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Author
Place, W.

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Lawrence Berkeley Laboratory

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W. Place, P. Coutier, M. Fontoynont, R. Kammerud,
B. Andersson, F. Bauman, W.L. Carroll, M. Wahlig,
and T.L. Webster

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DISCLAIMER

THE IMPACT OF GLAZING ORIENTATION, TILT, AND AREA ON THE ENERGY PERFORMANCE OF ROOF APERTURES*

Wayne Place, Pascal Coutier, Marc Fontoynont, Ron Kammerud,
Brandt Andersson, Fred Bauman, William L. Carroll,
Michael Wahlig, and Thomas L. Webster
Building Systems Analysis Group
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

September 1986

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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 the systems analysis and applications research area concerning the evaluation of daylighting systems in residential and nonresidential buildings.

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ABSTRACT

An investigation has been made of potential reductions in electric lighting and associated thermal impacts of replacing electric light with sunlight admitted through rooftop glazing (i.e., roof monitors and skylights) on a single-story, prototypical office building. Experimental scale models have been used to determine the fraction of the solar radiation entering the aperture that 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 impact on energy consumption for heating and cooling the building. The results indicate that a large fraction of the electricity consumed for lighting in a single-story office building can be displaced using modest amounts of glazing in the roof. Reductions in both heating and cooling energy consumption are also possible using a roof aperture system in conjunction with proper control of the electric lights, but the potential heating and cooling benefits are substantially smaller than the potential reductions in electric lighting. The design implications of the results are discussed and future directions for the work are outlined.

INTRODUCTION

Approximately 5% of the United States' primary energy is consumed providing illumination in commercial and industrial buildings. Approximately another 3% is consumed for cooling these buildings. Furthermore, buildings account for a substantial fraction of the peak electricity demand on U.S. utilities (McMahon et al. 1980; ASHRAE 1985). All of these issues can be beneficially affected by using sunlight as a substitute for electric light to illuminate buildings. Daylighting buildings is attractive for several reasons.

1. During most working hours, the solar illumination on a building is several times greater than that required to illuminate the interior, indicating that it would be possible to design solar apertures that provide enough illumination to offset most of the lighting electricity consumption.

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*Present address if not at Lawrence Berkeley Laboratory: Wayne Place, Architecture Dept., North Carolina State University, Raleigh, NC 27605; Pascal Coutier, 38 rue Jean Arland, 31500 Toulouse, France; Marc Fontoynont, ENTPE/LASH, Lyon, France; Fred Bauman, Building Science Laboratory, Architecture Dept., University of California, Berkeley, CA 94720; and Thomas L. Webster, Energyline Corp., 26500 Corporate Ave., Hayward, CA 94545.

[†] BLAST (Building Loads Analysis and System Thermodynamics) is in the process of being trademarked by the Construction Engineering Research Laboratory, U.S. Department of the Army, Champaign, Illinois. BLAST is also in the public domain.

2. The luminous efficacy of sunlight is generally superior to that of commercially available electric lamps with acceptable color rendering, which means that sunlight has the potential for reducing building cooling loads by replacing electric light of higher heat content.

3. 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 lighting and cooling electricity, with consequent demand charge savings for the building owners and reduced capacity requirements for the utility.

Roof aperture systems in particular are an interesting daylighting technique because:

1. The potential impact is very large—on the order of 50% of the commercial building floor area in the United States is in single-story buildings or the top floor of multistory buildings (DOE 1983).

2. The solar exposure is generally good for sprawling single-story buildings or for the top floor of multistory buildings.

3. Roof apertures allow a choice of glazing orientation and tilt, which is crucial in using passive techniques to regulate the flow of sunlight into the building, i.e., in compensating for seasonal and diurnal variations in the direction and intensity of solar radiation.

4. Roof apertures have both new and retrofit potential.

5. The illuminance can be made highly uniform by using closely spaced apertures.

6. The quality of lighting can be very high, since (1) the source of light can be located up out of the primary field of view, thereby avoiding most of the visual discomfort associated with viewing the light source, and (2) diffusing glazing (or other optical treatments) can be used to disperse the light around the space, thereby avoiding the extreme contrast associated with allowing beam sunlight to impinge on the work surface.

