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Place, W.

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Wayne Place, Marc Fontoynont, Craig Conner,
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Wayne Place, Marc Fontoynont, Craig Conner, Ronald C. Kammerud,
Brandt Andersson, Fred Bauman, William Carroll, T.C. Howard,#
Atila Mertol, and Tom Webster
Passive Research and Development Group
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

An investigation has been made of potential lighting electricity reductions and associated thermal impacts of replacing electric light with sunlight admitted through rooftop glazing on a single-story, prototypical office building. Experimental scale models have been used to determine the fraction of the solar radiation entering the aperture which reaches the work plane as useful illumination. This information is used in a developmental version of the building energy analysis computer program BLAST-3.0$ to predict reductions in lighting electricity and the impacts on energy consumption for heating and cooling the building. The results indicate that a large fraction of the electricity consumed for lighting a single-story office building can be displaced using modest amounts of glazing in the roof. Also, both heating and cooling energy consumption reductions are possible from a daylighting system, but they are substantially smaller than the potential lighting electricity reductions. The design implications of the results are discussed and future directions for the work are outlined.

INTRODUCTION

Providing illumination in buildings using sunlight as a substitute for electric light is attractive for several reasons: .

- The amount of energy used for lighting is significant; lighting accounts for about one quarter of the total primary energy use in the existing American commercial building stock [1], and the fraction is closer to one-half for office buildings constructed with current-practice thermal envelope integrity and HVAC efficiency [2].
- The solar illumination resource is substantial; during most working hours, the solar illumination incident on a building is several times greater than that required to illuminate the building interior, indicating that it should be possible to design solar apertures that provide enough illumination to offset most of the lighting electricity consumption.
- The luminous efficacy of natural light is generally higher than that of commercially available electric lamps, which means that sunlight has the potential for reducing cooling loads by replacing electric light of higher heat content.
- Reductions in site electricity (for both cooling and lighting) result in substantially larger savings in primary energy, owing to utility generating inefficiencies and network losses.
- Sunlight is plentiful during the hot, clear summer periods when many utilities experience their peak demand, suggesting that there is potential for reducing demand for both cooling and lighting electricity, with consequent demand charge savings for the building owners and the potential for reduced capacity requirements for the utility.

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#Synergetics, Inc., P.O. Box 33422 Method Station, Raleigh, North Carolina 27606.

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

- The electronic equipment which regulates the power to the electric lights in response to the presence of sunlight in the building can also regulate that power in response to the presence of light from the electric lighting system itself; thus, equipment which is a basic part of the daylighting system makes the electric lighting system self-regulating, thereby limiting electricity consumption to the minimum level consistent with the state of maintenance of the system.
- In contrast to seasonal solar applications, such as building space heating, the daylighting system can be used throughout the year, resulting in more rapid payoff of capital equipment costs.
- Well designed daylighting systems can be aesthetically pleasing, thereby increasing the value of the building.

PROBLEM APPROACH

The purpose of this study is to make a preliminary assessment of the potential for reducing energy consumption in a commercial building using simple daylighting apertures constructed with current technology. Although daylight can be admitted through any aperture in the building, achieving the most efficient and effective interior illumination with sunlight requires care in the placement and design of the illumination glazing. To achieve the maximum potential energy savings without reducing illumination effectiveness, the following requirements must be satisfied:

(1) The illumination aperture should be oriented to collect sunlight effectively throughout the diurnal and seasonal cycles. More specifically:

  - An attempt should be made to maximize the solar intensity on the illumination glazing, in order to minimize the required area of glazing, thereby minimizing both the capital cost of the glazing and the deleterious thermal effects of conductive gains and losses through the building envelope.
  - The collection of sunlight during the winter should be comparable to, or exceed, the collection during the summer, so that excess solar gains tend to occur more often during the heating season than during the cooling season.
  - The collection of sunlight during a summer day should be as uniform as possible, in order to meet the building illumination requirements without aggravating the cooling loads.

(2) The sunlight admitted through the apertures must be delivered to the task surface in an efficient and effective manner. In the case of the office building under study, this means delivering as much of the admitted sunlight as possible, as uniformly as possible, to the plane of the desk tops.

(3) The room must be free of any glare which would diminish the effectiveness of the illumination system.

Glazing Orientation

Figures 1 and 2 illustrate the effect of glazing orientation on the collection of beam and diffuse sunlight. Figure 1 shows the light transmitted by double-pane glass in Atlanta during the month of June, while Fig. 2 shows the corresponding data for the month of December. Each figure contains seventeen graphs corresponding to seventeen different combinations of glazing tilt and orientation. The graph at the center of the array corresponds to horizontal glazing. The eight outer graphs correspond to vertical glazings facing north, northeast, east, southeast, south, southwest, west, and northwest--with north at the upper center. The eight graphs surrounding the center square have the same azimuthal orientations as the corresponding outer squares, but are tilted 60 degrees up from horizontal. For each graph, the vertical axis indicates transmitted light in units of thousands of lumens per square meter of glazing (kLux). The hours of the day are listed along the horizontal axis of each graph, with midday in the middle. For each hour, there is a black area which varies in width as a function of the vertical coordinate. The width of the black area at any particular level of transmitted light indicates the frequency of occurrence of that level of transmitted light for the hour, month, and location specified. Hours during which the light transmission is essentially zero have not been indicated. Two continuous lines are drawn through the data on each graph: the dashed lower line indicates the average amount of beam sunlight transmitted during the hour indicated and the solid upper line represents the average total sunlight (beam plus diffuse) transmitted during the hour indicated. Typical Meteorological Year (TMY)* weather tapes were used in preparing these statistical summaries. In converting radiation data on the TMY tapes to sunlight data for the graphics of Figs. 1 and 2, the following constant luminous efficacies were assumed: 105 lumens per watt for beam radi-

