORIES, INC. 730 Central Florida Parkway Orlando, FL 32809 (305) 857-9000		730A Radiometer/Photometer	10^0–10^6 fc		±5%	1 cm^2	●		●			●		●	15" × 5" × 9"	8 lbs.		4-6'	$2750 5/83	Direct reading in 14 units. Autoranging radiometer/photometer. Detector spectral response cal. 250–1100 hm. Radiometric & photopic filters, BCD output, and pulse integrator.
		85 Cosine Receptor		●															$265 5/83	Optional receptor for 730A.
		80 Relay Lens	10^0 – 10^6 fc									●		●					$825 5/83	Optical lens enables luminance and radiance measurements.
PHOTODYNE INC. 5356 Sterling Center Dr. Westlake Village, CA 91361 (213) 889-8770		88XLA Radiometer/ Photometer			±6%		●		●			●		●		.6 kg	●	3'*	$825 5/83	Range achieved with sensor model 650/750. *With 3001 Extension Head & cable ($95).
		650 Photometric Sensor Head	10^{-6}–10^3 fc		±6%	*	●					●	●	●	*1" diam., 1¼" length				$295 5/83	Sensor heads may be set to match CIE curve at specific wavelength.

Survey of Light Measuring Instruments
Lawrence Berkeley Laboratory
University of California, Berkeley 94720

LBL-12897

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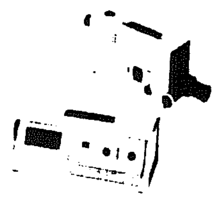
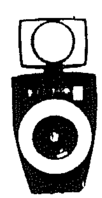
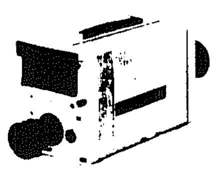
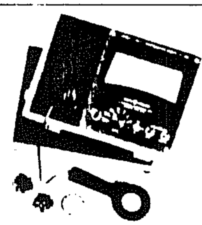
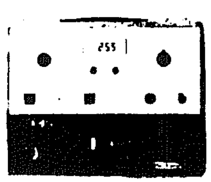
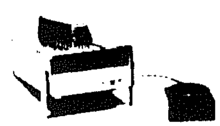
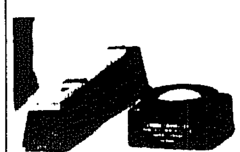
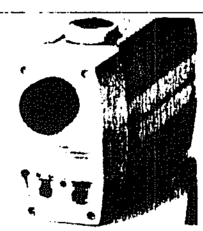
PHOTO RESEARCH DIV. OF KOLLMORGEN CORPORATION 3000 N. Hollywood Way Burbank, CA 91505 (213) 843-6100		Pritchard 1980A Photometer	2×10^{-5}–2×10^{7} fc 10^{-5}–10^{7} fl	●					●		●	●		●	19½″ × 6½″ × 9″	20½ lbs.		5′	$13,000 5/83	Photometer requires accessories for full range luminance and illuminance readings.
		Litemate/Spotmate System 500	10^{-2}–1.999×10^{4} fc 10^{-2} – 1.999×10^{4} fl*	●			●		●							1½-2 lbs.	●		$950 5/83	Handheld photometer and a luminance spotmeter with a 1° acceptance angle. *With Spotmate attached.
		1605 Spectraspot Photometer/Radiometer	10^{1}–2×10^{5} fl				●		●	●			●	●	12½″ × 6¼″ × 5¾″	8½ lbs.	●	5′*	$6400 5/83	Photometer/radiometer ½° measuring field. *With optional illuminance accessories.
		1610	10^{0}–2×10^{4} fl				●						●	●			●			1° measuring.
		Spectra Photometer Model FC-200	10^{-1}–3×10^{4} fc 10^{-1}–3×10^{4} fl	●				●	●	●	●	●		●	11½″ × 8½″ × 4″	6 lbs.	●	6′	$1355 5/83	Low-cost, portable, solid-state, multi-ranging photometer.
		Spectra Digital Photometer/Radiometer Model 301	1.999×10^{-2}–1.999×10^{4} fc 1.999×10^{0} – 1.999×10^{5} fl** **Luminance with 10° field	●	±1%*		●		●		●	●	●	●	13¼″ × 10¼″ × 4½″	8 lbs.	●	6′	$2900 5/83	Model 301 provides direct measurement readings of illuminance, luminance, irradiance, radiance, radiant power, & integrated energy. Additional features: auto-null ambient light control, zero reset button, meter reading button & zero adjust for temperature & drift control. *% dev. depends on individual sensor/filter combination.

Survey of Light Measuring Instruments
Lawrence Berkeley Laboratory
University of California, Berkeley 94720

LBL-12897

MANUFACTURER	PHOTO	MODEL	SENSITIVITY RANGE	COSINE CORRECTION	CIE PHOTOPIC % DEVIATION	SENSOR SIZE	SILICON SENSOR	SELENIUM SENSOR	DIGITAL DISPLAY	ANALOG DISPLAY	LUMINANCE	ILLUMINANCE	METRIC	ENGLISH	SIZE	WEIGHT	PORTABLE	LENGTH OF CORD SENSOR TO READOUT	COST DATE	COMMENTS
TEKTRONIX, INC P.O. BOX 500 BEAVERTON, OR 97077 (503) 644-0161		J16 Photometer/Radiometer			NA				●		●	●	optional	●	2.4" × 4.6"x8"	3.3 lbs.	●		$1180 5/83	Digital photometer/radiometer. Battery powered.
		J6511 Illuminance Probe	10^{-3}–1.999×10^{3} fc	●	±2%		●					●	optional	●	*	11 oz.	●	25'	$540 5/83	*Probe consists of 2 pieces, 1½" × 6¾" × 1⅞" and 2½" × 1½" × 2½".
		J6503 8° Luminance Probe	10^{-1}–1.999×10^{5} fl		±2%		●		●		●		optional	●	1⅞" × 6¾" × 1½"	4 oz.	●		$545 5/83	
		J6523 1° Luminance Probe	10^{-1}–1.999×10^{5} fl		±2%		●		●		●		optional	●	5" × 9½" × 2½"	2½ lbs.	●		$1575 5/83	

Survey of Light Measuring Instruments
Lawrence Berkeley Laboratory
University of California, Berkeley 94720

LBL-12897

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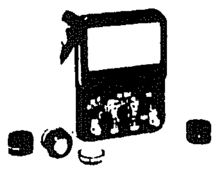
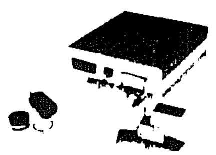
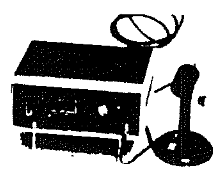
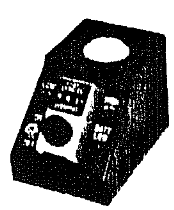
UNITED DETECTOR TECHNOLCGY 3939 Landmark Street Culver City, CA 90230 (213) 204-2250		40X Opto-Meter	10^{-3}–10^{4} fc 10^{-2}–10^{5} fl	●	±2%	1 cm²	●			●	●	●	●	●		3 lbs.	●	2 m	$495 5/83	Model 1153 Accessory Lens for luminance. Standard 248 sensing head optional $395
		181 PIC Radiometer/Photometer	10^{-6}–10^{3} fc 10^{-4}–10^{5} fl	●	±2%	1 cm²	●		●		●	●	●	●		6 lbs.	●	2 m	$1545 5/83	Offers plug in calibration modules, with programmable decimal points. Standard 248 sensing head optional $395
		111A Radiometer/Photometer	10^{-3}–10^{3} fc	●	±2%	1 cm²	●		●		●	●	●	●		6 lbs.		2 m	$1495 5/83	Laboratory standard. Model 1153 lens for luminance. Standard 248 sensing head optional $395
		3300 Digaphot Photometer	0–9.99 × 10^{2} fc	●	±2%		●		●			●		●		9 oz.	●	2 m	$445 5/83	Rechargeable battery available. #1606 carrying case optional $25
		S-350 Linear/Log Radiameter/Photometer	10^{-5}–10^{4} fc 10^{-4}–10^{5} fl	●	±2%	1 cm²	●		●		●	●	●	●		5 lbs.	●	2 m	$1294 5/83	Power and energy measurement capabilities. Model 1153 lens for luminance. Optional LED source #259 $55; #248 $395

APPENDIX D
FENESTRATION CONTROLS

Our energy analysis studies indicate that daylighting savings can be reduced or eliminated if cooling loads imposed by solar gains are not adequately controlled. The performance of available systems is a critical constraint on how well solar gains can be controlled. In Section 9 we discuss the issues and hardware options for sun control; in this appendix we provide more detailed performance data on a sampling of the available systems to indicate their capabilities and limitations. We emphasize interior and exterior operable systems because heat-absorbing, reflective glazings and permanently mounted shade screens are familiar commercial products.

Product descriptions, performance claims, and data are reproduced from information supplied by the manufacturers. No claims are made concerning the validity, accuracy, or completeness of any product descriptions. Owing to the number of manufacturers of these products, only a representative sample could be included. Absence of any product, trade name, or manufacturer should not be construed to reflect unfavorably on that trade name or manufacturer, and the mention of certain company names or brand-name products is not intended as a recommendation of them over other companies or similar products on the market. Inclusion in this document does not constitute an endorsement by the authors or sponsors of this report.

