Title

IMPACT OF ELECTRIC LIGHTING EFFICIENCY ON THE ENERGY SAVING POTENTIAL OF DAYLIGHTING FROM ROOF MONITORS

Permalink

https://escholarship.org/uc/item/70c5q9d4

Authors

Fontoynont, M.
Place, W.
Bauman, F.

Publication Date

1983

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE
DIVISION

Presented at the 1983 International Daylighting
Conference, Phoenix, AZ, February 16-18, 1983;
and published in Energy and Buildings, Volume 6,
(1984): 375-386

IMPACT OF ELECTRIC LIGHTING EFFICIENCY ON THE ENERGY SAVING POTENTIAL OF DAYLIGHTING FROM ROOF MONITORS

M. Fontoynont, W. Place, and F. Bauman

January 1983

**APPLIED SCIENCE
DIVISION**

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

IMPACT OF ELECTRIC LIGHTING EFFICIENCY ON THE ENERGY SAVING POTENTIAL OF DAYLIGHTING FROM ROOF MONITORS

Marc Fontoynont, Wayne Place, and Fred Bauman

Building Systems Analysis Group
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

SOLAR BUILDINGS RESEARCH AND DEVELOPMENT PROGRAM
CONTEXT STATEMENT

November 21, 1985

In keeping with the national energy policy goal of fostering an adequate supply of energy at a reasonable cost, the United States Department of Energy (DOE) supports a variety of programs to promote a balanced and mixed energy resource system. The mission of the DOE Solar Buildings Research and Development Program is to support this goal, by providing for the development of solar technology alternatives for the buildings sector. It is the goal of the program to establish a proven technology base to allow industry to develop solar products and designs for buildings which are economically competitive and can contribute significantly to building energy supplies nationally. Toward this end, the program sponsors research activities related to increasing the efficiency, reducing the cost, and improving the long-term durability of passive and active solar systems for building water and space heating, cooling, and daylighting applications. These activities are conducted in four major areas: Advanced Passive Solar Materials Research, Collector Technology Research, Cooling Systems Research, and Systems Analysis and Applications Research.

Advanced Passive Solar Materials Research. This activity area includes work on new aperture materials for controlling solar heat gains, and for enhancing the use of daylight for building interior lighting purposes. It also encompasses work on low-cost thermal storage materials that have high thermal storage capacity and can be integrated with conventional building elements, and work on materials and methods to transport thermal energy efficiently between any building exterior surface and the building interior by nonmechanical means.

Collector Technology Research. This activity area encompasses work on advanced low-to-medium temperature (up to 180°F useful operating temperature) flat plate collectors for water and space heating applications, and medium-to-high temperature (up to 400°F useful operating temperature) evacuated tube/concentrating collectors for space heating and cooling applications. The focus is on design innovations using new materials and fabrication techniques.

Cooling Systems Research. This activity area involves research on high performance dehumidifiers and chillers that can operate efficiently with the variable thermal outputs and delivery temperatures associated with solar collectors. It also includes work on advanced passive cooling techniques.

Systems Analysis and Applications Research. This activity area encompasses experimental testing, analysis, and evaluation of solar heating, cooling, and daylighting systems for residential and nonresidential buildings. This involves system integration studies, the development of design and analysis tools, and the establishment of overall cost, performance, and durability targets for various technology or system options.

This report is an account of research conducted in systems analysis and applications concerning how efficient electric lighting systems affect energy saving in buildings with roof monitors for daylighting.

IMPACT OF ELECTRIC LIGHTING EFFICIENCY ON THE ENERGY SAVING POTENTIAL OF DAYLIGHTING FROM ROOF MONITORS*

Marc Fontoynont, Wayne Place, and Fred Bauman§
Building Systems Analysis Group
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

A developmental version of the building energy analysis computer program BLAST† was used to perform simulations of a prototypical, single-story office building. Total annual energy consumption was computed using Typical Meteorological Year (TMY) [1] weather data from three locations in the United States. For each location, two electric lighting designs were tested on the baseline building (no roof monitors) to compare the energy requirements of current-practice and more efficient electric lighting designs. The roof monitors had highly diffusing, vertical glazings facing southeast and southwest.

The results show that improving electric lighting system efficiency and adding roof monitors for daylighting both have the potential for substantially reducing lighting electricity and the energy cost of operating the building. The potential benefits of daylighting are substantially lower for a building outfitted with a more efficient electric lighting system, although they are still significant. To determine the limits of validity of the simulations, a number of sensitivities studies were performed. Among the issues investigated were: dirt deposits, snow accumulation, glazing optical properties, interior design, luminous efficacy of admitted sunlight, and thermostatic controls.

1. INTRODUCTION

Solar radiation admitted to a commercial building in an appropriately controlled manner has the potential to reduce the energy cost of operating the building in a number

---

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Heat Technologies, Passive and Hybrid Solar Energy Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

§The authors' current addresses are: Marc Fontoynont, LASH/ENTPE, rue Maurice Audin, 69120 - Vaulx-en-Velin France; Wayne Place, Architecture Dept., North Carolina State University, Raleigh, NC 27605; and Fred Bauman, Architecture Dept., 232 Wurster, University of California, Berkeley, CA 94720.