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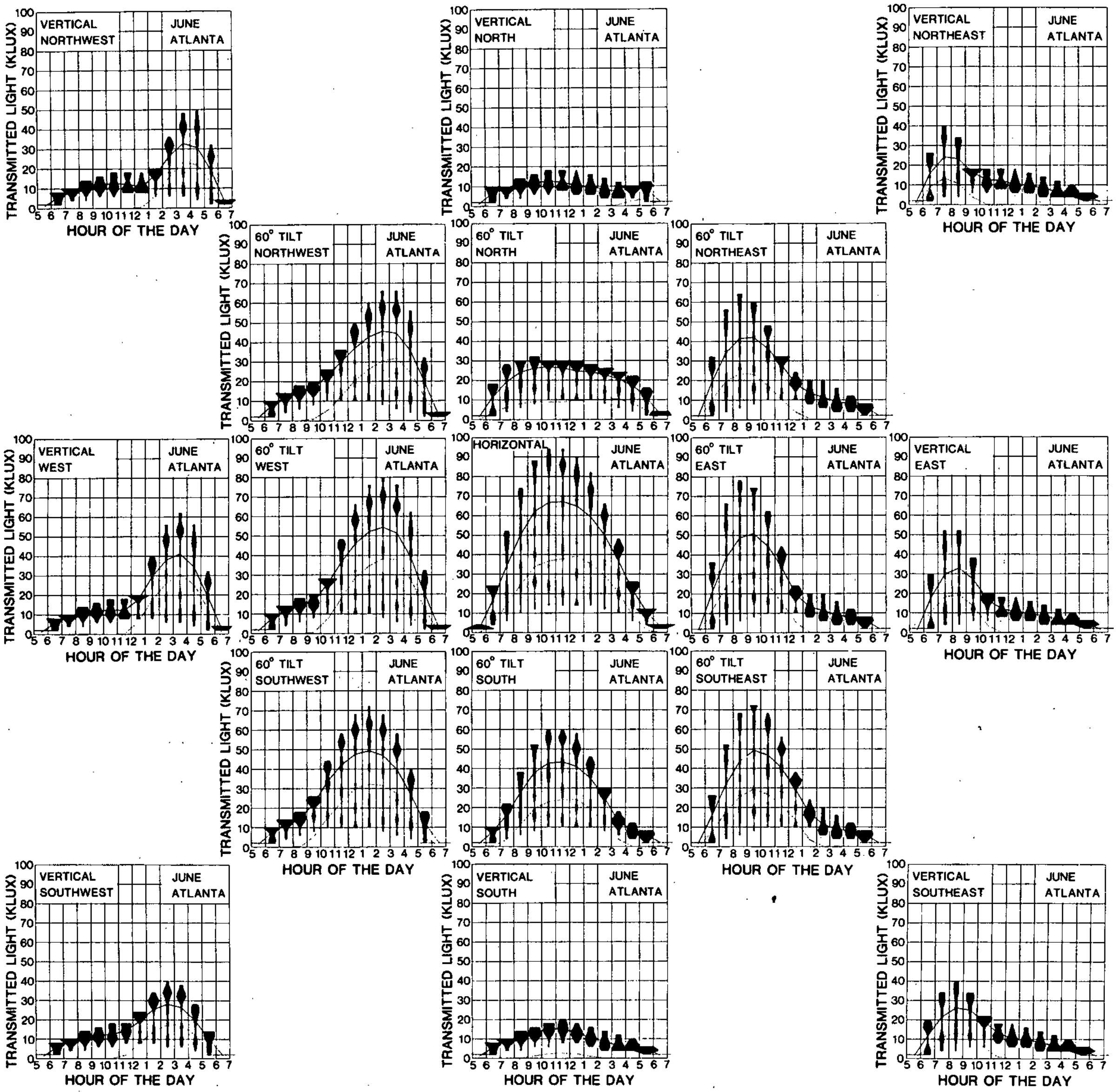
*"Typical Meteorological Year User's Manual: Hourly Solar Radiation - Surface Meteorological Observations," TD-9734, National Climatic Center, April, 1981.



XBL 831-7646

FIG. 1.
THE EFFECT OF GLAZING ORIENTATION ON THE COLLECTION OF BEAM AND DIFFUSE SUNLIGHT

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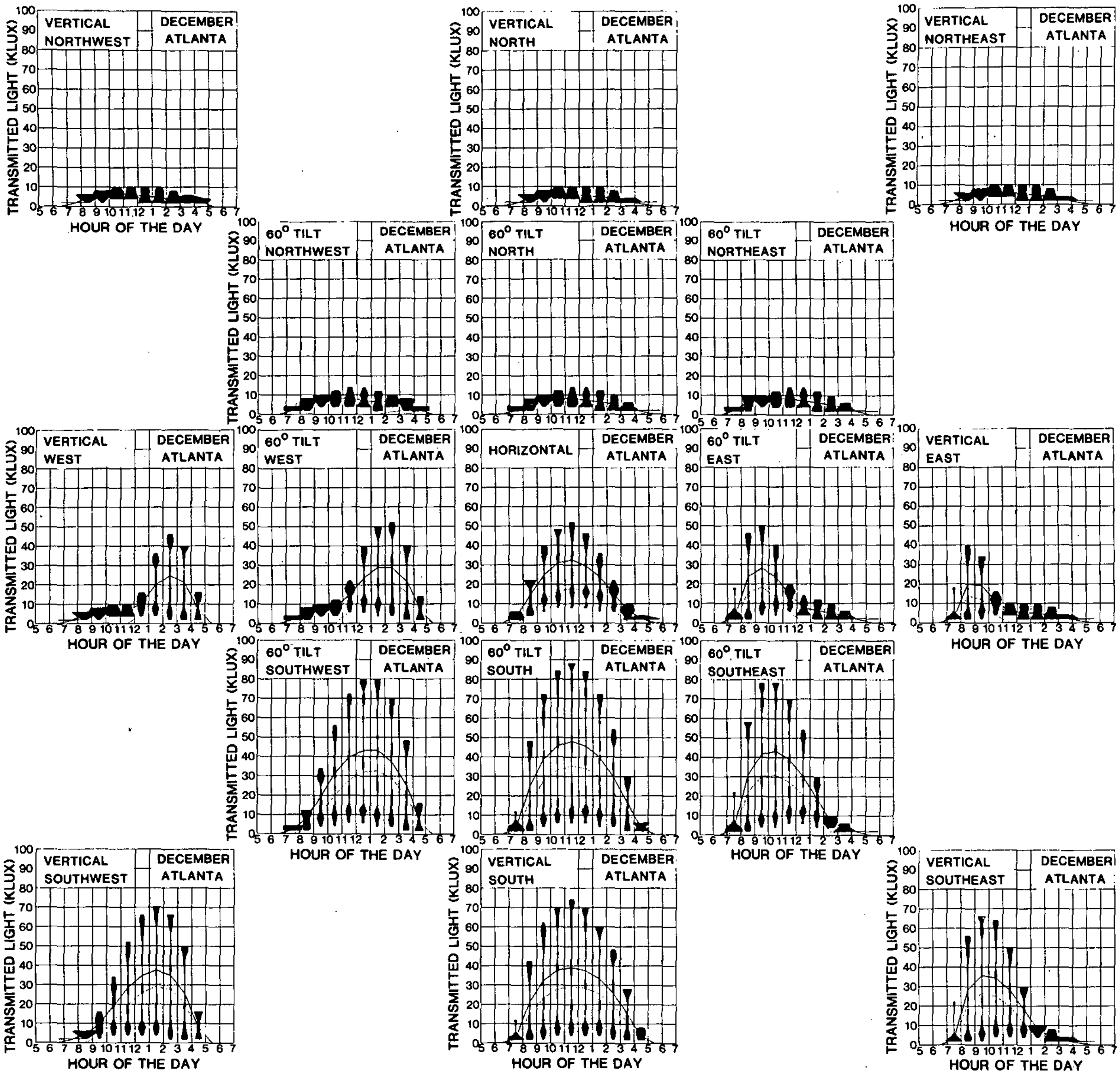

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FIG. 2.