Glossary

T_v: visible transmittance

R_v: visible reflectance

T_s, R_s: solar transmittance, reflectance

S.C.: shading coefficient

U_{sg}: overall U-value, device plus single glazing

U_{dg}: overall U-value, device plus double glazing.

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : External Awning

PRODUCT NAME : Constant Tension Mechanism Awning

MANUFACTURER : John Boyle and Co., Inc.
3 Westchester Plaza, Elmsford, NY 10523

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal
[ ] Fixed
[X] Operable
[X] Retractable
[ ] Adjustable
[ ] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[ ] Wind Resistant

DESCRIPTION

This movable external awning is deployed over slopping or vertical glazing by a constant tension mechanism (CTM) powered by a tubular motor. The mechanism maintains taught fabric throughout the deployment cycle. Areas from 2' by 2' to 20' by 20' can be covered by one standard unit. Available fabrics include triple-ply vinyl-polyester laminate, resin impregnated cotton duck, vinyl-polyester industrial cover fabrics, translucent vinyl-polyester and spun-dyed acrylic materials. The motor may be controlled by time clock or by weather sensors.

COST

Not available.

PERFORMANCE CHARACTERISTICS

Not available.

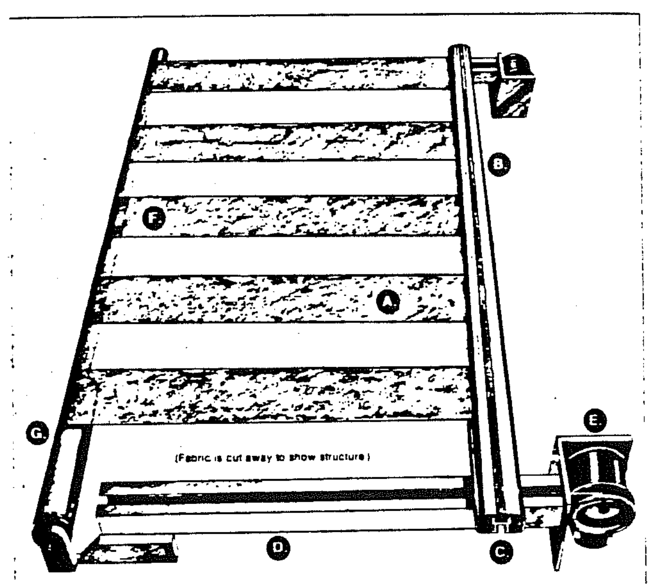
LIMITATIONS

May impede egress if used over operable glazing. Certain fabrics are not flame retardant.

COMMENTS

REFERENCES

Constant Tension Mechanism brochure.



A Fabrics by John Boyle & Company
B. Front bar of extruded, anodized aluminum, channeled for high rigidity
C. Trolley wheels
D. Tracks of extruded, anodized aluminum
E. Constant Tension Mechanism
F. Roller bar of galvanized steel
G. Somfy® tubular geared motor

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : Exterior Venetian Blinds
PRODUCT NAME : Baumann Exsotrol™ Blinds
MANUFACTURER : Baumann Inc. (Distributor)
1301 N. Main St., Wauconda, IL 60084.
(312) 526-7755

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[X] Retractable
[X] Adjustable

[ ] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[X] Wind Resistant

DESCRIPTION

Slats are fabricated from aluminum and are approximately 80mm wide. Side tracks guide the ends of the slats and prevent rattling and distortion due to wind. Certain models use plastic lips on the slats to effect a better seal when fully closed and to minimize noise by eliminating metal-to-metal contact. The slats deploy into a blind box above the window by means of manual crank operation, or by action of an electric motor controlled by one or more of the following: manual switch, anemometer, timer, thermostat and rain detector. An automatic unit is available to cause the blinds to open to a preset slat angle after lowering. Blinds are available in several colors, slat widths and slat profiles.

COST

Not available.

PERFORMANCE CHARACTERISTICS

Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
Light color					0.15	1.00	0.45
Dark color					0.25	1.00	0.45

LIMITATIONS

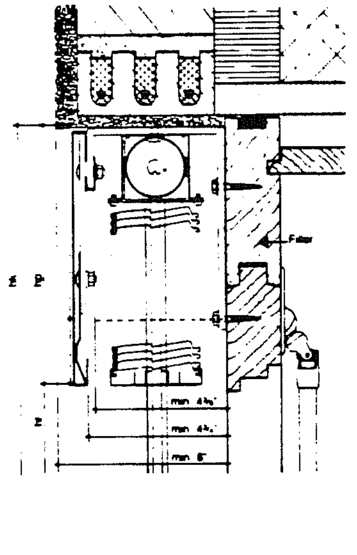
May impede egress.

COMMENTS

Automatic features are available on some models to insure opening in case of fire.

REFERENCES

Manufacturer's brochure.



SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : External Shutters

PRODUCT NAME : Rolladen

MANUFACTURER : American German Industries, Inc.
14611 North Scottsdale Road, Scottsdale, Arizona 85260
(602) 991-2345

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[X] Retractable
[ ] Adjustable

[X] Thermal Insulation
[X] Acoustic Insulation
[X] Air Tight
[X] Wind Resistant

DESCRIPTION

Roll-down exterior (or interior) shutter made of interlocking extruded profiles, either in *PVC* with dead air space, or in *Aluminum* with polyurethane insulation. *PVC* is available in beige, white, gray, saddle tan and wood grain. *Aluminum* is available in gray, white, silver, light wood grain and dark wood grain. When forcible entry is attempted, an automatic locking mechanism releases teeth which dig into the aluminum guard rail to hold the Rolladen in a fixed position. Available types of operation include manual crank, pulley strap and electric motor. For electric operation, in addition to individual switching, a central control panel is available with electric timer, photocell, or radio command.

COST

Not available.

PERFORMANCE CHARACTERISTICS

Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
White Aluminum			0.00		0.04	0.49	
White PVC			0.00		0.03	0.47	

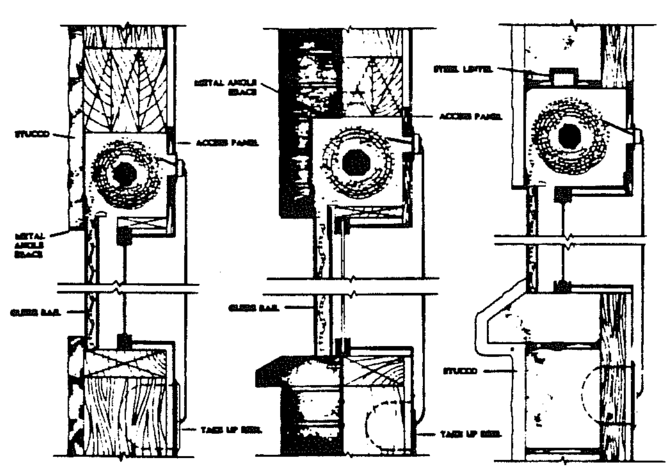
LIMITATIONS

COMMENTS

SC refers to closed slats. U-values are for winter. Noise reduction is 85% @closed position and 52% @vented position.

REFERENCES

Manufacturer's brochure (1977).



Initials: kmp Date: January 1984 LBL File No.: 4.2.3

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : External Shades, Internal Shades

PRODUCT NAME : Thermo Veil™, Thermo Shade™

MANUFACTURER : Mecho Shade Corporation
42-03 35th Street, Long Island, NY 11101
(212) 729-2020

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[X] Retractable
[ ] Adjustable

[X] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[ ] Wind Resistant

DESCRIPTION

Thermo Shade™ and Thermo Shade™ are technologically advanced woven vinyl fabrics. They are washable, flame retardant and fade resistant. They content 79% vinyl and 21% dernier polyester core. They are suitable for both interior and exterior applications. Thermo Veil™ has 91-21% openness, while Thermo Shade™ has 2-4%. They are available in linen, beige, grey and black/brown. Also available in ***Dual Weave*** (black/white). Complete line of Mecho Shade hardware is available for both interior and exterior use. They are chain operated, manually or automatically through available programmed window management controls (photocell, anemometer).

COST

Not available.

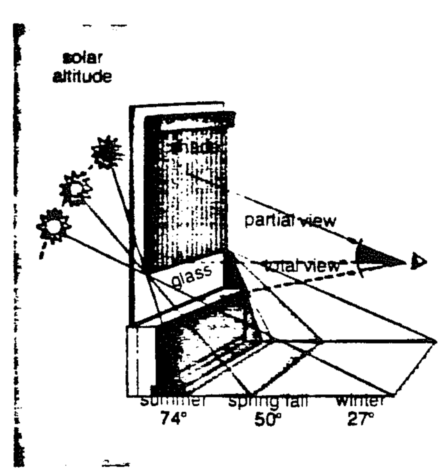
PERFORMANCE CHARACTERISTICS

Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
Interior linen Thermo Veil	0.28		0.37	0.46	0.51	0.85	0.43
Interior linen Thermo Shade	0.10		0.25	0.54	0.43	0.85	0.43
Interior gray Thermo Veil	0.29		0.28	0.27	0.61	0.85	0.43
Interior gray Thermo Shade	0.05		0.07	0.30	0.54	0.85	0.43
Exterior linen Thermo Veil	0.28		0.37	0.46	0.40	0.85	0.43
Exterior gray Thermo Shade	0.05		0.07	0.30	0.14	0.85	0.43

LIMITATIONS

COMMENTS

Additional performance characteristics are available for the rest of the product types and with various types of glass. Performance characteristics were measured by Matrix Inc. and Professor John Yellott, Arizona State University.