7. The energy payback potential is quite high—as will be demonstrated in the results section of this paper.

This study assesses the potential for reducing energy consumption in a commercial building using simple roof apertures constructed with current technology. It also provides an information base that designers can use in the process of selecting a roof aperture configuration.

BUILDING DESCRIPTION

The floor plan of the building chosen for analysis is shown in Figure 1. The building is square, with a length and width of 100 feet (30.5 meters) and a floor area of 10,000 square feet (930 square meters). For simulation purposes, the building is divided into five thermal zones: four perimeter zones with a depth of 15 feet (4.57 meters) and one larger core zone with a length and width of 60 feet (18.3 meters).

The external walls have a height of 12 feet (3.66 meters) and contain view glazing with a height of 3.5 feet (1.07 meters) extending the full length of each wall. The view glazing is double-pane with a solar transmittance of 15%. The opaque roof is assumed to have a thermal conductance of 0.05 Btu/hr ft^2 F = 0.284 Kw/m^2 °C and the opaque walls a thermal conductance of 0.091 Btu/hr ft^2 F = 0.515 Kw/m^2 °C. The floor is 4-inch-thick (10.2-centimeter-thick) concrete on top of 2-inch-thick (5.1-centimeter-thick) rigid insulation with a thermal conductance of 0.11 Btu/hr ft^2 F = 0.630 Kw/m^2 °C. The entire floor area of the four perimeter zones is covered with carpet and half the floor area of the core zone is covered with carpet. The interior partitions are assumed to be gypboard on light frame construction. Infiltration rates were assumed to be 1.5 air changes per hour in the perimeter zones and 0.5 changes per hour in the core zone. The building is assumed to sit on a flat site with no significant obstructions to solar radiation.

The normal occupancy level is assumed to be one person per 175 square feet (16.3 square meters) of floor area. Occupancy is assumed to be at 100% of this value between 8 a.m. and 5 p.m., Monday through Friday; at 50% between 5 p.m. and 6 p.m., Monday through Friday; and 0% otherwise. The sedentary metabolic rates per person are assumed to be 250 Btuh (73 watts) sensible and 200 Btuh (58 watts) latent (ASHRAE 1985). Internal heat generated from office equipment is assumed to be 1.20 Btuh/ft^2 (3.77 W/m^2).

The air-handling system is variable air volume (VAV) with a direct-expansion, vapor-compression chiller operating with a cold deck temperature of 55 F (12.8 °C) with a constant 5 F (2.78 °C) throttling range. The nominal cooling thermostatic setpoint is 78 F (25.6 °C) between 7 a.m. and 6 p.m., Monday through Friday. Cooling is not provided during the other hours, except to the extent that the economizer can provide it. The ventilation rate is assumed to be 10 cubic feet per minute per person (0.283 cubic meters per minute per person) during hours of occupancy. Heating for the perimeter zones is provided by baseboard convectors with circulating water heated by a boiler having an efficiency of 0.8 at rated design capacity. The nominal thermostatic setpoint for heating is 68 F (20 °C) between 7 a.m. and 6 p.m., Monday through Friday, and 55 F (12.8 °C) between 6 p.m. and 7 a.m., Monday through Friday, and on weekends and holidays. The HVAC equipment is resized for each parametric simulation of the building.

THE DAYLIGHTING SYSTEM

In this study, a clear distinction has been drawn between view glazing and illumination glazing. For purposes of view, the prototypical office building has vertical glazing mounted in the walls. In order to reduce cooling loads and glare, this view glazing is assigned a normal solar transmissivity of only 15%. In the energy analyses performed for this paper, account is taken of the thermal impacts of this view glazing (i.e., account is taken of solar radiation gains and conductive gains and losses), but no illumination credit is given for sunlight transmitted through the view glazing. For purposes of illumination, a more transmissive glazing is mounted in the roof. The use of closely spaced roof apertures allows highly uniform light penetration into the building.

Roof apertures also allow the selection of any glazing orientation (or combination of orientations) that is favorable to the energy needs of the building. In this study, we have examined a number of glazing orientations that are subjected to substantial amounts of beam sunlight. Admitting beam sunlight into any space where critical tasks are performed is not normally an acceptable procedure. The worst possibility is that the beam will hit someone directly in the eye. Also of extreme importance is keeping beam light off of the task surface, where its presence can create extreme contrasts within the primary field of view. Even if these two most dire possibilities are avoided, there can be visual adaptation problems associated with the high luminance of interior surfaces that are receiving direct beam sunlight.