THE EFFECT OF GLAZING ORIENTATION ON THE COLLECTION OF BEAM AND DIFFUSE SUNLIGHT

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ation and 120 lumens per watt for diffuse radiation. Diffuse radiation and diffuse sunlight were both assumed to be uniformly distributed over the sky vault. Ground reflected radiation was not included in the graphic summary. Double-pane, clear glass (without shading) was assumed.

The December data (Fig. 2) indicate that low levels of transmitted daylight make the following orientations seem unpromising: vertical glazing facing northwest, north, or northeast and tilted glazing facing northwest, north, or northeast. Also, low levels of transmitted light during parts of the work day limit the attractiveness of the following orientations: vertical glazing facing west or east and tilted glazing facing west or east. However, the combination of vertical glazings facing west and east and the combination of tilted glazings facing west and east both look attractive because of the potentially high uniformity of collection throughout the day. The approach of using multiple glazing orientations to collect solar illumination is in marked contrast to most conventional solar thermal systems. For solar thermal systems with diurnal storage, the collection surface should be oriented in the single direction which provides the maximum total energy collection for the day. In contrast, the daylighting system should have highly uniform collection throughout the day, particularly during the cooling season, since there is no storage; periods of low collection fail to provide the needed illumination and periods of high collection can aggravate the building cooling loads. For the daylighting system, some sacrifice in total light collection and building envelop thermal resistance can be justified for the sake of greater uniformity of light collection. A comparison of June data (Fig. 1) and December data (Fig. 2) indicates that substantially more sun is collected during the summer than during the winter for the following glazing orientations: vertical facing west, tilted facing west, horizontal, tilted facing east, and vertical facing east. The thermal disadvantages of collecting more solar radiation during the summer than during the winter diminish the attractiveness of these orientations and combinations of these orientations. Tilted glazing facing southwest or southeast is also limited by poor light collection during parts of the day. However, combinations of these two orientations look extremely attractive, because the transmitted sunlight for each orientation is highly uniform throughout the year (with slightly higher transmission during the winter) and because the combination of orientations has the potential for highly uniform collection throughout the day. A combination of vertical glazing facing southwest and southeast is also quite attractive, although the summer collection efficiency may be lower than desirable. Vertical glazing facing south has even lower summer collection efficiency. Of the glazing orientations shown, the best single orientation from a point of view of high transmitted light levels and low seasonal variation is tilted, south-facing. The major disadvantage of tilted, south-facing glazing is the large diurnal variation in the transmitted light.

In the current study, two glazing systems were examined: 1) south-facing glazing tilted up sixty degrees from the horizontal and 2) a combination of east-facing and west-facing glazing tilted up sixty degrees from the horizontal. Future studies will examine the following systems: vertical glazing facing south; a combination of vertical glazings facing southeast and southwest; a combination of tilted glazings facing southeast and southwest; and horizontal glazing, which is of interest because of its widespread use.

Light Distribution within the Building

Requirement (1), that the aperture be oriented to effectively collect sunlight, was addressed in the previous section. Both requirements (2) and (3) can be addressed by careful selection of:

- the aperture position relative to the occupied space;
- the configuration and surface treatment of materials around the aperture; and
- the properties of the glazing material.

Avoiding glare is important. It is possible for sunlight to increase the electric lighting illumination levels required to achieve a satisfactory luminous environment. Such an effect is likely to be created in any situation where beam sunlight is allowed to slash through the work plane, thereby creating extreme contrast in the immediate field of view of the person engaged in the primary work task. A common response to this kind of glare is to close any drapes that are available or to turn up the lights in order to even out the illumination and reduce the contrast. In fact, with beam sunlight on the work plane, the level of electric lighting necessary to reduce the contrast to acceptable levels may be much higher than the level required to produce an acceptable illumination intensity in a situation where the high contrast does not exist. Because of the glare, it is difficult to quantify the illumination benefit of unfiltered, direct-beam sunlight incident on the work plane. For the tilted, south-facing aperture under consideration, the use of diffusing glazing or reflective surfaces is essential in order to prevent the penetration of beam sunlight to the work plane. For simplicity, diffusing illumination glazing is assumed in this study.

To avoid discomfort glare in the prototype building under study, a clear distinction has been drawn between view glazing and illumination glazing. View glazing is by definition something through which the building occupants are expected to look. To avoid visual discomfort, light admitted by the view glazing should not be very intense. If the view glazing is bright enough to provide illumination efficiently, then there is a significant likelihood it will cause discomfort when viewed. Another problem with trying to use view glazing for illumination purposes is the fact that view glazing is normally set low in the wall where the light admitted through the glazing impinges on most parts of the work plane at an unfavorably low angle. Finally, view glazing must be optically clear, which means that beam sunlight admitted through the view glazing can cause glare. By contrast, an illumination aperture should admit intense light in order to maximize the illumination benefits per area of glazing. It should also disperse light to avoid high contrast in the space and provide light from a sufficient height that reasonably intense and uniform illumination can be achieved on most of the work plane.

Requirements (2) and (3) can be satisfied in a single-story building (or on the top floor of a multi-story building) by:

- using highly diffusing, closely spaced, illumination apertures in the roof, thereby producing uniform illumination on the work plane and minimizing visual discomfort by keeping the light sources above the normal field of view of the building occupants (see Fig. 3);
- using reflective view glazing in the walls, thereby eliminating a bright source in the field of view of the occupants;
- using light-colored interior surfaces, thereby increasing the amount of light reaching the work plane from the apertures and reducing contrasts between the light sources and opaque surfaces within the space.

This roof aperture system has light quality comparable to the electric lighting system which it is replacing, so that all the design criteria which apply to the electric lighting system (e.g., required intensity and uniformity of light in the work plane) are equally applicable to the daylighting system. Consequently, there are no qualitative deficiencies of the daylighting system which would require that we discount its quantitative illumination contribution when making comparisons to the electric lighting system.