REFERENCES

Manufacturer's brochure (February 1982).

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : External Louvers

PRODUCT NAME : Brown Louvers

MANUFACTURER : Brown Manufacturing Company
P.O. Box 14546, Oklahoma City, OK 73114
(405) 751-1323

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[ ] Retractable
[X] Adjustable

[ ] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[X] Wind Resistant

DESCRIPTION

Brown Company manufactures both horizontal and vertical louvers in several blade profiles. Vane widths are typically in the range 4-12", depending on the model. Numerous mounting options and locations for manual operator (crank) are available. Operation is controlled by pushbutton, time control with pushbutton over-ride and timer, again with pushbutton over-ride.

COST

Not available.

PERFORMANCE CHARACTERISTICS

Not available.

LIMITATIONS

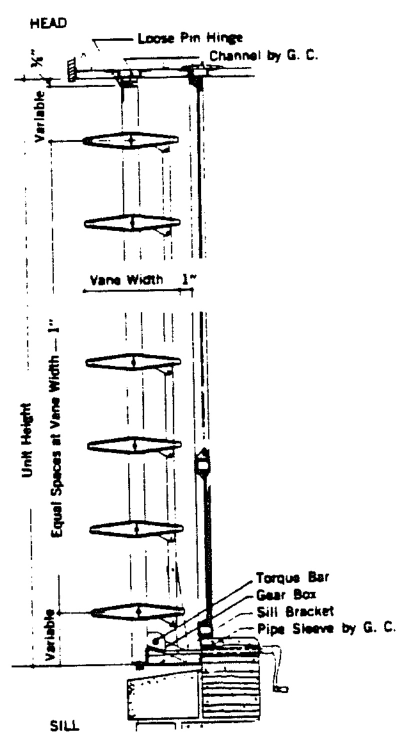
Interferes with egress.

COMMENTS

REFERENCES

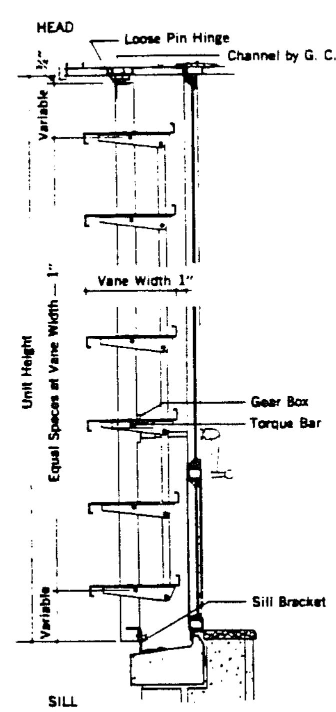
Manufacturer's brochure (1962).

HORIZONTAL BA-1800-H



VERTICAL SECTION

HORIZONTAL BA-1000-H



VERTICAL SECTION

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : External Louvers
PRODUCT NAME : Moore Louvers
MANUFACTURER : The Moore Company
Marceline, MO 64658
(816) 376-3583

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal
[ ] Fixed
[X] Operable
[ ] Retractable
[X] Adjustable
[ ] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[X] Wind Resistant

DESCRIPTION

The hollow aluminum, aerodynamically configured louvers, can span 16' and be vertically linked with similar modules to shade 200'. Each louver assembly can have its louvers tilted by electrical or pneumatic actuators which are controlled manually, or by automatic control systems. The automatic control system opens the louvers as wide as possible without admitting direct sunlight. The basic operational logic can be over-ridden by manual control, as well as by other control options, including "Solar Control Delay Time and Night Closer" which prevents positioner from responding to transient conditions (e.g. clouds) by means of a user-set delay (0-15 min), "Light Intensity Over-Ride" which keeps interior illumination from exceeding a preset value and "Analog Signal Input".

COST

Not available.

PERFORMANCE CHARACTERISTICS

Not available.

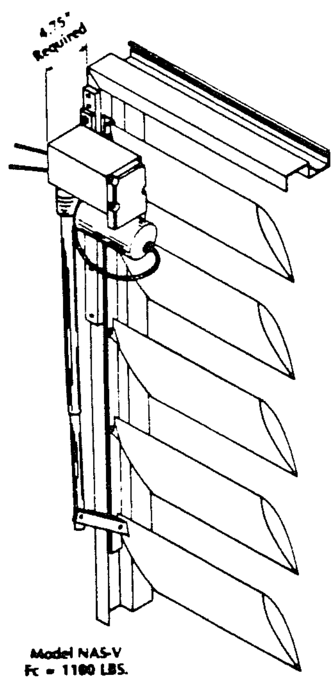
LIMITATIONS

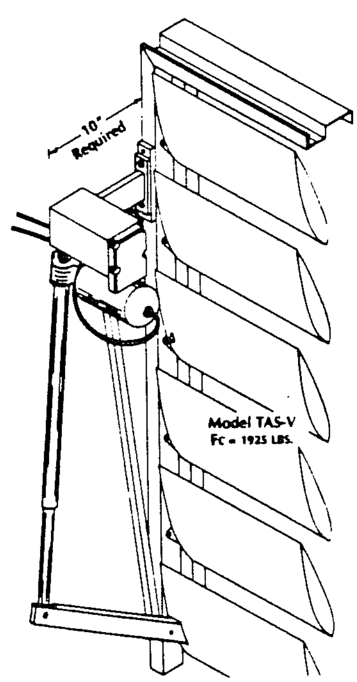
Interferes with egress.

COMMENTS

REFERENCES

Manufacturer's brochure.





Fc = Force On Control Rod

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : External Metal Screen

PRODUCT NAME : KoolWall

MANUFACTURER : KoolShade Corporation
P.O. Box 210, Solana Beach, CA 92075
(619) 755-5126

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[ ] Retractable
[X] Adjustable

[ ] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[X] Wind Resistant

DESCRIPTION

Tiny horizontal bronze louvers (0.05" wide by 0.007" thick) are held by bronze vertical wires at proper spacing and tilt within aluminum frame. Available as *Standard* (17 louvers per vertical inch) or *Low Sun Angle* (23 louvers per vertical inch). Available in widths up to 72.5". The standard color is black, with others available by special order. The KoolWall system utilizes movable KoolShade screen panels which can be deployed as desired over windows. A torque tube drive motor provides the power. Control may be by means of sensors responding to solar flux, wind speed, external temperature, or manual over-ride.

COST

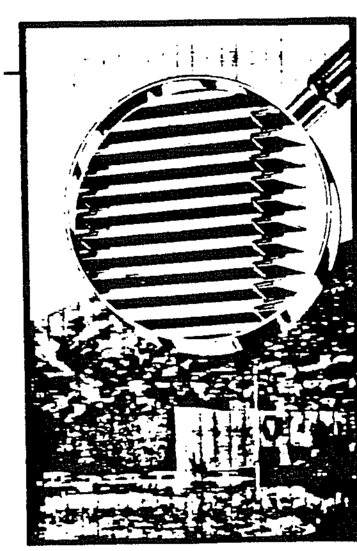
Not available.

PERFORMANCE CHARACTERISTICS

Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
Standard @ 10° profile angle	0.515		0.04	0.14	0.45	0.85	0.50
Low Sun Angle @ 10° profile angle	0.465		0.04	0.04	0.27	0.85	0.50
Standard @ 30° profile angle	0.515					0.26	0.85
Low Sun Angle @ 30° profile angle	0.465					0.10	0.85
Standard @ 50°+ profile angle	0.515					0.12	0.85
Low Sun Angle @ 50°+ profile angle	0.465					0.10	0.85

LIMITATIONS

May impede egress.



COMMENTS

This system is a recent modification of the older KoolShade system which utilizes fixed panels, movable only for cleaning.

REFERENCES

KoolWall and KoolShade brochures (KW-80-1 and KS-7701). John I. Yellott "Energy Conservation and Economy through Sun Control".

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : External Fiber-glass Screen, Internal Fiber-glass Screen
PRODUCT NAME : 3s Halu-Rollscreen
MANUFACTURER : 3s Halu-Rollscreen & Selinger Sun Screen
2340 Gold River Road, Rancho Cordova, CA 95670

DESCRIPTIVE CHARACTERISTICS

[ ] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal
[ ] Fixed
[X] Operable
[X] Retractable
[ ] Adjustable
[X] Thermal Insulation
[X] Acoustic Insulation
[ ] Air Tight
[ ] Wind Resistant

DESCRIPTION

Roll-down fiber-glass screen, for both exterior and interior use. The material is light-and-air-admitting fiber-glass fabric (fiber-glass yarn, coated with flame-proof PVC: 27% glass and 73% PVC). The material is known as Lyverscreen®, manufactured by J. Brochier et Fils, in France. It is available in various colors and color-combinations, such as *Gris*, *Chamois*, *Bronze*, *Salbe*, *Blanc* and their combinations. Manual operation is performed by a gear-box with rod and collapsible handle. Operation options include electric motors that may be activated with a solar control and an anemometer over-ride.