†BLAST (Building Loads Analysis and System Thermodynamics) is trademarked by the Construction Engineering Research Laboratory, U.S. Department of the Army, Champaign, Illinois.

of ways. Sunlight is a high quality source of illumination, which is available in ample quantities during most of the nation's working hours. Using this illumination source can substantially reduce the consumption of electricity for lighting. In addition to providing illumination, large quantities of solar radiation admitted during the winter can also help to reduce the heating requirements of the building. The cooling requirements of the building can also be reduced by substituting controlled quantities of sunlight for electric light of higher heat content. Finally, since many utilities are summer peaking, reducing the building cooling loads during the peak summer hours can benefit the building owner by reducing the electricity demand charges and the cooling system size, and the utility by reducing capacity requirements.

Ultimately, the magnitude of any energy benefits derived from admitting solar radiation to the building depends on the details of both the daylighting system design and the electric lighting system design. In fact, not only does the design of the electric lighting system affect the potential benefits derivable from the daylighting system, but in many instances improved hardware or control strategies for the electric lighting system compete with daylighting for the building's energy budget. Making comparisons between the two technologies is difficult, since the state of the art is changing rapidly in both fields. However, some attempt should be made to put daylighting into proper context with respect to electric lighting developments.

Current developments in electric lighting systems include more efficient hardware, improved lighting control strategies, and proposed reductions in the required illuminance on the work plane for common office tasks. The minimum required illumination on the work plane in an office building is the subject of an ongoing debate and is itself a complex function of several factors.

2. PROBLEM APPROACH

To keep this preliminary study simple, it was decided to avoid task lighting solutions and controversial reductions in the recommended illumination levels. In other words, it was decided that 538 lux (50 footcandles) of illumination would be provided uniformly across the entire work plane [2]. Down-facing ceiling lamps were provided to assure the desired illumination level. Two lighting designs were compared. The first simulated fluorescent lamps with core-coil ballasts in diffusing luminaires corresponding to a lighting power of 27 W/m^2 of floor area (2.5 W/ft^2); the second one simulated fluorescent lamps with high frequency electronic ballasts [6] and an alternate luminaire design corresponding to 16 W/m^2 of floor area (1.5 W/ft^2).

Sunlight was admitted to the building through roof monitors outfitted with highly diffusing glazing, thereby providing daylight throughout the building and avoiding the illumination problems associated with beam sunlight impinging on the work plane. For this study, the roof monitors were spaced closely enough and were sufficiently effective in dispersing light that the admitted daylight was comparable in uniformity and general quality to the light from the electric lighting system. For this reason, a simple substitution of daylight for electric light was easily justified.

In order to perform daylighting calculations, BLAST has been provided with an algorithm allowing the simulation of continuous linear dimming of the electrical lights in response to the transmitted solar radiation. Reductions of lighting electric power below 20% of the maximum level were not allowed in the simulations, because of limitations in the hardware for continuous control of the lights. High frequency electronic ballasts allow a continuous dimming to lower levels than do core-coil ballasts, but for the purpose of this study, the dimming was assumed to be identical for the two designs. Although this may appear to be an optimistic performance for core-coil ballasts, it is possible to achieve this level of performance by a combination of continuous control and digital switching of some of the lamps. Of course, digital switching could also be used in conjunction with continuous control of the high frequency ballasts; but to keep this preliminary study simple, the same 20% lower limit for the power was assumed for both the current-practice and the more efficient electric lighting designs.

Each hour BLAST calculates the solar radiation gains through all the glazing elements in the building. It then reduces the lighting electricity in response to solar radiation entering the roof apertures by comparing the "system luminous efficacies" (SLE) for the electric lighting system and the daylighting system. For the electric lighting system, we define the SLE as the ratio of electric light on the work plane (in lumens) to the total power introduced to the building by the electric lighting system (in watts). (In this study, 60% of this energy that the lights introduce to the building goes directly to the building cooling system via return air passing through the luminaires.) Similarly, we define the solar SLE as the ratio of sunlight on the work plane (in lumens) to the total solar power entering the building through the illumination glazing (in watts). For both the current-practice and more efficient electric lighting systems the SLEs were calculated from information contained in the Illumination Engineering Society (IES) handbook [2]. The SLE of the current-practice design was 20 lumens per watt (lm/W) and the SLE of the more efficient design was 33.3 lm/W. The SLE of the roof monitors was set at 72 lm/W, based on tests of a scale model of the building. Surface reflectivities within the building were as follows: 80% for the ceiling, 70% for the walls, and 30% for the floor. Knowledge of the solar SLE of the roof monitors and the electrical lighting SLE permits BLAST to perform a trade-off between the two light sources. The reduction in power to the lights is equal to the solar power admitted to the building through the roof glazing multiplied by the solar SLE divided by the electrical SLE. BLAST keeps track of the hourly, monthly, and annual consumption for lighting electricity, and also automatically accounts for the thermal effect of reduced power to the lights. The thermal zones for the building are shown in Fig. 1.

For the purposes of this study, a clear distinction has been drawn between the glazing in the roof monitors, which was put there for illumination purposes, and the glazing in the walls, which was put there primarily to provide a view for the building occupants. Natural lighting admitted by the glazing in the wall can provide illumination in a limited area near the exterior walls. However, the illumination level varies rapidly as a function of the distance from the window. Use of this light as a substitution for electrical light is more complicated than a simple trade-off, because the high levels of transmitted solar radiation lead to high contrast in the field of view of the occupants. A common response of building occupants to the visual discomfort associated with this high glare is to pull the shades or simply to turn on the electric lights in an attempt to reduce the contrast. To avoid the complications associated with glare, the wall glazing was assumed to be highly reflective (16% normal solar transmittance) and none of the sunlight admitted by this glazing was considered in the control of the electric lights. This means that in the vicinity of the external walls the illumination level would normally be greater than the minimum value of 538 lux.