This paper presents BLAST estimates of the lighting electricity reductions and heating and cooling energy impacts of daylighting in a single-story office building designed according to the rules outlined above. Future papers will deal with the energy implications of daylighting schemes in multistory buildings.

BUILDING DESCRIPTION

The floor plan of the building chosen for analysis is shown in Fig. 4. The building is square, with a length and width of 30.5 meters (100 feet) and a floor area of 930 square meters (10,000 square feet). The external walls have a height of 3.66 meters (12 feet) and contain view glazing with a height of 1.07 meters (3.5 feet) extending the full length of each wall. The view glazing is double-pane with a solar transmittance of 15%. For simulation purposes, the building is divided into five thermal zones: four perimeter zones and one larger core zone. A more complete description of the building's thermal envelope, internal loads, operating schedules, and HVAC system can be found in Ref. [2].

The daylighting system consists of roof monitors fitted with double-pane glass tilted 60 degrees up from the horizontal. Two glazing configurations have been examined: 1) all the glazing facing south or 2) the glazing area divided equally between east and west. In both configurations, the glazing was assumed to extend the full width (or length) of the building. Figure 3 is a sectional view of the south-facing configuration, showing the roof structural elements and the arrangement of ducts and electric light fixtures. The illumination glazing consists of two panes of 0.625 centimeter (0.25 inch) thick glass with a combined normal solar transmissivity of 0.624. The inner glass pane is assumed to be an excellent diffuser. Simulations were performed for both configurations for a range of aperture ratios from 1.25% to 10.0%. (Aperture ratio is defined here as the ratio of the total illumination glazing area to the total building floor area.) Both experiments and analysis have been used to estimate the appropriate spacing between roof monitors for achieving satisfactory uniformity of the illumination on the work plane. A future report will describe the experimental model and present the illumination measurements.

The electric lighting system consists of standard, cool-white, fluorescent lamps in diffusing luminaires mounted at ceiling level between the roof monitors. The Illumination Engineering Society (IES) room cavity calculation [3] was used to determine the number and spacing of lamps and fixtures required to supply the design illumination level of 540 Lux (50 footcandles) on the work plane. From this calculation, an electric lighting power level of about 27 Watts per square meter (2.5 watts per square foot) was deduced. (The impact of electric lighting efficiency on the energy savings potential of the daylighting

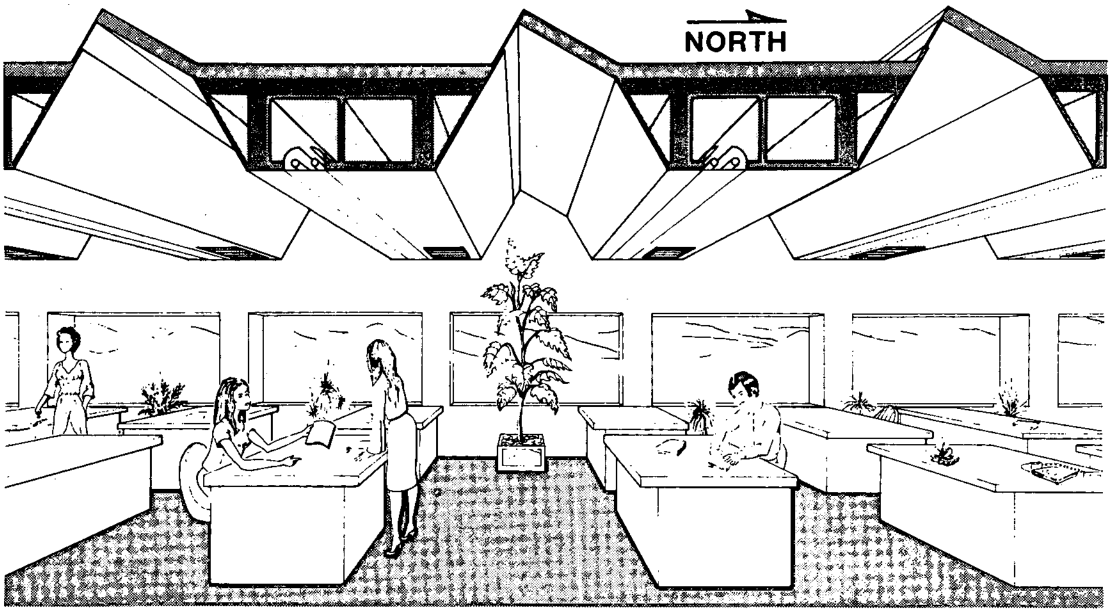

FIG. 3. PERSPECTIVE SECTION OF PROTOTYPE COMMERCIAL BUILDING.

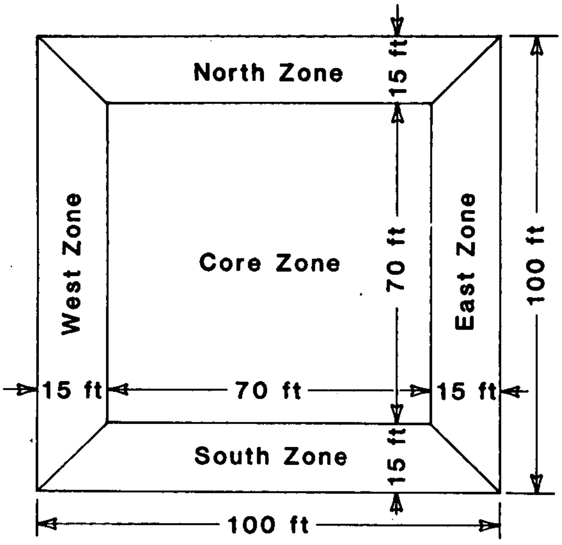

FIG. 4. SCHEMATIC FLOOR PLAN OF PROTOTYPE COMMERCIAL BUILDING.

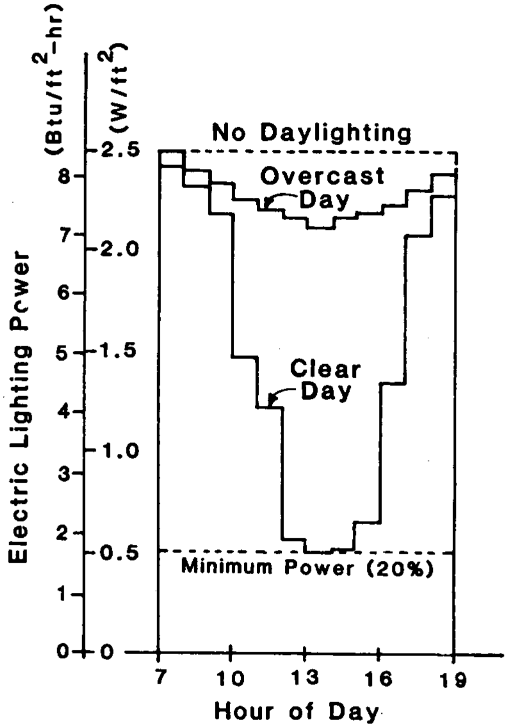

FIG. 5. HOURLY VARIATIONS OF ELECTRIC LIGHTING POWER.