COST

From $ 263 (36" by 36") to $ 801 (120" by 120").

PERFORMANCE CHARACTERISTICS

Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
Internal Gris	0.07		0.05	0.16	0.64		
Internal Salbe	0.06		0.06	0.29	0.51		
Internal Blanc	0.12		0.14	0.45	0.36		
External Gris	0.07		0.05	0.14	0.16		
External Salbe	0.06		0.06	0.36	0.15		
External Blanc	0.12		0.14	0.63	0.21		

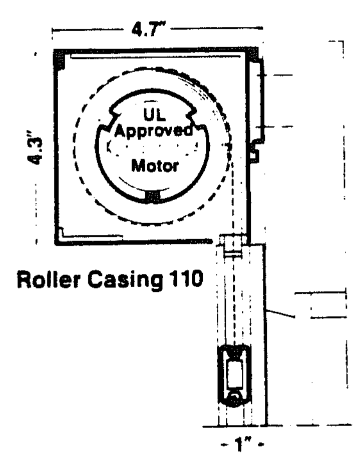
LIMITATIONS

COMMENTS

Completed project applications include: Union Pacific, General Electric, U.S. Navy and Airforce and State of California. U_{sg} values for Lyverscreen are 0.70-0.85, according to air circulation.

REFERENCES

Manufacturer's brochure (September 1980). Matrix Inc. test reports, submitted by manufacturer.



Initials: kmp Date: February 1984 LBL File No.: 4.2.7

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : Blinds Between Glasses
PRODUCT NAME : Vision Control®
MANUFACTURER : Unicell, Inc.
88 de Vaudreil, Boucherville, Québec, Canada J4B5G4
(514) 665-1580

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement
[ ] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[ ] Retractable
[X] Adjustable

[X] Thermal Insulation
[X] Acoustic Insulation
[X] Air Tight
[ ] Wind Resistant

DESCRIPTION

Vision Control® consists of pivoting hollow-chambered louvers between insulated and tempered glass panels. Louvers may be mounted either horizontally or vertically. They can rotate 180°. Many kinds of special glazing are available, such as tinted, reflective, laminated, heat strengthening, bullet resistant, etc. Slats are available in many color finishes. There is a wide selection of standard baked-enamel colors, in either matte or gloss finishes. Special anodized finishes are available in light, medium and dark bronze. Other special options include chrome and gold tone finishes. Applications include inclined window openings.

COST

Not available.

PERFORMANCE CHARACTERISTICS

Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
White slats @45°	0.184	0.218			0.53	0.57	
White slats @90°	0.408	0.148			0.53	0.49	
White slats @135°	0.158	0.181			0.28	0.51	
White slats @180°	0.00	0.408			0.09	0.53	

LIMITATIONS

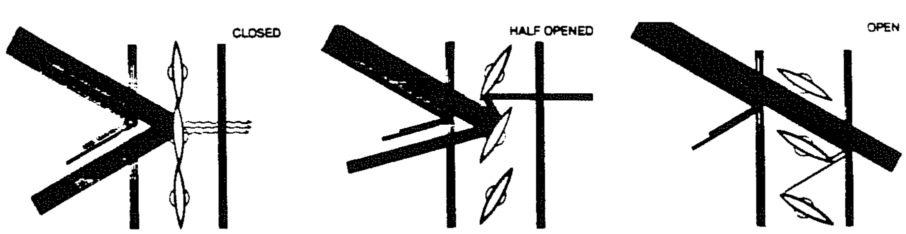
Dark colors are not recommended for exterior use and are not warranted.

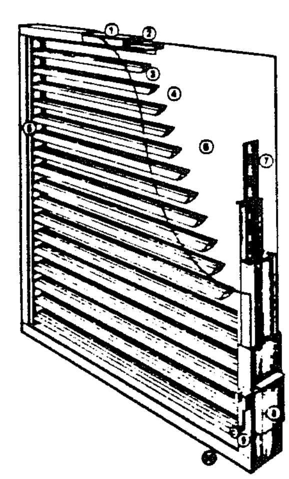
COMMENTS

Performance characteristics were determined through tests in accordance with ASTME E-774 and 773 test methods and Canadian Specification CAN2-12.8-M.76. Also in accordance with I.G.C.C. standards 'A' 'B' 'C'.

REFERENCES

Manufacturer's brochure (May 1984).





SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : Interior Venetian Blinds
PRODUCT NAME : Levolor Aluminum Blinds
MANUFACTURER : Levolor Lorentzen Inc.
720 Monroe Street, Hoboken, New Jersey 07030
(201) 792-2600, (212) 964-0431

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[X] Retractable
[X] Adjustable

[ ] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[ ] Wind Resistant

DESCRIPTION

The slats in Levolor Blinds are made from virgin aluminum alloyed with a high percentage of magnesium. Some of the available types are: the *Riviera Blind* (0.984" wide) in more than 100 colors, the *Flex-King Blind* (2" wide) in 33 colors, the *Monaco Blind* (2" wide) in 33 colors, the *Venasco Blinds* (2" wide) in 22 colors, the *Century Blind* (2" wide) in 2 colors, the *Kre-Blay Magic Blind* which is a perforated version of many types, and others, including blinds between glasses, audiovisual blinds, etc. They are suitable for all kinds of applications, including skylights, inclined windows, greenhouses, irregular shapes, etc.

COST

Available information is $60,115 for 62,500 ft^2.

PERFORMANCE CHARACTERISTICS

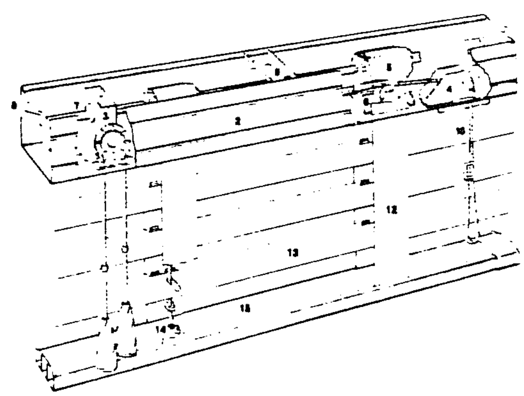
Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
Bright mirror, slats fully open			0.600	0.075	0.721		
Bright mirror, slats @45° upwards			0.170	0.230	0.466		
Bright mirror, slats closed			0.000	0.770	0.140		
Gray linen, slats fully open			0.300	0.140	0.563		
Gray linen, slats @45° upwards			0.060	0.300	0.381		
Gray linen, slats closed			0.010	0.390	0.320		

LIMITATIONS

There are specific limitations with respect to spacing between ladders and cords, according to size of opening.

COMMENTS

The performance characteristics are based on a study made by the College of Engineering at the University of Florida. Additional performance characteristics are available for a wide variety of product types, colors and finishes.



REFERENCES

Manufacturer's brochure.

Initials: kmp Date: March 1984 LBL File No.: 4.4.1

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : Interior Louvers

PRODUCT NAME : Verticals (various types)

MANUFACTURER : Louverdrape Inc.
1100 Colorado Avenue, Santa Monica, CA 90401
(213) 450-6100

DESCRIPTIVE CHARACTERISTICS

[ ] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[X] Retractable
[X] Adjustable

[X] Thermal Insulation
[X] Acoustic Insulation
[ ] Air Tight
[ ] Wind Resistant

DESCRIPTION

Louverdrape Inc. has seven basic hardware models and a wide variety of louvers to provide light and view control. There are more than 30 different types of textures, each of which is available in a wide variety of colors and color combinations. Types include *Solid Vinyl*, *Solid Vinyl Perforated*, *One* or *Two Sided Mirror* finishes, etc. The louvers are available in 2", 3", 3.5", 4.375" and 5" widths. Operation is done by chain, allowing 180° rotation. Operation through electric motors is also available, including remote control capabilities.

COST

Not available.

PERFORMANCE CHARACTERISTICS

Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
Fiberglass filled, louvers closed			0.000	0.740	0.100	0.340	
Fiberglass filled, louvers @45°			0.220	0.410	0.480	0.700	
Black, foam filled, louvers closed			0.000	0.540	0.236	0.340	
Black, foam filled, louvers @45°			0.315	0.315	0.550	0.700	
White, foam filled, louvers closed			0.055	0.700	0.238	0.356	
White, foam filled, louvers @45°			0.310	0.415	0.498	0.710	

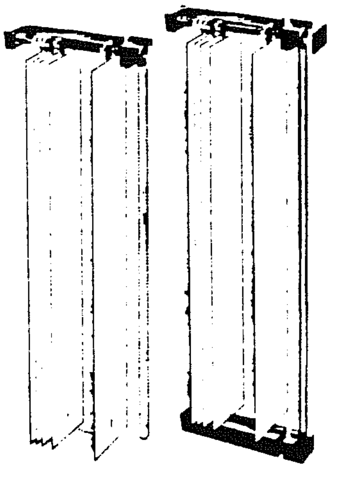
LIMITATIONS

COMMENTS

Solar-optical properties were measured by MATRIX INC., Mesa, Arizona (August 1971). Solar altitude was from 35° to 38°. U values for louvers @45° were estimated.