A more complete building description and other details of the analytic method are described in previous papers [3-5].

3. DAYLIGHTING SYSTEM DESIGN

The selection of a daylighting system design for the present study was based on two requirements:

(1) The daylighting system should produce a distribution of illumination at least as uniform as the one produced with the electrical lighting system.

(2) The daylighting system should have a high potential for reducing the total annual energy consumed to light, heat, and cool an office building.

As described earlier, the first requirement can be satisfied with a system of roof monitors, distributed either in parallel arrays or in light wells of various design, having a carefully chosen spacing, and being outfitted with highly diffusing glazing that disperses the incoming sunlight. The second requirement has been addressed by examining a variety of tilts and orientations for the roof monitor glazing. In so doing, it has been kept in mind that the designs that can save the largest amount of lighting electricity are not necessarily the ones which perform best when account is taken of cooling electricity and boiler fuel consumption. For example, too much solar radiation from roof systems in summer can substantially increase the cooling requirements and decrease the thermal comfort of the occupants.

The bulk of the simulation results reported in this paper are for roof monitors having unshaded, vertical glazings facing southeast and southwest, as shown in Fig. 2. The thermal advantages of this system over the more conventional skylights (with horizontal glazing) can be illustrated by the results presented in Figs. 3 and 4. Figure 3 shows BLAST computations of hourly-average electric lighting power for the building when illuminated by sunlight admitted through horizontal glazing. Results are presented for two design days in Atlanta, Georgia: a clear summer day and a clear winter day. Figure 4 shows similar results for the combination of vertical glazings facing southeast and southwest. In both Figs. 3 and 4, the total area of the glazing in the roof is 1.25% of the building floor area. The combination of vertical glazings facing southeast and southwest is a promising system for two reasons:

1. during the summer, it collects effectively during the morning and afternoon, without overcollecting during the hot period around midday; and

2. it collects more strongly during the winter than during the summer.

It is therefore possible to select a glazing area that admits substantial sunlight and solar radiation during the heating seasons and which satisfies most of the summertime illumination needs without thermally overloading the building. The relative uniformity of collection for the combination of vertical glazings results from the fact that the glazings face partially toward the east and west, allowing the effective collection of sunlight in early morning and late afternoon hours when solar radiation is normally weakest. In contrast, horizontal glazing faces upward toward the midday summer sun, causing more effective collection near midday than in the early morning and late afternoon. Also, horizontal glazing collects much more effectively during the summer than during the winter. Because of the apparent thermal advantages of the combination of vertical glazings, this system was chosen as the focus for this investigation. Future studies will examine horizontal glazing in more detail and will also look at intermediate systems, such as the combination of tilted glazings facing southeast and southwest.

4. RESULTS

Results for the baseline building presented in Table 1 show that using the more efficient electric lighting system produces substantial savings in electricity costs. The more efficient electric lighting system also has a significant beneficial impact on the cooling requirements of the building, even for ceiling lamps through which return air is circulated. Using the more efficient electric lighting design results in an annual energy cost savings for each location on the order of $5/m^2 of floor area ($0.50/ft^2).

Annual BLAST simulations were also performed for a range of daylighting glazing areas on the baseline building with both electric lighting designs. In these simulations, the aperture ratio (defined as the ratio of the total roof glazing area to the building floor area) was varied over the values 1.25%, 2.5%, 5.0%, and 10.0%. Some results of these simulations for the combination of vertical glazings facing southeast and southwest are shown in Figs. 5-8. The energy values plotted refer to site energy consumption of electricity and boiler fuel, not to primary energy at the utility or thermal loads for the building. The consumption of primary energy for generating electricity at the utility would be on the order of three to four times higher than the consumption of electricity at the site, because of generating inefficiencies and utility network losses.

Figure 5 shows the annual lighting electricity consumption as a function of the aperture ratio. Of the three energy end uses (lighting, heating, and cooling), lighting electricity consumption is by far the most sensitive to the glazing area. This is in part due to the glazing system, which was designed to minimize the deleterious thermal effects of admitted solar radiation. For small aperture ratios, lighting electricity consumption decreases rapidly with increasing glazing area. For large aperture ratios, lighting electricity consumption goes down less rapidly with increasing glazing area, eventually approaching an asymptotic limit. This lower limit results partly from the continuous lighting controller, which does not reduce power levels below 20%, and partly from the twelve-hour building operating schedule, which includes many hours during the winter when there is no sunlight available. At any specific aperture ratio, the percent reduction in lighting electricity consumption achieved by the daylighting is the same for both the high-wattage and the low-wattage electric lighting systems.

Figure 6 shows the annual cooling electricity consumption as a function of the aperture ratio. Cooling electricity consumption is substantially less sensitive to the glazing area than is the lighting electricity consumption. For small aperture ratios, cooling electricity consumption decreases with increasing glazing area, because the admitted sunlight is replacing electric lighting of higher heat content. At larger aperture ratios, cooling loads increase with increasing glazing area, as a result of the excess solar gains. The more efficient (low-wattage) electric lighting system reduces the potential cooling benefits associated with replacing electric light with sunlight.