There are a number of techniques for handling the potential glare problems associated with beam sunlight. For example, louvres can be placed in the aperture to deflect beam sunlight over secondary surfaces, such as the ceiling, which then serve as secondary, low-luminance sources of light for the space. Also, diffusing glazing can be placed in the aperture to disperse light around the space. If a diffusing aperture has a high transmittance and is subjected to intense beam sunlight, it can be very luminous, which can create adaptation problems for the occupants of the space. This problem can be solved by using a secondary diffusing element of larger area inside the primary glazing element. (This is a classic technique used with incandescent electric lighting, where a diffusing bulb is used to shield the brilliant filament from view, and then a shade is used as a secondary diffuser to further enhance the visual comfort in using the light source.) It can also be solved by using fixed louvres to shield the occupants from a direct view of the glazing surface. Finally; a larger primary aperture can be used, with a lower transmittance to reduce excessive solar heat gains and to reduce the luminance of the aperture. If a very large roof aperture is used (e.g., greater than 20% of the floor area being illuminated), then steps should be taken to improve the thermal resistance of the glazing. For example, multiple glazing panes can be used, or a translucent insulation can be added between the existing panes. In performing the simulations reported in this paper, it has been assumed that good light quality has been achieved using some appropriate optical treatment of beam sunlight, such as one of the treatments outlined above.

The results reported in this paper have been divided into two broad categories, corresponding to linear (or extended) roof apertures and localized roof apertures, examples of which are shown in Figures 2 and 3, respectively. The distinction has been drawn between linear and localized roof apertures because there are significant structural and detailing differences between these two system types. The following roof aperture configurations are analyzed and discussed in this paper:

1. Linear roof apertures with the following glazings: vertical facing north; vertical facing south; vertical facing both north and south; tilted 45° up toward the north; tilted 60° up toward the south; and tilted 60° up toward both east and west.

2. Localized roof apertures with the following glazings: vertical facing north, south, west, and east; vertical facing northwest, northeast, southwest, and southeast; vertical facing southwest and southeast; tilted 60° up toward the southwest and

southeast.

3. Horizontal glazing (skylights), which will be used as reference throughout this study.

For all glazing combinations, it was assumed that the glazing area was equally divided among the various orientations.

THE ELECTRIC LIGHTING SYSTEM

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 (Kaufman, ed. 1981) was used to determine the number and spacing of lamps and fixtures required to supply the design illumination level of 50 footcandles (540 lux) on the work plane. From this calculation, an electric lighting power density of 2.5 W/ft^2 was deduced. The lighting hardware and the daily 12-hour operating schedule were chosen as representative of typical practice at the time this study was initiated, rather than being representative of the current state of the art. (The impact of electric lighting efficiency on the energy savings potential of the daylighting system has been examined in related papers [Fontoynont et al. 1984; Place and Siminovitch 1984; Siminovitch et al. 1985].)

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. For the purposes of this study, a lower limit for the electric lighting power was set at 20% of full power. Advances in control hardware that have been made since this study was initiated have reduced this lower limit to 10% of full power.

The assumption has been made that air from the occupied space is returned to the central air conditioning unit through the electric lights. To simulate this effect, 60% of the lamp heat was returned directly to the cooling system without entering the conditioned space. This is consistent with measured data, which indicates that 50% to 60% of the heat from a fluorescent lamp is convectively transferred to the air around the lamp and the remaining 40% to 50% is emitted in the form of visible and infrared radiation. Assuming that all the convective heat is carried away in the return air, along with a fraction of the radiant lamp emission that is absorbed within the luminaire, about 60% of the total lamp heat output returns directly to the air conditioner. The remaining 40% of the lamp heat is radiated directly to the occupied space.