REFERENCES

Manufacturer's brochure (November 1983).



Initials: kmp Date: March 1984 LBL File No.: 4.4.1

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : Interior Blinds
PRODUCT NAME : Thermocell Blind
MANUFACTURER : Thermal Technology Corporation of Aspen, Inc.
601 Alter Street, Broomfield, Colorado 80020
(303) 466-1848

DESCRIPTIVE CHARACTERISTICS

[ ] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[X] Retractable
[ ] Adjustable

[X] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[ ] Wind Resistant

DESCRIPTION

The Thermocell Blind is a series of hollow, honeycomb-shaped structures. Fully extended, the blind traps air in these cells and creates and creates an additional air space between itself and the window, resulting in high insulating values. Edge sealing tracks accent the installation and increase insulating effectiveness. It retracts accordion style, compacting each linear foot into one eighth of an inch. It is available in opaque, translucent and transparent finishes. Thermocell Blind is available in vertical drop, parallel bar and continuous loop operating systems, thus suitable for all kinds of uses and applications.

COST

From $ 75 (30" by 30") to $ 470 (96" by 144"), according to width and height (6/1/84).

PERFORMANCE CHARACTERISTICS

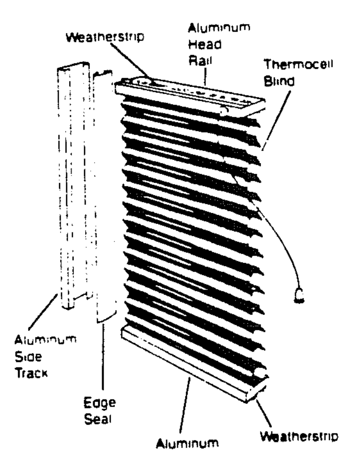
Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
Chrome			0.00	0.82			0.20
Pewter			0.00	0.92		0.18	0.15
White metalized			0.00	0.85		0.27	0.20
White translucent			0.20	0.72	0.32	0.39	0.25
Blue smoke			0.16	0.35			0.20
Gray tint			0.26	0.13	0.63		0.20

LIMITATIONS

Opaque versions do not allow view. Maximum width is 96". Maximum height is 144".

COMMENTS

The solar-optical properties were measured by Yellot Engineering Associates, Phoenix, Arizona. U values were measured with 0mph wind.



REFERENCES

Manufacturer's brochure (June 1984).

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : Interior Shutter
PRODUCT NAME : Skyview™
MANUFACTURER : Skyview Control Systems, Inc.
4780 Beidler Avenue, Willoughby, OH 44094
(216) 953-1011

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal
[ ] Fixed
[X] Operable
[X] Retractable
[ ] Adjustable
[ ] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[ ] Wind Resistant

DESCRIPTION

Skyview™ is a complete skylight system. It uses double acrylic dome and aluminum frame with thermal break. The motor-driven, multi-fold shutter deploys in a track beneath the skylight. The shutter is available in three standard colors: bronze, white and white in blackout version. Single units are available in 4-6-8' by 4-6-8'. These may be assembled into multiple units at the factory or on-site. The shading units may be ordered separately, to retrofit existing skylights. Barrel vault and sloped wall (flat) skylight configurations are also available. Each panel of the folding shutter measures 5" by the width of the skylight. A manually actuated motor deploys the multi-fold shutter horizontally beneath the skylight.

COST

Not available.

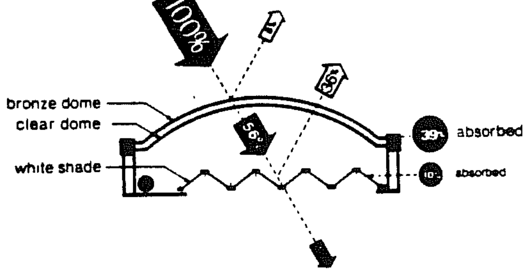
PERFORMANCE CHARACTERISTICS

Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
Clear dome, no shutter			0.850		0.850	0.660	
Clear dome, white shutter			0.150	0.092	0.267	0.550	
Clear dome, bronze shutter			0.170	0.046	0.588		
Bronze dome, no shutter			0.560		0.560	0.660	
Bronze dome, white shutter			0.100	0.092	0.249	0.550	
Bronze dome, bronze shutter			0.110	0.046	0.444		

LIMITATIONS

COMMENTS

R_s and U values are for double (bronze/clear) dome. For this combination, white shutter offers T_s = 0.035 and S.C. = 0.160, while bronze shutter offers T_s = 0.076 and S.C. = 0.230.



REFERENCES

Manufacturer's brochure and information, including reports from National Certified Test Laboratories (2/26/82).

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : Interior Shades

PRODUCT NAME : Sun Shades

MANUFACTURER : The Plastic Sun Shade Company, Inc.
389-91 Union Avenue, Irvington, New Jersey 07111
(201) 373-8181, (201) 373-8182

DESCRIPTIVE CHARACTERISTICS

[ ] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[X] Retractable
[ ] Adjustable

[X] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[ ] Wind Resistant

DESCRIPTION

Sun Shade material is a formulated cast cellulose acetate. It is transparent, yet filters the sun's infra-red and ultra-violet rays. It has all the necessary properties for maximum protection against ultra-violet rays within the wave-lengths from 150 to 4000 Angstroms. Sun Shade is available in various colors and color combinations, such as *Silver*, *Smoke*, *Bronze*, *Gold*, *Amber* and *Green* in various combinations. It is used as a roll-down shade, operated by a cord mechanism.

COST

Not available.

PERFORMANCE CHARACTERISTICS

Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
Silver / Silver	0.116		0.048	0.731	0.160	0.490	
Bronze / Bronze	0.109		0.204	0.242	0.310	0.480	
Smoke / Smoke	0.120		0.387	0.112	0.510	0.490	
Amber	0.800		0.645	0.150	0.760	0.45	
Smoke / Silver	0.087		0.104	0.537	0.170	0.480	
Smoke / Silver / Smoke	0.075		0.157	0.232	0.260	0.480	

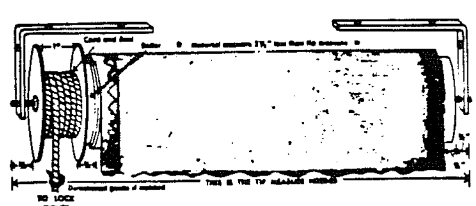
LIMITATIONS

Clear Sun Shade should be rotated in window at least once every 10-14 days, to avoid infra-red fading.

COMMENTS

Manufacturer indicates that 12% of the absorbed solar radiation will flow inwards. Additional performance characteristics are available for other colors and color combinations.

CORD & REEL SHADES



REFERENCES

Manufacturer's brochure and information (June 1978).

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : Interior Drapes
PRODUCT NAME : Generic

DESCRIPTIVE CHARACTERISTICS

[ ] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[X] Seasonal

[ ] Fixed
[X] Operable
[X] Retractable
[ ] Adjustable

[X] Thermal Insulation
[X] Acoustic Insulation
[ ] Air Tight
[ ] Wind Resistant

DESCRIPTION

Indoor draperies have long been used in residential and commercial applications, to afford sun control and privacy. Draperies are available in a very wide range of fabrics, resulting in a wide range of performance. Some installations use multiple layers of draperies, thereby allowing for both additional thermal resistance (by means of the created air spaces), as well as choices of degree of outward vision. Large commercial installations may use electric motors for the deployment of draperies.

COST

Not available.

PERFORMANCE CHARACTERISTICS

Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
						0.83	0.43

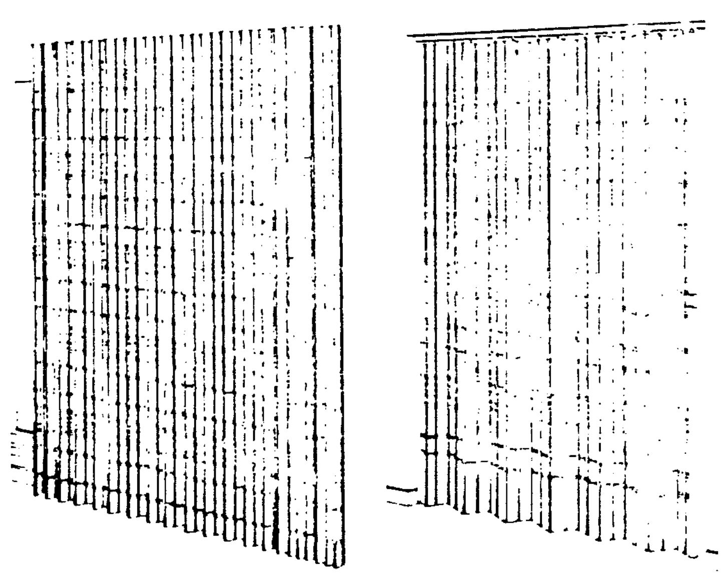
LIMITATIONS

COMMENTS

A single layer of tightly woven fabric, in close proximity to the wall, provides an air space that results in an additional thermal resistance of 0.29.

REFERENCES

ASHRAE Handbook 1977 Fundamentals.