Figure 7 shows the annual boiler fuel consumption (for space heating and hot water) as a function of aperture ratio. The boiler fuel consumption is less sensitive to glazing area than is either lighting or cooling electricity consumption. Also, the cost per unit of energy at the site is much lower for boiler fuel than it is for electricity. As a consequence, the variations in boiler fuel as a function of aperture ratio are relatively inconsequential from an energy economics point of view (see Table 2).

Figure 8 shows the annual operating cost for energy, based on the local cost for boiler fuel and local electric utility consumption rates and peak demand charges. At small aperture ratios, the energy cost curves decrease rapidly with increasing glazing area, because of the decreases in both lighting electricity consumption and cooling electricity consumption. At larger aperture ratios, the energy cost curves level off (or even rise slightly) as increasing cooling electricity and associated demand charges negate the diminishing benefits in decreasing lighting electricity consumption. For all the cost curves shown, negligible benefits accrue for aperture ratios beyond 5%, and in most cases most of the potential cost benefits are achieved at significantly smaller areas.

The effectiveness of small areas of glazing is a result of the extreme intensity of sunlight compared with the illumination level required in an office building. Bright sunlight can exceed 100,000 lux in intensity. This implies that for the glazing transmission of 0.62 assumed in this study, the transmitted illumination can be as high as 60,000 lux, for normal incidence. If we multiply this by a factor of 0.7, which is about the fraction of the admitted daylight which reaches the work plane as useful illumination, and then assume a 1.25% aperture ratio, we conclude that the illumination on the work plane would be on the order of 500 lux, which is the recommended level for office spaces. In other words, at the peak brightness of the sun, an aperture ratio of 1.25% can supply all the illumination required for the building. Somewhat larger aperture ratios are desirable in order to collect adequate illumination during periods of lesser solar brightness, but the aperture should not be made radically larger if excessive solar gains are to be avoided.

In both Atlanta and Los Angeles, the potential energy cost reduction from adding daylighting to the current-practice (high-wattage) electric lighting system is about equal to the energy cost reduction from converting to the more efficient (low-wattage) electric lighting system. In New York, which is a less sunny climate, the potential energy cost reduction from adding daylighting is smaller than the energy cost reduction from converting to the low-wattage system. (It should be pointed out that the high energy cost in New York is more a result of the high electric utility rates than the large consumption of boiler fuel. Table 2 give a breakdown of the electricity and boiler fuel costs for each of the locations, glazing areas, and electric lighting designs.)

At any specific aperture ratio, the percent reduction in energy cost resulting from the daylighting is slightly less for the low-wattage system than for the high-wattage system. (This is in contrast to lighting electricity, for which the percent reductions were the same for the two lighting systems. The discrepancy in percent reductions of costs is primarily the result of the reduced cooling benefits of daylighting in the case of the low-wattage system.) Since the amount of energy cost to be reduced is already smaller for the low-wattage system, the absolute magnitude of the cost reduction achievable with daylighting is less for the low-wattage system than for the high-wattage system (at any specific aperture ratio).

The energy cost reduction resulting from daylighting is still significant even for the building with the low-wattage electric lighting system. Annual energy cost savings due to daylighting can be on the of $\$5/m^2$ of building floor area ($\$0.50/ft^2$) for the current-practice lighting design and $\$2/m^2$ of floor area ($\$0.20/ft^2$) for the more efficient design. For the daylighting system examined in this paper, these savings are achieved at an illumination glazing area which is about 4% of the building floor area, which means that the annual energy cost savings are about $\$120/m^2$ of illumination glazing ($\$12/ft^2$) for the current-practice electric lighting design and about $\$50/m^2$ of glazing area ($\$5/ft^2$) for the more efficient electric lighting design.

5. SENSITIVITY STUDIES

Various assumptions and approximations were made in generating the prototype building design and in performing the BLAST simulations reported in this and other publications [3-5]. It was therefore necessary to use BLAST to perform a number of sensitivity studies in order to show the limits of validity of these simulations. The impact on annual lighting electricity consumption was evaluated for the following factors: dirt deposits, glazing transmissivity, snow accumulation, interior design, and the difference in luminous efficacy between beam and diffuse radiation. The sensitivity of cooling electricity consumption to the use of a thermostatic control based partly on mean radiant temperature was also computed. All of the simulations were performed for south-facing glazing tilted up sixty degrees from the horizontal. This roof monitor configuration was used extensively in simulations reported in other publications [3-5]. To first order, for all the issues examined in these sensitivity studies, the results can be extended to the combination of vertical glazings facing southeast and southwest. All the sensitivity studies were performed in Atlanta, except for the investigation of snow, which was performed in New York. The results of the studies are shown in Table 3 and are discussed below.

Variations in Glazing Transmissivity

The transmission of daylight can be affected by dirt deposits on the glazing or by the use of an alternate glazing material. To investigate this effect, a simulation was performed with the normal solar transmissivity of the roof glazing reduced by 40% (from 0.62 to 0.37). The effect was substantial, reducing the lighting electricity savings due to daylighting from 30.8% to 22.8% at an aperture ratio or 1.25% and from 58.4% to 54.4% at an aperture ratio of 10%. However, these results do not mean that the BLAST simulation results cannot be extended to glazing transmissivities other than 0.62. These same simulations have indicated that for small values of the aperture ratio (less than 5%), the thermal impact of the conductive gains and losses through the roof glazing are relatively inconsequential when compared with the other two major effects:

(1) the lighting electricity reductions (and associated internal load reductions), and

(2) the thermal impact of solar radiation gains.