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system is examined in another paper [4].) Sixty percent of the power which the electric lighting system introduces to the building is assumed to return directly to the building cooling system via insulated return air ducts. The lighting hardware and the daily 12-hour operating schedule were chosen as representative of current practice rather than the current state of the art. Controls are provided to adjust the electric lighting power level in response to the presence of sunlight, thereby expending no more electric power than necessary to maintain 540 lux on the work plane.

ANALYTIC METHOD

For each hour and thermal zone, BLAST-3.0 calculates: thermal exchanges between the environment and external surfaces of the building; solar radiation absorbed on external surfaces; conductive gains and losses through opaque elements of the building structure (using response factors to account for mass effects); radiant exchanges between interior surfaces; convective exchanges between the zone air and the associated interior surfaces; radiant heat transferred to interior surfaces from internal heat sources (lights, equipment, and people); convective heat transferred to the zone air from internal heat sources; and solar gains through all glazing. These calculations are based on detailed descriptions of the building elements and weather contained on TMY weather tapes.

In the BLAST daylighting simulation, it is assumed that:

(i) Power to the electric lights is reduced linearly in response to the usable amount of sunlight entering the illumination glazing each hour.

(ii) Electric lighting illumination on the work plane is directly proportional to the power supplied to the electric lights.

(iii) Power to the lights is adjusted to maintain the combined illumination (solar plus electric) at a constant level of fifty footcandles on the work plane (unless constrained by assumption (iv) below).

(iv) Power to the lights cannot be reduced below 20% of full power. (At the time this study was initiated, this assumption was consistent with prevailing limitations of the technology for continuous control of fluorescent bulbs. Future papers will treat the potential benefits derivable from improved continuous controllers or combinations of continuous controllers and on-off switches.)

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 the solar radiation entering the roof apertures, by comparing the effective "System Luminous Efficacies" (SLE) for the electric lighting system and the daylighting system. We define the Electric System Luminous Efficacy (ESLE) as the ratio of useful electric light on the work plane (in lumens) to the total power introduced to the building by the electric lighting system (in watts). Similarly, we define the Solar System Luminous Efficacy (SSLE) as the ratio of useful daylight on the work plane to the total power emanating from the interior surface of the illumination glazing. For this study, ESLE was set at 20 lumens per watt, based on information from the IES Handbook [3]. (The ESLE can be obtained by multiplying the following quantities: the initial lumens per watt from the combination of lamps and ballast; the lumen depreciation factor for the lamps; the dirt depreciation factor for the luminaires; and the coefficient of utilization for the combination of luminaires and room cavity.) The SSLE of the roof monitors was set at 72 lumens per watt, based on tests of a scale model of the building. Knowledge of the ESLE and the SSLE allows BLAST to perform a trade-off between the two light sources. The reduction in power to the electric lights is equal to the solar power admitted to the building through the roof glazing multiplied by the SSLE divided by the ESLE. BLAST keeps track of the hourly, monthly, and annual consumption for lighting electricity, and also automatically accounts for the thermal effects of reduced power to the lights.

RESULTS

A number of annual and design-day BLAST simulations of the prototype building were performed with TMY weather data from New York, Atlanta, and Los Angeles. The results from some of these simulations are presented in Figs. 5-13. The information in Figs. 5-9 pertain only to south-facing illumination glazing. Figures 10-13 compare the results for south-facing glazing to the results for the combination of east-facing and west-facing glazing.

Figure 5 shows the hourly variations in lighting requirements in Atlanta on July 10th for two design conditions: one clear day (maximum normal beam = 877 W/m^2, maximum horizontal diffuse = 118 W/m^2) and one overcast day (maximum normal beam = 15 W/m^2, maximum horizontal diffuse = 120 W/m^2). South-facing glazing with an aperture ratio of 1.25% was used for both simulations. The plots indicate that the illumination aperture works much better near midday than in the morning and afternoon--a result of diurnal variations of solar radiation direction and intensity, reinforced by the directional selectivity of the south-facing illumination glazing. As indicated earlier, the diurnal variation in the direction of beam sunlight can be addressed by using glazing of more than one orientation.

In Fig. 6, the annual energy consumption for lighting electricity (at the site) is plotted as a function of the aperture ratio for south-facing glazing. (The consumption of primary energy by the utility to generate power would be on the order of three to four times higher than the consumption at the site, owing to generating inefficiencies and utility network losses.) The units on the vertical axis are kBtu per square foot of building floor per year, an unconventional electrical unit which was chosen to allow easy comparison with predictions of boiler fuel consumption. For small aperture ratios (0 to 2.5%), the electric consumption goes down rapidly with each additional increment of aperture area. At larger aperture ratios (above 2.5%), the electric consumption goes down less rapidly with each additional increment of aperture area, indicating the diminishing number of hours during which additional sunlight can have a beneficial impact. The curve approaches asymptotically toward a lower limit which is imposed by the 20% lower limit on electric lighting power and by the daily 12-hour lighting schedule, which includes many hours when there is little or no sunlight available. The reductions in lighting electricity were greater in Atlanta than New York, because the lower latitude of Atlanta results in more availability of sunlight, particularly during the winter months when short days and cloudy conditions seriously limit the effectiveness of daylighting in New York. The greatest reductions in lighting electricity were observed in Los Angeles, which has almost exactly the same latitude as Atlanta, but clearer weather.

In Fig. 7, annual energy consumption for cooling electricity at the site (fans plus direct expansion cooling unit) is plotted as a function of aperture ratio, for south-facing glazing. For small aperture ratios, cooling electricity consumption decreases with increasing aperture ratio for all three locations. At small aperture ratios, all of the admitted sunlight is effective in displacing electric light of higher heat content, thereby reducing cooling loads. For larger aperture ratios, the excess solar gains outweigh the cooling benefits associated with the higher luminous efficacy of the sunlight, and the cooling loads increase with increasing aperture ratio.