Initials: jk, kmp Date: January 1983 LBL File No.: 4.4.4

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : External Awning
PRODUCT NAME : Constant Tension Mechanism Awning
MANUFACTURER : John Boyle and Co., Inc.
3 Westchester Plaza, Elmsford, NY 10523

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[X] Retractable
[ ] Adjustable

[ ] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[ ] Wind Resistant

DESCRIPTION

This movable external awning is deployed over slopping or vertical glazing by a constant tension mechanism (CTM) powered by a tubular motor. The mechanism maintains taught fabric throughout the deployment cycle. Areas from 2' by 2' to 20' by 20' can be covered by one standard unit. Available fabrics include triple-ply vinyl-polyester laminate, resin impregnated cotton duck, vinyl-polyester industrial cover fabrics, translucent vinyl-polyester and spun-dyed acrylic materials. The motor may be controlled by time clock or by weather sensors.

COST

Not available.

PERFORMANCE CHARACTERISTICS

Not available.

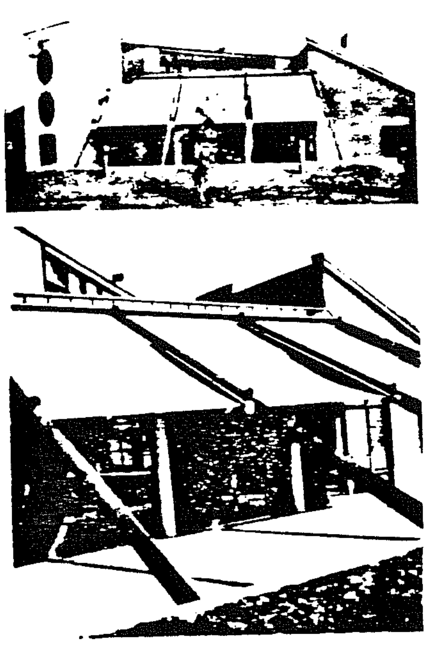
LIMITATIONS

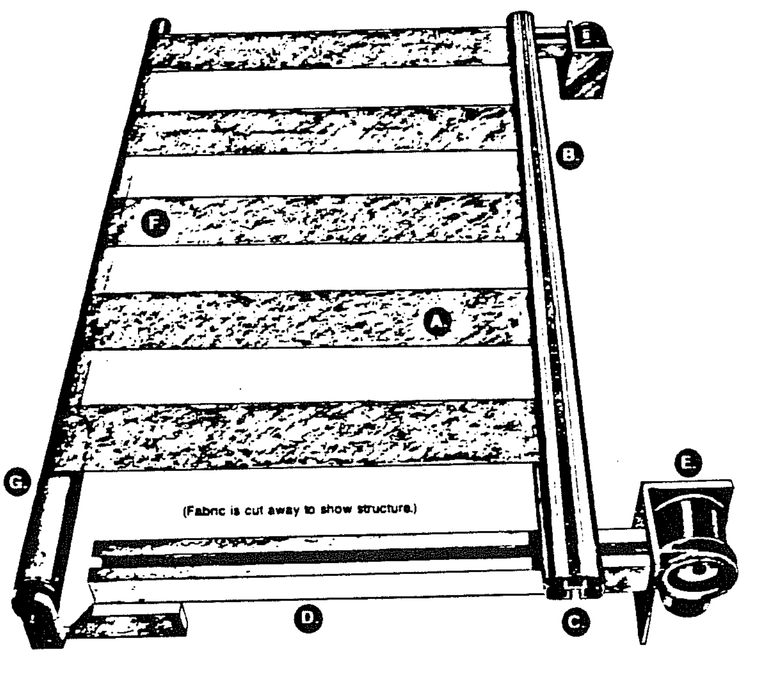
May impede egress if used over operable glazing. Certain fabrics are not flame retardant.

COMMENTS

REFERENCES

Constant Tension Mechanism brochure.





A. Fabrics by John Boyle & Company
B. Front bar of extruded, anodized aluminum, channeled for high rigidity.
C. Trolley wheels
D. Tracks of extruded, anodized aluminum
E. Constant Tension Mechanism
F. Roller bar of galvanized steel
G. Somfy® tubular geared motor

Initials: jk, kmp Date: January 1983 LBL File No.: 4.2.1

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : External Shades, Internal Shades
PRODUCT NAME : Thermo Veil™, Thermo Shade™
MANUFACTURER : Mecho Shade Corporation
42-03 35th Street, Long Island, NY 11101
(212) 729-2020

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[X] Retractable
[ ] Adjustable

[X] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[ ] Wind Resistant

DESCRIPTION

Thermo Shade™ and Thermo Shade™ are technologically advanced woven vinyl fabrics. They are washable, flame retardant and fade resistant. They content 79% vinyl and 21% dernier polyester core. They are suitable for both interior and exterior applications. Thermo Veil™ has 91-21% openness, while Thermo Shade™ has 2-4%. They are available in linen, beige, grey and black/brown. Also available in *Dual Weave* (black/white). Complete line of Mecho Shade hardware is available for both interior and exterior use. They are chain operated, manually or automatically through available programmed window management controls (photocell, anemometer).

COST

Not available.

PERFORMANCE CHARACTERISTICS

Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
Interior linen Thermo Veil	0.28		0.37	0.46	0.51	0.85	0.43
Interior linen Thermo Shade	0.10		0.25	0.54	0.43	0.85	0.43
Interior gray Thermo Veil	0.29		0.28	0.27	0.61	0.85	0.43
Interior gray Thermo Shade	0.05		0.07	0.30	0.54	0.85	0.43
Exterior linen Thermo Veil	0.28		0.37	0.46	0.40	0.85	0.43
Exterior gray Thermo Shade	0.05		0.07	0.30	0.14	0.85	0.43

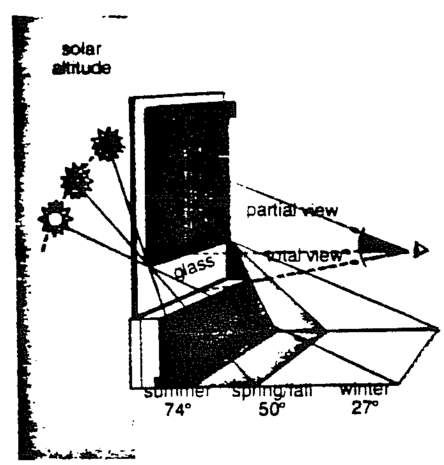
LIMITATIONS

COMMENTS

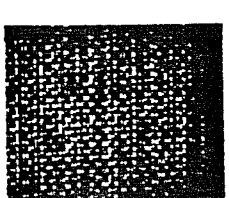
Additional performance characteristics are available for the rest of the product types and with various types of glass. Performance characteristics were measured by Matrix Inc. and Professor John Yellott, Arizona State University.

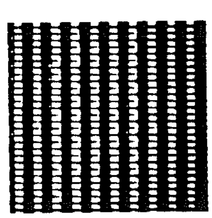
REFERENCES

Manufacturer's brochure (February 1982).



Interior "overhangs" change with sun angle. Mecho Shades act as adjustable interior overhangs which in effect, control glare, and insure personal comfort by providing shade and insulation at the window wall.





Initials: kmp Date: April 1984 LBL File No.: 4.2.4, 4.4.3

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : External Louvers

PRODUCT NAME : Brown Louvers

MANUFACTURER : Brown Manufacturing Company
P.O. Box 14546, Oklahoma City, OK 73114
(405) 751-1323

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement	[ ] Fixed	[ ] Thermal Insulation
[X] Add On / Retrofit	[X] Operable	[ ] Acoustic Insulation
[X] Permanent	[ ] Retractable	[ ] Air Tight
[ ] Seasonal	[X] Adjustable	[X] Wind Resistant

DESCRIPTION

Brown Company manufactures both horizontal and vertical louvers in several blade profiles. Vane widths are typically in the range 4-12", depending on the model. Numerous mounting options and locations for manual operator (crank) are available. Operation is controlled by pushbutton, time control with pushbutton over-ride and timer, again with pushbutton over-ride.

COST

Not available.

PERFORMANCE CHARACTERISTICS

Not available.

LIMITATIONS

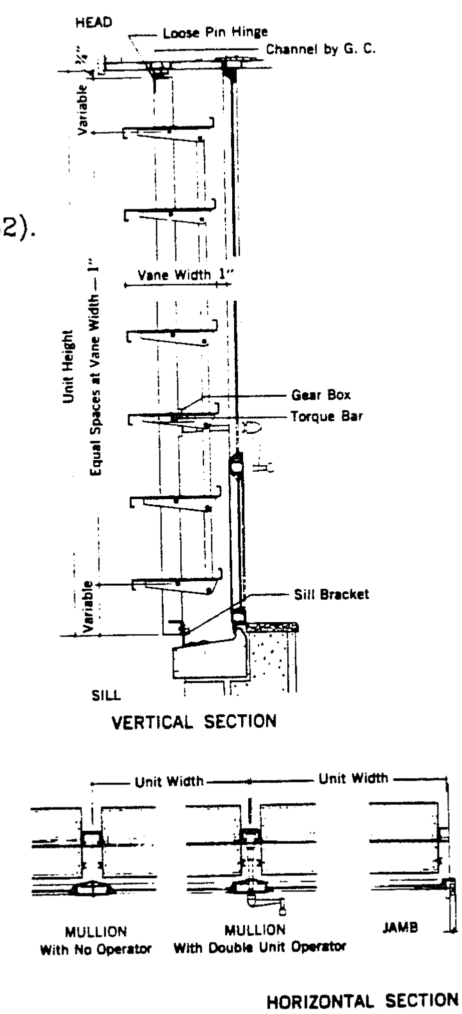
Interferes with egress.