This fact allows us to apply the results in all the Figures and Tables to glazings having transmissivities different from the 0.62 assumed in the simulations. The key point is the following: for any two glazings with the same product of transmissivity and area, the transmitted illumination and radiation will be the same. The only difference will be in conductive gains and losses, which, as noted above, are relatively inconsequential. If we want to estimate the effect of a glazing with a transmissivity which is larger by a factor f than the one used in this study, then we reduce the aperture ratio of interest by the factor $1/f$ before looking for the appropriate effects in the Figures or Tables. These results and this approach are consistent with other published research [7]. Dirt accumulation can be accounted for in designing the daylighting system by simply oversizing the glazing area. This can be done fairly safely, since the energy cost curves (Fig. 8) have broad minima, thereby allowing 20% to 30% oversizing of the glazing area, with minimal risk of serious overheating during the summer.

Effects of Snow Deposits

As in the case of dirt deposits, the overwhelming impact of the snow covering the roof glazing is in the lighting electricity impact of reduced sunlight transmission, rather than in the thermal impacts of altered heat gains and heat losses. In all of the BLAST simulations reported to this point in the paper, it was assumed that the roof reflectivity was normally 20%, increasing to 70% any time that the TMY weather tape indicated the presence of snow on the ground. Furthermore, no obstruction of the roof aperture was assumed. In other words, the simulations assumed all the benefits that might be associated with the presence of snow (increased roof reflectivity), with none of the disadvantages (obstruction of the aperture).

In order to determine the effect of these assumptions on the results, additional BLAST simulations were performed for New York, which is the snowiest of the three climates examined in this study. These additional simulations assumed that no daylight entered the building on any day on which the TMY weather tape indicated the presence of snow on the ground. This is a conservative assumption, since snow against glazing would normally melt sooner than under most other conditions, particularly if the glazing is mounted on a roof with good solar exposure, which was assumed in all of these simulations. For New York, the predicted savings in annual lighting electricity decreased from 36.9% to 35.4%, in going from a simulation where maximum credit was given to daylighting to a simulation where no credit was given to daylighting on those days when snow was present on the ground. This small effect can be understood by the fact that snow is present only a small fraction of the year, even in New York City, and also by the fact that snow tends to occur during the part of the year when the daylight resource is weakest, i.e., on cloudy winter days.

Interior Design

For all of the BLAST simulations reported to this point in the paper, a value of 72 lm/W was used for the daylighting system luminous efficacy (defined as the amount of useful daylight reaching the work plane divided by the solar power entering the building through the illumination glazing on the roof). The geometry and reflectivity of the interior surfaces of an office space can have a substantial impact on the daylighting system luminous efficacy. Simulations for Atlanta indicate that when the daylighting system luminous efficacy is reduced from 72 lm/W to 50 lm/W, the savings in annual lighting electricity decrease from 30.8% to 23.1% (25% reduction in savings) for an aperture ratio of 1.25%; and from 51.5% to 46.4% (10% reduction in savings) for an aperture ratio of 10%. The results are highly nonlinear. For very small aperture ratios (less than 1%) where the sunlight does not exceed the illumination requirements of the building even for the brightest sunlight, the percent reductions in the savings of lighting electricity are equal to the percent reduction in the daylight system luminous efficacy. However, at larger aperture ratios, the percent reduction in savings of lighting electricity will be substantially less than the percent reduction in the daylighting system luminous efficacy, since on many days the large aperture will collect the required amount of light, in spite of the reduced efficiency in utilizing the sunlight inside the space. These results indicate that more BLAST simulations will be required to extend the results to designs with daylighting system luminous efficacies different from 72 lm/W assumed in this study.

Using Different Luminous Efficacies for Beam and Diffuse Sunlight

Diffuse solar radiation normally will have a somewhat higher luminous efficacy than beam radiation. In all of the BLAST simulations presented up to this point, the same average luminous efficacy was assigned to both the beam and diffuse radiation. To determine the effect of this assumption, a BLAST simulation was performed in which th luminous efficacy for diffuse sunlight was increased by 20% and the luminous efficacy of beam sunlight was reduced by 20%. For this change in the assumptions, the savings in lighting electricity decreased from 30.8% to 30.0% for an aperture ratio of 1.25% (where the contribution of beam sunlight dominates) and increased from 58.4% to 59.5% for an aperture ratio of 10% (where the contribution of diffuse sunlight dominates). The small magnitude of the effect is a result of the system on which the study was performed; south-facing glazing tilted up sixty degrees from the horizontal relies about equally on beam and diffuse sunlight to illuminate the building. Increasing the luminous efficacy of the diffuse light and reducing the luminous efficacy of the beam sunlight for such a system would be expected to have a very small net impact on the overall performance of the system. Since vertical glazing facing southeast and southwest also relies about equally on beam and diffuse light, it is reasonable to expect that reliable predictions can be obtained for this system by assigning the same average luminous efficacy for the beam and diffuse sunlight.