In Fig. 8, the annual energy consumption of boiler fuel is plotted versus aperture ratio, for south-facing glazing. For small aperture ratios, boiler fuel consumption increases with increasing aperture ratio, resulting from the replacement of electric light with sunlight of lower heat content. This apparently negative effect is of little consequence, since the effect is small and boiler fuel is a much cheaper and more efficient source of heat than dissipating electric power in lamps. For large aperture ratios, the excess solar gains dominate the effect of the sunlight's higher luminous efficacy, and the boiler fuel consumption decreases with increasing aperture ratio. In all three locations, and at large aperture areas, boiler fuel consumption is less sensitive than cooling electricity consumption to the aperture ratio, since the net heat gain through the glazing is lower during the winter. Figures 6, 7, and 8 suggest that movable insulation could produce significant reductions in energy consumption for lighting and cooling, and some reductions in energy consumption for heating, if the insulation were controlled to: (1) limit summer gains to the level needed for illumination and (2) maximize winter gains when heating is required and the glazing is a net gainer.

Figure 9 shows the annual operating costs which have been computed for each location using local billing policies for gas and electricity, including peak demand charges.* In all three locations, costs decrease rapidly with increasing glazing area, up to an aperture ratio between 2% and 3%. Reductions in both lighting and cooling electricity consumption contribute to these utility cost decreases (see Figs. 6 and 7). Beyond an aperture ratio of 3%, increases in cooling electricity dominate decreases in lighting electricity, and the costs increase gradually with aperture area. The shapes of the energy cost curves in Fig. 9 were influenced by two important assumptions in the study:

(1) The COP of the cooling system may have been somewhat higher than appropriate when compared to the general quality of the other energy systems in the building. (Unlike the electric lighting system, no account was taken of cooling system performance degradation over time.)

(2) The thermal control in the building was based strictly on air temperature, which by itself is not a sufficient indicator of occupant comfort.

If the simulations were rerun with a lower COP for the cooling system, the cooling consumption curves would rise more rapidly for large aperture ratios. Furth-

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*The rate schedules for the utilities serving each of the three cities were obtained from the Johnson Environmental and Energy Center at the University of Alabama. No demand ratchet was used in the cost calculation.

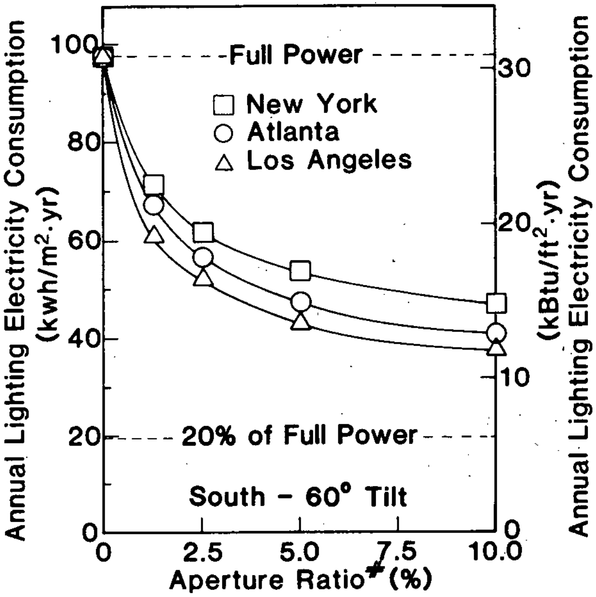

FIG. 6. ANNUAL LIGHTING ELECTRICITY

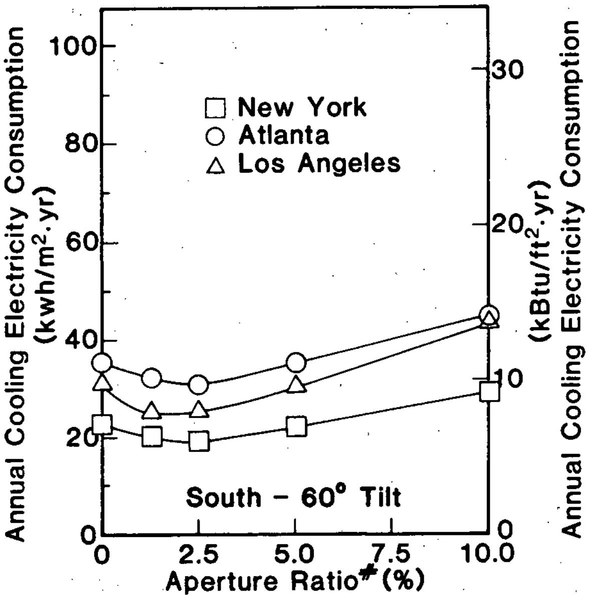

FIG. 7. ANNUAL COOLING ELECTRICITY

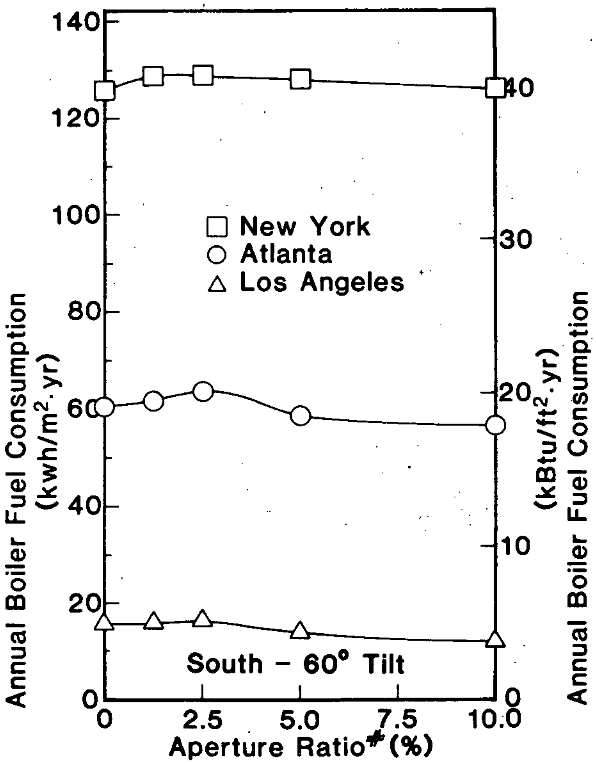

FIG. 8. ANNUAL BOILER FUEL

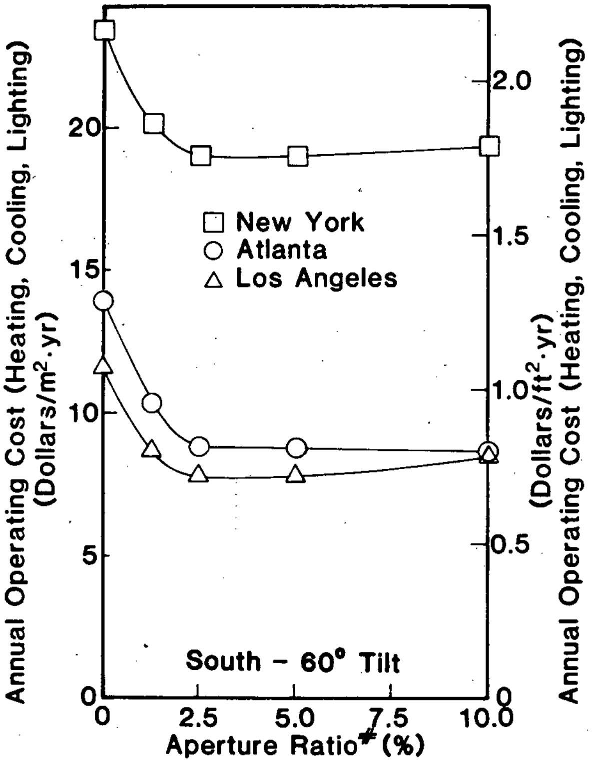

FIG. 9. ANNUAL OPERATING COSTS.