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:

1. Power to the electric lights is reduced linearly in response to the usable amount of sunlight entering the illumination glazing each hour.
2. Electric lighting illumination on the work plane is directly proportional to the power supplied to the electric lights.
3. Power to the lights is adjusted to maintain the combined illumination (solar plus electric) at a constant level of 50 footcandles (540 lux) on the work plane (unless constrained by assumption 4 below).
4. 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 (Kaufman, ed. 1981). (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 under a range of solar conditions.*

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*The same SSLE has been assumed for all of the roof glazing configurations. Clearly, the SSLE will depend on the geometric relationship of the interior surfaces to the roof glazing, which is dispersing sunlight around the interior space. Since the geometry of the interior surfaces will normally vary with the configuration of roof glazing, it is reasonable to expect that the SSLE will also vary from one configuration of roof glazing to another. However, without going through highly specific and detailed design processes, it is impossible to assign a specific SSLE to each configuration. In order to keep things fairly general, we have examined a range of interior geometries and selected a typical SSLE on which to base these analyses. (For a discussion of the effect of variations in SSLE, see Fontoynont et al. [1984].) The philosophical basis for the

Knowledge of the ESLE and the SSLE allows BLAST to perform a trade-off between the two light sources. The reduction in electric power to the lights (REP) is equal to the solar power admitted to the building through the roof glazing (SP) multiplied by the SSLE divided by the ESLE:

$$\text{REP} = \text{SP} \times \frac{\text{SSLE}}{\text{ESLE}}$$

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.

FORMAT FOR PRESENTATION OF RESULTS

The results and discussion in this report have been formatted in terms of the Effective Roof Aperture Area, which, for the purposes of this paper, is defined as the product of the glazing area times the solar transmittance of the glazing. The rationale for this approach is developed in the following paragraphs.

It has been established in a variety of studies (Fontoynont et al. 1984; Selkowitz et al. 1983; Arasteh et al. 1985) that in commercial buildings having moderate to high internal heat loads, the energy impacts of the solar aperture can be divided into the following three categories, (listed in descending order of importance):

1. Lighting electricity reductions (and associated internal load reductions) resulting from the substitution of daylight for electric light.
2. Thermal impact of excess solar gains through the aperture.
3. Thermal impacts of conductive gains and losses through the glazing.

The low relative importance of conductive gains and losses can be understood in terms of the following arguments. In most U.S. climates, outdoor temperatures during the cooling season are not high enough to generate significant conductive gains. The major contributors to the cooling load are: (1) solar gains through glazing, (2) internal heat generation from lights, people, and equipment, and (3) solar loading on the opaque surfaces of the building (which induces conductive gains through the opaque envelope). Compared with the collective impact of these contributors to the cooling load, conductive gains through the glazing are relatively inconsequential and can be ignored.

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approach is to focus on the interaction of the roof glazing with the solar resource. By choosing a single SSLE, we are deemphasizing the details of processes inside the occupied space, and are thereby isolating (i.e., emphasizing) the interaction of the glazing with the solar resource. Once the analysis of that interaction is completed, we can select one or more of the promising roof glazing configurations and pursue more detailed design studies that will more precisely define the likely SSLE(s). In other words, the analysis that we are performing is part of a larger design process that, like all such processes, is iterative.

Also, there is another very subtle point related to the effects of conductive gains and losses: in many nonresidential buildings, conductive losses can have a beneficial effect in reducing cooling loads during those portions of the year when internal loads and solar gains create an "anomalous" cooling load, i.e., they create a cooling load in spite of the fact that outside air temperatures are well within the comfort zone. These cooling benefits of conductive losses tend to offset the negative effects of conductive gains during the remainder of the cooling season. In other words, internal heat sources and solar gains effectively extend the cooling season. In many buildings the increase in duration of the cooling season is sufficient that the overall cooling impact of conductive gains and losses is more beneficial than deleterious.

Outdoor air temperatures during the heating season are low enough in many parts of the country that conductive losses through glazing can be substantial. However, in nonresidential buildings, solar gains through the building envelope and internal heat generated by lights, people, and equipment can provide a large part of the heating energy that would be "required" based on a simple degree-day calculation, so that the full impact of the conductive losses through the glazing will not be reflected in the heating fuel consumption.

Also, heating fuel is generally inexpensive compared with the electricity used for lighting and cooling, so that the contribution of auxiliary heating to the annual energy operating cost is small. Hence, the net cost impact of the increased conductive gains and losses associated with adding glazing is therefore small compared with other energy issues associated with introducing the solar aperture.