Modified Thermostatic Control

The BLAST simulations reported in other sections of this paper have assumed a thermostat control based strictly on the mean air temperature (MAT). Of particular concern to this study is the fact that adding roof glazing increases the amount of radiation entering the interior of the building. This additional solar radiation impinges directly on the building occupants and on the surfaces of the building (thereby increasing the mean radiant temperature [MRT] in the occupied space), reducing occupant comfort during the summer and increasing the occupant comfort during the winter. In order to investigate the effect of MRT, an alternate comfort standard was assumed [8, 9], and the new energy requirements of the building were calculated. In this alternate scheme, the thermostatic control was based on a equivalent temperature (TEQ), which is a weighted average of MAT and MRT:

$$\text{TEQ} = 0.45\text{MRT} + 0.55\text{MAT}$$

BLAST simulations using this thermostatic control strategy were performed for Atlanta. The results indicate small changes in cooling electricity for aperture ratios less than 5% but significant changes in cooling electricity for aperture ratios on the order of 10%. The comfort impacts of the large aperture are not fully indicated by this sensitivity study, since the effect of solar radiation incident directly on the occupants has not been considered. However, these results do indicate that the simulations performed with a simple MAT thermostatic control should not be relied upon in assessing the potential energy impacts of large aperture areas, and that the energy costs are probably substantially greater at large aperture ratios than the curves in Fig. 8 would indicate. The relationship between comfort criteria and energy consumption is currently being studied in detail and will be the subject of a future paper.

6. CONCLUSIONS

The energy saving potential of reducing lighting electricity in response to daylight admitted through roof monitors has been investigated for two electrical lighting designs, one a current-practice design using 27 W/m^2 of floor area (2.5 W/ft^2) and the other a more energy efficient design using 16 W/m^2 (1.5 W/ft^2). The results show that:

- Adding daylighting and improving electric lighting system efficiency both have the potential for substantially reducing electricity consumption and the energy cost of operating the building. In fact, adding daylighting to the building with the current-practice electric lighting design yields about the same energy cost savings as converting to the more efficient electric lighting system.

- The potential benefits of daylighting are substantially lower for a building outfitted with a more efficient electric lighting system, although the potential benefits of daylighting are still significant.

- Relatively small areas of illumination glazing are required to reduce substantially the lighting electricity consumption and the energy cost of operating the building.

- Larger areas of illumination glazing are not only not needed, but are undesirable. The undesirable nature of large glazing areas is particularly obvious when proper account is taken of the effect of radiation on the comfort of the building occupants.

- The energy impacts of the solar aperture studied can be divided into the following three categories (listed in order of decreasing importance): (1) lighting electricity reductions (and associated internal load reductions); (2) thermal impacts of solar radiation gains through the glazing; and (3) thermal impacts of conductive gains and losses through the glazing.

BLAST simulations were performed to investigate the sensitivity of the results to a number of daylighting factors. These simulations indicated that:

- The annual consumption of lighting electricity is relatively sensitive to changes in the transmissivity of the glazing (due to dirt accumulation or glazing material changes), but the energy effects of glazing transmissivity changes can be understood in terms of the energy effects of glazing area, which have been thoroughly investigated.
- The annual consumption of lighting electricity is relatively sensitive to the daylighting system luminous efficacy, and further simulations are required to extend the results to interior designs which are significantly different from the one simulated in this study.
- The annual consumption of lighting electricity is relatively insensitive to the effects of snow deposits for the systems examined to date.
- Assigning the same average luminous efficacy to both beam and diffuse solar radiation has very little effect on the annual consumption of lighting electricity for south-facing glazing tilted up sixty degrees from the horizontal or the combination of vertical glazings facing southeast and southwest.
- The use of a simple air temperature control in the BLAST simulations limits the validity of the results for large aperture areas where solar gains affect occupant comfort by impinging directly on occupants and by increasing the mean radiant temperature in the building. A reasonable assumption is that beyond an aperture ratio of 5% the real cooling requirements of the building would be significantly higher than predicted by simulations based strictly on air temperature control.

ACKNOWLEDGMENTS

The authors express their appreciation to Michael Wahlig, Stephen Selkowitz, Frederick Winkelmann, Rudy Verderber, and Francis Rubinstein for serving as technical advisors, and to Carolyn Mangeng for the energy cost calculations.

REFERENCES

1. *Typical Meteorological Year User's Manual: Hourly Solar Radiation-Surface Meteorological Observations, TD-9734,* National Climatic Center, April 1981.

2. J. E. Kaufman, ed., *IES Lighting Handbook,* Illuminating Engineering Society of North America, New York, 1981.

3. W. Place et al., "Roof Apertures in Office Buildings," Lawrence Berkeley Laboratory Report LBL-14790, 1983; also published as "The Predicted Impact of Roof Aperture Design on the Energy Performance of Office Buildings," *Energy and Buildings,* 6 (1984): 361-373.

4. W. L. Carroll et al., "Passive Cooling Technology Assessment: Synthesis Report," Lawrence Berkeley Laboratory Report LBL-15184.

5. W. L. Carroll et al., "Passive Cooling Strategies for Nonresidential Buildings: An Impact Assessment," Lawrence Berkeley Laboratory Report LBL-14558.