*Aperture Ratio Equals Ratio of Illumination Glazing Area to Building Floor Area

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ermore, the peak-power demand charges, which are highly sensitive to cooling loads [2], would also rise rapidly at large aperture ratios. Both effects would tend to make the cost curves in Fig. 9 rise more rapidly than indicated after the minimum cost point. The assumption that control of the building thermal conditions was based solely on air temperature also tends to underestimate the rate of rise of the cost curves for aperture ratios beyond the minimum. In a real situation, the larger aperture ratios would produce higher mean radiant temperatures in the building and would also cause more solar radiation to impinge directly on the occupants of the illuminated space. The likely effect would be that the occupants of a building with a large aperture ratio would want a lower air temperature to compensate for the warmer radiant environment. Lower air temperatures would result in higher cooling loads and higher costs than indicated by the results presented. It is likely that the minimum energy cost would still occur between 2% and 3% aperture ratio, but the shape of the curve would change in a manner to make the minimum more pronounced.

In Fig. 10, annual energy consumption for lighting electricity at the site is plotted as a function of aperture ratio for both south-facing glazing and the combination of east-facing and west-facing glazing. For the combination, the aperture ratio is still defined as the total area of illumination glazing to the total floor area of the building, and it is assumed that the total area of illumination glazing is equally divided between east and west. The results presented for both configurations are for Atlanta, Georgia. For small aperture ratios, the south-facing glazing displaces more lighting electricity. This result is not surprising, since for small aperture ratios all of the accepted light is useful in displacing electric light, and the south-facing system has all of its glazing oriented in the direction which collects the maximum amount of sunlight over the course of the day. For larger aperture ratios, the combination of east-facing and west-facing glazing displaces more lighting electricity. This is a result of the superior collection of the combination of east-facing and west-facing glazing during early morning and late afternoon hours in the summer. Monthly performance information from BLAST indicates that in December the lighting electricity consumption is lower for the south-facing glazing than for the combination of east-facing and west-facing glazing for all aperture ratios, with the most pronounced difference occurring at small aperture ratios. In June the lighting electricity consumption is lower for the combination of east-facing and west-facing glazing than for the south-facing glazing, with the most pronounced difference occurring at large aperture ratios. For small aperture ratios, the superior wintertime collection of the south-facing glazing dominates the slightly superior summertime collection of the combination of east-facing and west-facing glazing, resulting in lower annual lighting electricity consumption for the south-facing glazing. For large aperture ratios, the superior summertime collection of the combination of east-facing and west-facing glazing dominates the slightly superior wintertime collection of the south-facing glazing, resulting in lower annual lighting electricity consumption for the combination of east-facing and west-facing glazing.

In Fig. 11, annual cooling electricity consumption at the site (fans plus DX cooling unit) is plotted as a function of aperture ratio for both south-facing glazing and the combination of east-facing and west-facing glazing. As before, the results presented for both configurations are for Atlanta. At all aperture ratios, the cooling electricity consumption is higher for the south-facing glazing than for the combination of east-facing and west-facing glazing. The differences are most pronounced at large aperture ratios. These results can be understood in terms of the summertime collection of solar radiation by the two glazing systems. For small aperture ratios, the poor morning and afternoon collection of sunlight by the south-facing glazing results in higher electric lighting levels, with consequent higher cooling loads. For large aperture ratios, the extremely effective midday collection of solar radiation by the south-facing aperture results in excessive solar gains which aggravate the cooling loads even more.

In Fig. 12, annual boiler fuel consumption is plotted as a function of aperture ratio for both south-facing glazing and the combination of east-facing and west-facing glazing. For small aperture ratios, the boiler fuel consumption is slightly higher for the south-facing glazing. For large aperture ratios, the boiler fuel consumption is substantially higher for the combination of east-facing and west-facing glazing. Both these results are explained by the superior wintertime collection of the south-facing glazing. For small aperture ratios, where all the collected sunlight is effective in displacing electric light, the superior collection of the south-facing glazing causes the displacement of more electric light with sunlight of lower heat content, with consequent increase in the use of boiler fuel to heat the building. At larger aperture ratios, the superior collection of the south-facing glazing provides more solar gains in excess of the lighting requirements of the building, with consequent reduction in the use of boiler fuel for heat.