COMMENTS

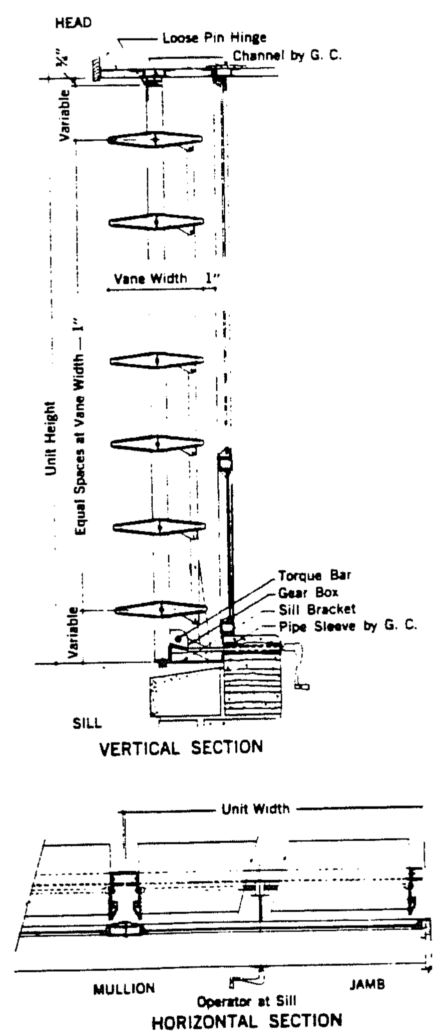
REFERENCES

Manufacturer's brochure (1962).

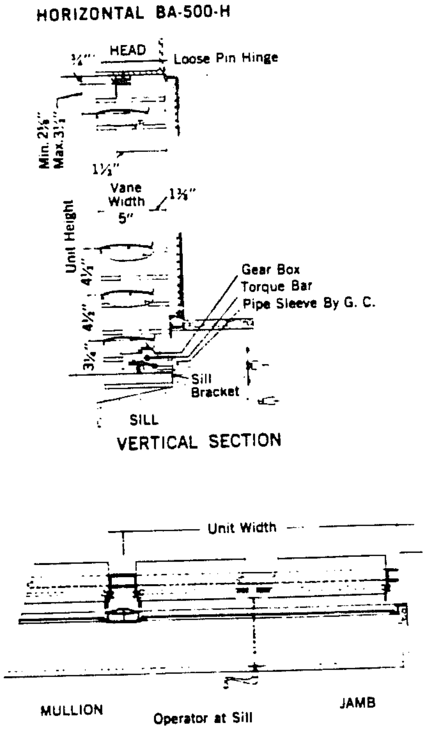
HORIZONTAL BA-1000-H



HORIZONTAL BA-1800-H



HORIZONTAL BA-500-H



Initials: jk, kmp Date: November 1982 LBL File No.: 4.2.5

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : External Louvers

PRODUCT NAME : Moore Louvers

MANUFACTURER : The Moore Company
Marceline, MO 64658
(816) 376-3583

DESCRIPTIVE CHARACTERISTICS

[X] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[ ] Retractable
[X] Adjustable

[ ] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[X] Wind Resistant

DESCRIPTION

The hollow aluminum, aerodynamically configured louvers, can span 16' and be vertically linked with similar modules to shade 200'. Each louver assembly can have its louvers tilted by electrical or pneumatic actuators which are controlled manually, or by automatic control systems. The automatic control system opens the louvers as wide as possible without admitting direct sunlight. The basic operational logic can be over-ridden by manual control, as well as by other control options, including "Solar Control Delay Time and Night Closer" which prevents positioner from responding to transient conditions (e.g. clouds) by means of a user-set delay (0-15 min), "Light Intensity Over-Ride" which keeps interior illumination from exceeding a preset value and "Analog Signal Input".

COST

Not available.

PERFORMANCE CHARACTERISTICS

Not available.

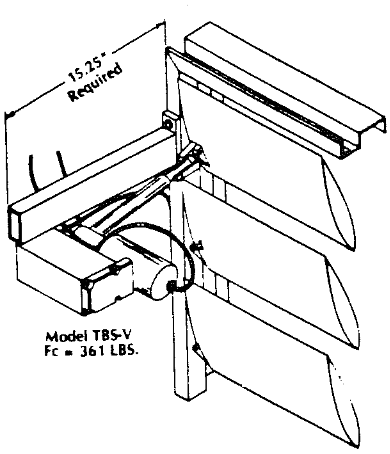
LIMITATIONS

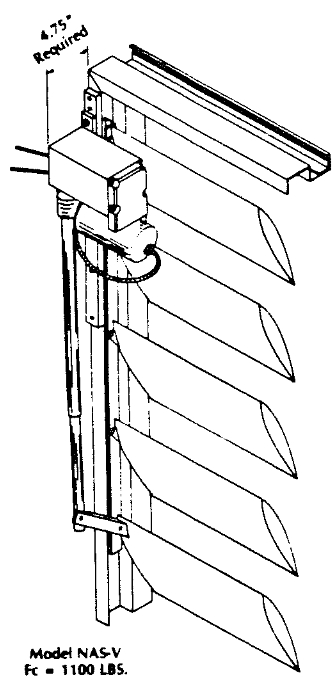
Interferes with egress.

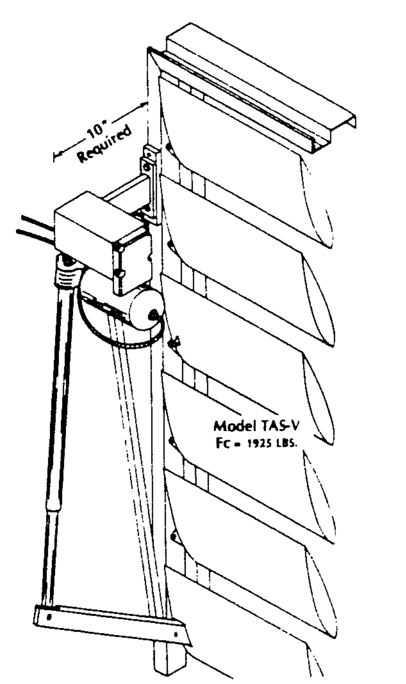
COMMENTS

REFERENCES

Manufacturer's brochure.







Fc = Force On Control Rod

Initials: jk, kmp

Date: November 1982

LBL File No.: 4.2.5

SOLAR CONTROL PRODUCT DATA SHEET

GENERIC TYPE : Interior Blinds

PRODUCT NAME : Thermocell Blind

MANUFACTURER : Thermal Technology Corporation of Aspen, Inc.
601 Alter Street, Broomfield, Colorado 80020
(303) 466-1848

DESCRIPTIVE CHARACTERISTICS

[ ] Prime / Replacement
[X] Add On / Retrofit
[X] Permanent
[ ] Seasonal

[ ] Fixed
[X] Operable
[X] Retractable
[ ] Adjustable

[X] Thermal Insulation
[ ] Acoustic Insulation
[ ] Air Tight
[ ] Wind Resistant

DESCRIPTION

The Thermocell Blind is a series of hollow, honeycomb-shaped structures. Fully extended, the blind traps air in these cells and creates and creates an additional air space between itself and the window, resulting in high insulating values. Edge sealing tracks accent the installation and increase insulating effectiveness. It retracts accordion style, compacting each linear foot into one eighth of an inch. It is available in opaque, translucent and transparent finishes. Thermocell Blind is available in vertical drop, parallel bar and continuous loop operating systems, thus suitable for all kinds of uses and applications.

COST

From $ 75 (30" by 30") to $ 470 (96" by 144"), according to width and height (6/1/84).

PERFORMANCE CHARACTERISTICS

Type / Condition	T_v	R_v	T_s	R_s	S.C.	U_{sg}	U_{dg}
Chrome			0.00	0.82			0.20
Pewter			0.00	0.92		0.18	0.15
White metalized			0.00	0.85		0.27	0.20
White translucent			0.20	0.72	0.32	0.39	0.25
Blue smoke			0.16	0.35			0.20
Gray tint			0.26	0.13	0.63		0.20

LIMITATIONS

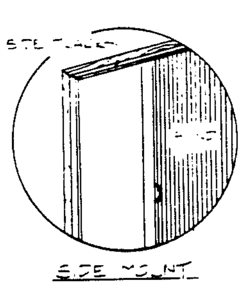
Opaque versions do not allow view. Maximum width is 96". Maximum height is 144".