In such buildings, we can safely ignore the effect of conductive gains and losses associated with roof glazings up to about 10% of the building floor area. Then our list of significant impacts of the solar aperture can be reduced to two categories, (listed in descending order of importance):

1. Lighting electricity reductions (and associated internal load reductions) resulting from the substitution of daylight for electric light.

2. Thermal impact of excess solar gains through the aperture.

This greatly simplifies the problem of depicting the impact of the aperture—more than would be apparent from the simple reduction in the number of categories. The important point is that both of these significant energy impacts are related to the overall transmittance of the aperture to solar radiation. The reductions in lighting electricity increase with the amount of transmitted light, which is in turn proportional to the amount of radiation admitted by the aperture. Similarly, the thermal impacts of excess solar gains are also proportional to the amount of radiation admitted by the aperture.

Because of these relationships, we can express all of our energy results as a function of a quantity called the effective roof aperture area, which we define as the product of the roof glazing area times the solar transmittance of the roof glazing. For example, a roof glazing system with a transmittance of 50% and an area that is 10% of the floor area being illuminated will have an effective roof aperture area that is 0.50 x 10% = 5% (of the floor area being illuminated). Similarly, a roof glazing system with a transmittance of 70% and an area that is 7.14% of the floor area being illuminated will have an effective roof aperture area that is also 5%. From an energy point of view, the effects of these two apertures will be essentially identical, since the only difference will be conductive gains and losses, which we have already argued are relatively inconsequential in the situation we are considering.

The diagrams at the end of this article indicate the impacts on energy consumption and energy operating cost of various glazing orientations as a function of the effective roof aperture areas* in a prototypical office building (Figures 1, 2, and 3) outfitted with fluorescent lighting with continuous dimming controls. The continuous dimming controls simulated in these studies assumed a lower power limit of 20% of full power. New developments in dimming controls allow this figure to be reduced to 10% of full power.

RESULTS

Glazing Tilted up 60° toward the South—An Example of a Linear Aperture in a Range of Climates

Annual simulations of the prototypical building were performed with TMY weather data from New York, Atlanta, and Los Angeles. These three locations were selected because they represent a substantial range of climates in terms of daylight availability and thermal conditions and also because they represent a large fraction of the built environment in the United States (Andersson et al. 1985). Figures 4-7 show results from some of these simulations for a linear roof aperture system with glazing tilted 60° up toward the south.

In Figure 4, the annual energy consumption for lighting electricity (at the site) is plotted as a function of the effective roof aperture area, expressed as a percentage of the floor area. (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.)

For small effective aperture areas (0% to 1%), the electric consumption goes down rapidly with each additional increment of effective aperture area. This rapid decrease primarily reflects the influence of beam sunlight, which is intense enough to displace substantial amounts of the electric light, even when the collecting aperture is quite small. In

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*In the simulations, account has been taken of the conductive gains and losses through the opaque roof and the glazing in the roof. The conductive gains and losses through the roof glazing are assumed to vary in accordance with the area of the glazing. However, the assumption is made that the conductive gains and losses through the opaque portions of the roof do not vary from one simulation to the next, as the area of roof glazing changes. There are two major reasons for this approach: (1) in most designs, incorporating the roof apertures does not appreciably reduce the area of opaque surface (e.g., for skylight in flat roofs, the area of curb is normally about equal to the area of roof surface removed to make the opening); and (2) for the aperture areas treated in this paper (up to 10%) and the thermal resistance assumed for the opaque envelope (0.05 $\text{Btu/hr}\cdot\text{ft}^2\cdot\text{F} = 0.284\ \text{Kw/m}^2\cdot{}^\circ\text{C}$), the conductive gains and losses through the opaque envelope in question are inconsequential. (The importance of conductive gains and losses through the roof glazing will be discussed further in the results section.)

fact, for intense beam sunlight that is incident on the collection aperture near the normal to the glazing, an effective aperture area of 1% is more than enough to meet the lighting requirements of the office space. At larger effective aperture areas (above 1%), the lighting electricity consumption goes down less rapidly, indicating primarily the effect of diffuse skylight during those hours when beam sunlight is not available or is only weakly incident on the collection glazing.