In Fig. 13, the total annual energy cost is plotted as a function of the aper-

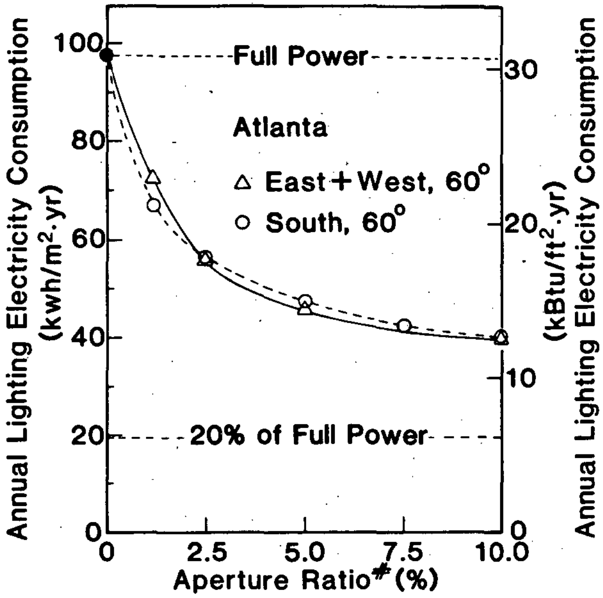

FIG. 10. ANNUAL LIGHTING ELECTRICITY

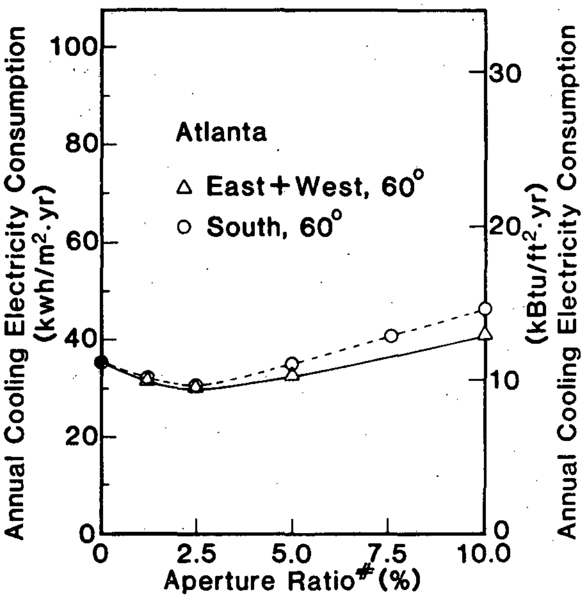

FIG. 11. ANNUAL COOLING ELECTRICITY

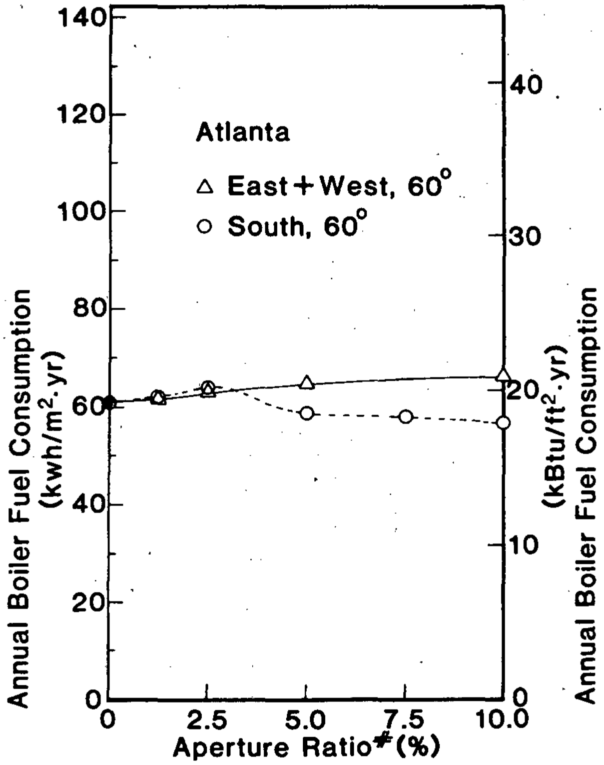

FIG. 12. ANNUAL BOILER FUEL

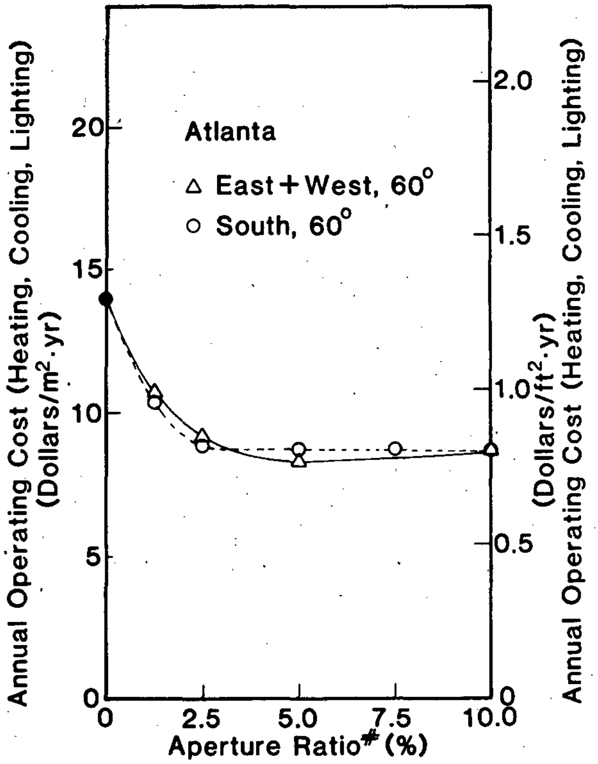

FIG. 13. ANNUAL OPERATING COSTS.

#Aperture Ratio Equals Ratio of Illumination Glazing Area to Building Floor Area

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ture ratio for both south-facing glazing and a combination of east-facing and west-facing glazing. For small aperture ratios (up to about 3 or 4%), the south-facing glazing has the lower annual energy cost. This results from the fact that the south-facing apertures have all of their glazing facing in directions where the solar radiation tends to be strong. For larger aperture ratios, the combination of east-facing and west-facing glazing has the lower annual energy cost. This results primarily from the fact that, for large aperture ratios, the south-facing glazing aggravates cooling electricity consumption by collecting excess solar radiation at midday during the summer. A secondary reason is that, even at large aperture ratios, the displacement of lighting electricity in the morning and afternoon during the summer is greater for the combination of east-facing and west-facing glazing, because those orientations collect more effectively during those hours when the solar radiation is weak. The lowest minimum in total annual energy cost is achieved by the combination of east-facing and west-facing glazing, at an aperture ratio between 5.0 and 6.0%. However, the minimum total annual energy cost for the south-facing glazing is only slightly higher than for the combination of east-facing and west-facing glazing, and it occurs at a substantially lower aperture ratio (between 2.5 and 3.0%), suggesting that south-facing glazing might be the more cost-effective system.

CONCLUSIONS

(1) A large fraction of the electricity consumed for lighting a single-story office building can be displaced using modest amounts of glazing to admit sunlight through the roof.

(2) Both cooling and heating energy consumption reductions are possible from a daylighting system, but they are much smaller than the potential lighting electricity reductions.

(3) Potentially deleterious thermal effects cannot be ignored in the proper design of a daylighting system.

(4) For south-facing, tilted illumination glazing, the total annual energy cost to operate the prototype building in each climate decreases rapidly with increasing glazing area, up to an aperture ratio between 2% and 3%, beyond which the cost increases gradually.

(5) The total annual energy cost can be slightly lower for a combination of east-facing and west-facing glazing than for south-facing glazing, but substantially more glazing is required to achieve these energy cost benefits.

(6) Movable insulation or external shades, which properly control the solar gains and/or thermal transfer through the illumination glazing, could enable the daylighting system to eliminate most of the lighting electricity consumption while significantly reducing the cooling electricity consumption.

(7) In contrast to typical solar thermal systems having diurnal storage capacity, a single orientation of collection surface may not be the preferred configuration for daylighting systems.

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TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
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