6. R. Verderber, "Electronic Ballast Increases Efficiency," *Electrical Consultant* 25 (Nov./Dec. 1981): 22.

7. S. Selkowitz, R. Johnson, R. Sullivan, and S. Choi, "The Impact of Fenestration on Energy Use and Peak Loads in Daylighting Commercial Buildings," Lawrence Berkeley Laboratory Report LBL-15889. Presented at Passive 83, the National Passive Solar Conference, 1983.

8. W. O. Wray, "A Simple Procedure for Assessing Thermal Comfort in Passive Solar Heated Buildings," *Solar Energy* 25, no. 4 (1980).

9. P. O. Fanger, *Thermal Comfort,* McGraw-Hill, 1970.

TABLE 1

Effect of increasing electric lighting efficiency for baseline building

Location	Annual boiler fuel consumption	Annual cooling electricity consumption	Annual lighting electricity consumption	Annual cost savings (\$/m^2)
New York	+8.76%	−24.2%	−40%	6.44
Los Angeles	+21.7%	−19.7%	−40%	3.54
Atlanta	+9.7%	−14.1%	−40%	5.31

TABLE 2

Annual operating energy cost

Location	Power to the lights	Annual costs (\$)	Aperture ratio				
			0%	1.25%	2.50%	5.00%	10.00%
New York	27 W/m^2	Electricity	19397	17261	15836	14858	14716
	(2.5 W/ft^2)	Boiler fuel	2260	2293	2327	2336	2388
		Total	21657	19554	18163	17194	17104
	16 W/m^2	Electricity	13214	11951	11128	10913	10998
	(1.5 W/ft^2)	Boiler fuel	2460	2496	2514	2522	2535
		Total	15674	14447	13642	13435	13533
Atlanta	27 W/m^2	Electricity	9922	8391	7207	6351	6230
	(2.5 W/ft^2)	Boiler fuel	683	745	758	755	756
		Total	10605	9136	7965	7106	6986
	16 W/m^2	Electricity	7103	6014	5422	5013	5062
	(1.5 W/ft^2)	Boiler fuel	801	802	814	813	792
		Total	7904	6816	6236	5826	5854
Los Angeles	27 W/m^2	Electricity	10438	8468	7231	6651	6668
	(2.5 W/ft^2)	Boiler fuel	186	193	193	182	163
		Total	10624	8661	7424	6833	6831
	16 W/m^2	Electricity	7111	5970	5233	4924	5204
	(1.5 W/ft^2)	Boiler fuel	225	227	220	202	178
		Total	7336	6197	5453	5126	5382

TABLE 3

Variation of annual lighting requirements

Issue	Method of simulation	Aperture ratio	Percent variation of annual lighting electricity from baseline building		
			Original simulation	Modified simulation	Change
Variation of roof glazing transmissivity (Dirt, change in glazing optical properties)	Decrease normal transmissivity of daylighting glazing from value of 0.62% to 0.37% (40% decrease)	1.25% 10%	−30.8% −58.4%	−22.8% −54.4%	+8.0% +4.0%
Snow accumulation	Eliminate use of daylight when there is snow (Location = New York)	2.5%	−36.9%	−35.4%	+1.5%
Interior design	Decrease of daylighting system luminous efficacy from 72 lm/W to 50 lm/W	1.25% 5%	−30.8% −51.5%	−23.1% −46.4%	+7.7% +5.1%
Using different luminous efficacies for beam and diffuse radiation	Increase luminous efficacy of diffuse by 20%	1.25%	−30.8%	−30.0%	+0.8%
	Decrease luminous efficacy of beam by 20%	10%	−58.4%	−59.5%	−1.1%

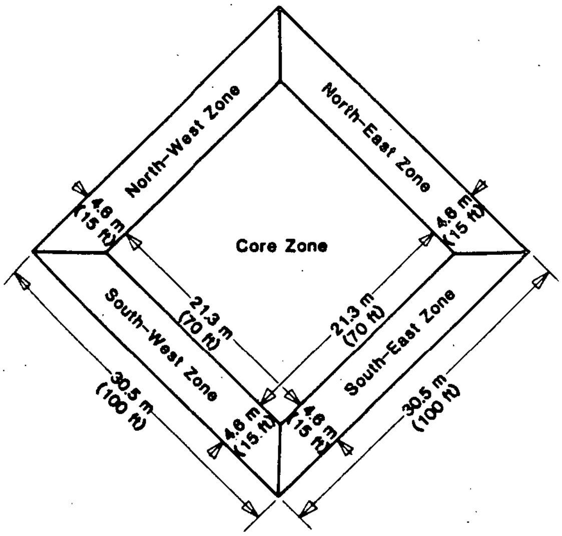

Fig. 1. Prototypical office building schematic floor plan.