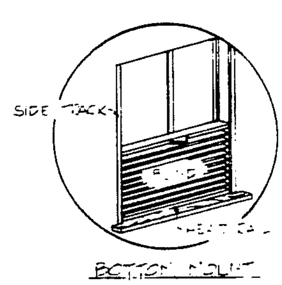
COMMENTS

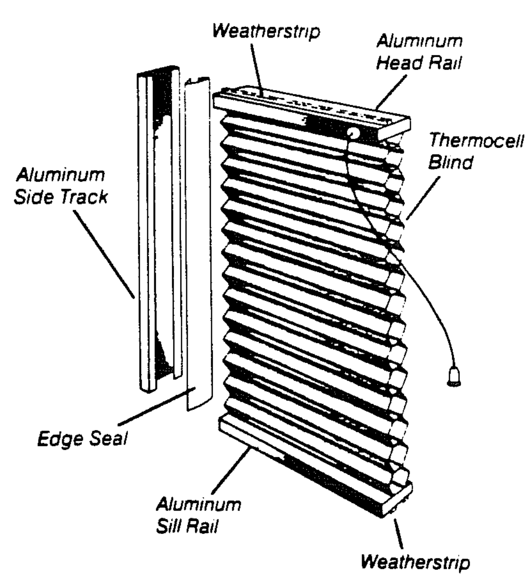
The solar-optical properties were measured by Yellot Engineering Associates, Phoenix, Arizona. U values were measured with 0mph wind.

REFERENCES

Manufacturer's brochure (June 1984).







Initials: kmp Date: October 1984 LBL File No.: 4.4.1

APPENDIX E
DESIGN TOOLS

This daylighting design tools matrix includes a sampling of tools that are currently commercially available as well as several still under development. One of a designer's more difficult tasks may not be using a particular design tool, but selecting a design tool. This matrix is a arranged into three levels: protractors and graphic tools, microcomputer software, and mainframe computer programs. Contact information is provided to facilitate requests for more complete information.

Over the next year or two, we expect to see a proliferation of microcomputer-based daylighting design tools. This will create additional difficulties for the average architect or lighting designer who will be faced with the task of comparing or evaluating relative merits of these particular models. Procedures to evaluate and compare different daylighting calculations or design techniques are needed. One approach is to develop a carefully structured data base of measured illuminance values in a series of test rooms under a variety of standard overcast and clear sky conditions. The design tool in question could then be run and the results compared to the standard data set. Careful selection of the conditions that are included in the data base should make it possible for a user to learn a considerable amount about the accuracy of the calculation procedure without looking at the algorithms or code. Defining the fundamental limitations for using each design tool should also help to guide the user to the tools that are most appropriate for the particular problem under study.

A NOMOGRAPHS

Daylighting Design Tool Survey

Windows and Daylighting Group/Lawrence Berkeley Laboratory

	TOOL NAME	CONTACT	DAYLIGHT	ELECTRIC LIGHT	LIGHT ENERGY	TOTAL ENERGY
1-A	Daylighting Nomographs	Windows & Daylighting Group Building 90-3111 Lawrence Berkeley Laboratory University of California Berkeley, CA 94720 (415) 486-5605	●		●	
2-A	Energy Nomographs	Burt Hill Kosar Rittelmann Associates 400 Morgan Center Butler, PA 16001 (412) 285-4761 **CONTACT::** Al Sain	●	●	●	●
3-A	Energy Nomographs	Ross & Baruzzini, Inc. 7912 Bonhomme St. Louis, MO 63105 (314) 725-2242				
4-A	Lumen Method Sun Angle Calculator Heat Gain Calculator	Libbey-Owens-Ford 811 Madison Avenue Toledo, OH 43695 (419) 247-4232	●			

B PROTRACTORS/TABLES

	TOOL NAME	CONTACT	DAYLIGHT	ELECTRIC LIGHT	LIGHT ENERGY	TOTAL ENERGY
1-B	BRS Protractors	Designers Software Exchange Laboratory of Architecture and Planning MIT 77 Massachusetts Avenue Cambridge, MA 02139 (617) 253-5017 **CONTACT:** Harvey Bryan	●			
2-B	LUNE Protractor	Lighting Research Laboratory P.O.Box 6193 Orange, CA 92667 (714) 771-1312 **CONTACT:** Bill Jones	●			
3-B	LBL Protractors	Windows & Daylighting Group Building 90-3111 Lawrence Berkeley Laboratory University of California Berkeley, CA 94720 (415) 486-5605	●			
4-B	WALDRAM Diagrams	Designers Software Exchange Laboratory of Architecture and Planning MIT 77 Massachusetts Avenue Cambridge, MA 02139 (617) 253-5017 **CONTACT:** Harvey Bryan	●			
5-B	BRS Daylight Tables	Designers Software Exchange Laboratory of Architecture and Planning MIT 77 Massachusetts Avenue Cambridge, MA 02139 (617) 253-5017 **CONTACT:** Harvey Bryan	●			

C MICROS

	TOOL NAME	CONTACT	DAYLIGHT	ELECTRIC LIGHT	LIGHT ENERGY	TOTAL ENERGY
1-C	CADLIGHT	Wiley Professional Software 605 Third Avenue New York, NY 10158 (212) 850-6788 **CONTACT:** Leslie Bixel	●			
2-C	CONTROLITE	Lighting Systems Research Group Building 90-3111 Lawrence Berkeley Laboratory University of California Berkeley, CA 94720 (415) 486-5607	●		●	
3-C	DALITE	National Fenestration Council 3310 Harrison Street White Lakes Prof. Building Topeka, KS 66111 (913) 266-7014 **CONTACT:** Bill Birch	●			
4-C	DAYLIT	Graduate School of Architecture and Urban Planning UCLA 405 Hilgard Avenue Los Angeles, CA 90024 (213) 825-7370 **CONTACT:** Murray Milne	●			
5-C	DAYLITE	Solarsoft 1406 Burlingame Ave., Suite 31 Burlingame, CA 94010 (415) 342-3338 **CONTACT:** Bill Ashton	●		●	
6-C	DYNALITE	Skidmore, Owings & Merrill 1 Maritime Plaza San Francisco, CA 94111 (415) 981-1555 **CONTACT:** Mark Smith	●			
7-C	ENSAR	Ensar Group 66 S. Van Gorden St. #107 Lakewood, CO 80228 (303) 989-9407 **CONTACT:** Greg Franta	●			
8-C	LUMEN III	Lighting Technologies 3060 Walnut St., Suite 209 Boulder, CO 80301 (303) 449-5791 **CONTACT:** Martin M. McCloskey	●	●		
9-C	MICROLITE 1.0	Designers Software Exchange Laboratory of Architecture and Planning MIT 77 Massachusetts Avenue Cambridge, MA 02139 (617) 253-5017 **CONTACT:** Harvey Bryan	●			

C MICROS continued

	TOOL NAME	CONTACT	DAYLIGHT	ELECTRIC LIGHT	LIGHT ENERGY	TOTAL ENERGY
10-C	QUICKLITE 1.0	Windows & Daylighting Group Building 90-3111 Lawrence Berkeley Laboratory University of California Berkeley, CA 94720 (415) 486-5605	●			
11-C	SDM	Heery Energy Consultants 880 West Peachtree St., NW Atlanta, GA 30367 (404) 881-0497 **CONTACT:** Mark Davenport	●		●	●
12-C	SKYKING	Princeton Energy Group 575 Ewing Street Princeton, NJ 08540 (609) 921-1965 **CONTACT:** Lawrence Lindsey	●			
13-C	SKYSIZE	Sunpine Associates 2275 Cox Road Cocoa, FL 32926 (305) 631-6225 **CONTACT:** Ross McCluney	●	●		
14-C	SOLITE	Keniston & Mosher, Architects 666 State Street San Diego, CA 92101 (619) 231-1312 **CONTACT:** James P. Brown	●			
15-C	THERMALITE	Designers Software Exchange Laboratory of Architecture and Planning MIT 77 Massachusetts Avenue Cambridge, MA 02139 (617) 253-5017 **CONTACT:** Harvey Bryan	●	●	●	●

D MINIS

	TOOL NAME	CONTACT	DAYLIGHT	ELECTRIC LIGHT	LIGHT ENERGY	TOTAL ENERGY
1-D	SHIS	S & H Information Systems 11 West 42nd Street New York, NY 10036 (212) 556-3212 **CONTACT:** Suro Das	●			

E MAINFRAMES

Daylighting Design Tool Survey

Windows and Daylighting Group/Lawrence Berkeley Laboratory

	TOOL NAME	CONTACT	DAYLIGHT	ELECTRIC LIGHT	LIGHT ENERGY	TOTAL ENERGY
1-E	DEROB	School of Architecture University of Texas Austin, TX 78712 (512) 471-1733 **CONTACT:** Francisco Arumi	●			●
2-E	DOE-2.1B	Building Energy Simulation Group Building 90-3147 Lawrence Berkeley Laboratory University of California Berkeley, CA 94720 **CONTACT:** Karen Olson	●		●	●
3-E	GLIM	Applied Research of Cambridge, Ltd. 4 Jesus Lane Cambridge CB5 8BA ENGLAND	●			
4-E	LUMEN II	Lighting Technologies 3060 Walnut St. Suite 209 Boulder, CO 80301 (303) 449-5791 **CONTACT:** Martin M. McCloskey	●	●		
5-E	SUPERLITE 1.0	Windows & Daylighting Group Building 90-3111 Lawrence Berkeley Laboratory University of California Berkeley, CA 94720 (415) 486-5605	●	●		
6-E	UWLIGHT	Department of Architecture Gould Hall JO-20 University of Washington Seattle, WA 98105 (206) 543-4180 **CONTACT:** Marietta Millet	●			