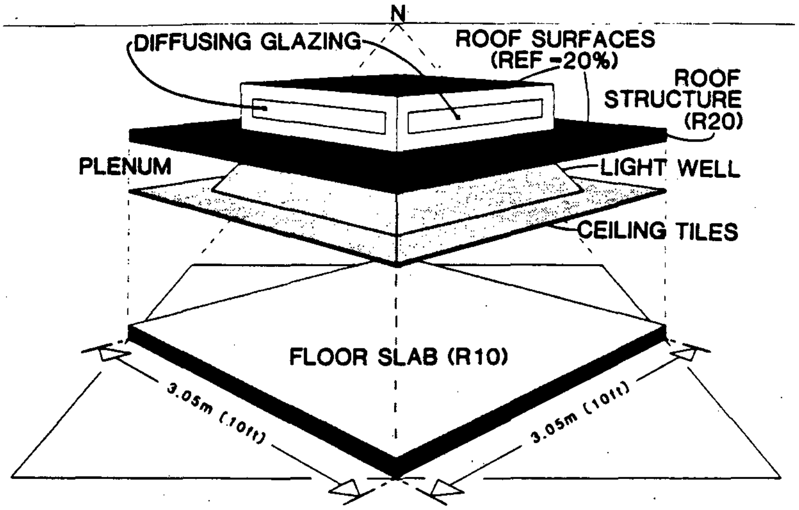

Fig. 2. Typical module from building.

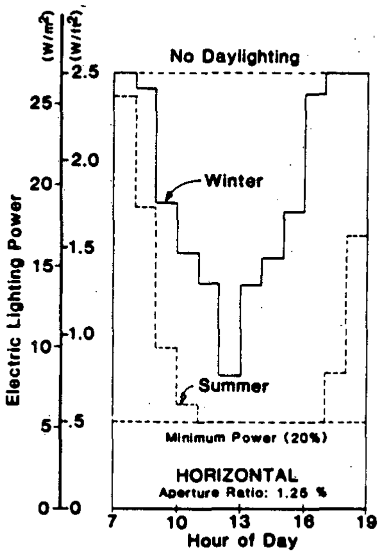

Fig. 3. Hourly variations of electric lighting power.

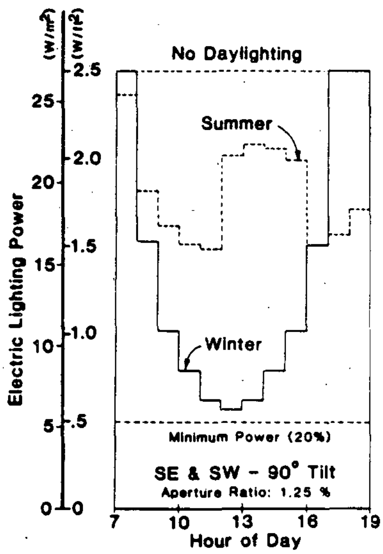

Fig. 4. Hourly variations of electric lighting power.

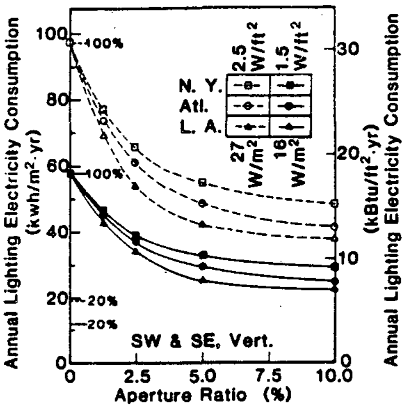

Fig. 5. Annual lighting electricity. The aperture ratio equals ratio of illumination glazing area to building floor area.

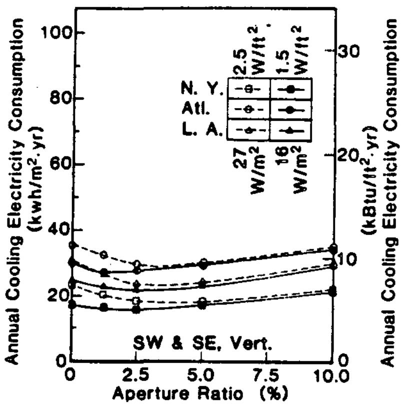

Fig. 6. Annual cooling electricity. The aperture ratio equals ratio of illumination glazing area to building floor area.

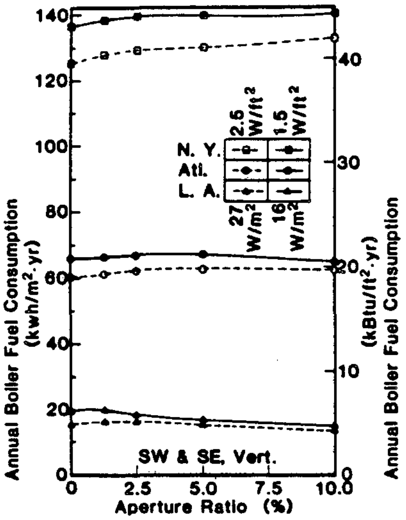

Fig. 7. Annual boiler fuel. The aperture ratio equals ratio of illumination glazing area to building floor area.

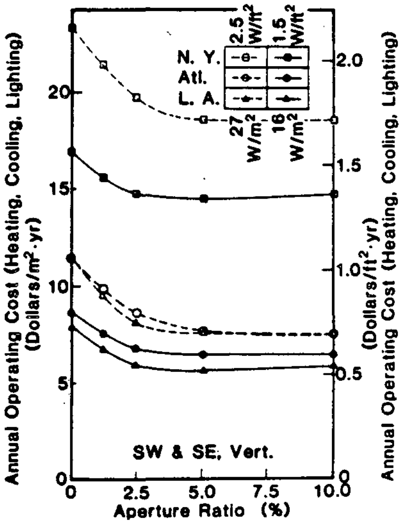

Fig. 8. Annual operating costs. The aperture ratio equals ratio of illumination glazing area to building floor area.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720