The curves in Figure 4 approach asymptotically toward lower limits 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. The differences in the lighting electricity consumption curves at small apertures (less than 1% effective aperture area) are primarily a result of differences in availability of beam sunlight. At small apertures, the lighting electricity consumption for Los Angeles is substantially lower than for Atlanta and New York. For larger apertures (above 2% effective aperture area), diffuse skylight becomes more significant, and the major differences in the lighting electricity consumption curves result from differences in the number of hours of daylight. For larger apertures, New York has significantly higher lighting electricity consumption compared with Los Angeles and Atlanta, because the higher latitude of New York limits the number of hours of daylight during the winter.

In Figure 5, annual energy consumption for cooling electricity at the site (direct expansion cooling unit plus fans) is plotted as a function of aperture area for glazing tilted 60° up toward the south. For small aperture areas, cooling electricity consumption decreases with increasing aperture area for all three locations. This result can be understood by the fact that at small aperture areas, all the admitted sunlight is effective in displacing electric light of higher heat content, thereby reducing cooling loads. For larger aperture areas, the excess solar gains outweigh the cooling benefits associated with the higher luminous efficacy of the sunlight, and the cooling loads increase significantly with increasing aperture area.

The generally sunny nature of the Los Angeles climate, compared with New York and Atlanta, causes the cooling electricity curve for Los Angeles to reach a minimum at a smaller aperture area and to increase more rapidly beyond the minimum. These increases in cooling load are significant; in all three locations, the cooling loads above 4% effective aperture area are larger than for the base-case building with no roof apertures (i.e., at zero aperture area).

A comparison of Figures 4 and 5 indicates that the total variation in cooling electricity is small compared with the reduction in lighting electricity for this particular combination of building type and roof glazing configuration in the climates shown. However, for effective aperture areas above 3%, the increases in cooling electricity consumption outweigh the decreases in lighting electricity consumption, suggesting that the larger aperture areas may not be desirable. These increases in cooling electricity consumption tend to occur during hours of peak electricity demand, which also makes it desirable to avoid oversized apertures.

In Figure 6, the annual energy consumption of boiler fuel is plotted versus effective roof aperture area for glazing tilted 60° toward the south. For small aperture areas, heating fuel consumption increases with increasing aperture area, resulting primarily from the replacement of electric light with sunlight of lower heat content and to a lesser degree from increased conductive losses associated with adding glazing to the roof. This increase in boiler fuel consumption is of little consequence, since the effect is small and heating fuel is a much cheaper and more efficient source of heat than dissipating electric power in lamps. For large aperture areas, the solar gains dominate the combined effect of reduced heat from the electric lights and increased conductive losses associated with increased glazing area, and the heating fuel consumption decreases with increasing aperture area.

In all three locations heating fuel consumption (Figure 6) is less sensitive than cooling electricity consumption (Figure 5) to variations in the aperture area. This result is primarily explained by the timing of solar gains through the aperture. During the summertime, excess gains have a large effect on cooling electricity consumption since they tend to occur during hours when cooling is required. By contrast, the effect of excess solar gains on boiler fuel is smaller because the gains frequently occur when heating is not required, i.e., around midday, after the boiler heat and internal gains have already heated the building to an acceptable temperature, and internal gains alone are adequate for sustaining that temperature.

Figure 7 shows the annual energy operating costs, which have been computed for each location using local billing policies for gas and electricity.* These costs include charges for gas consumption, cooling electricity consumption, lighting electricity consumption, and peak electric demand charges. They do not include any initial costs associated with the daylighting aperture or the HVAC equipment.

In all three locations, costs decrease rapidly with increasing aperture area, up to an effective roof aperture area of about 1.5%. Reductions in lighting electricity consumption and cooling electricity consumption contribute to these utility cost decreases (see Figures 4 and 5). Beyond an effective aperture area of about 3%, increases in cooling electricity exceed the decreases in lighting electricity, and the costs increase with increasing aperture area. In general, the shape of the cost curves is almost independent of heating effects for this particular combination of building and roof aperture configuration; the heating curves are relatively flat and the cost per unit of heating energy is substantially lower than the cost per unit of electricity at the site.†

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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 of the University of Alabama. The effective rates per kilowatt-hour (including demand charges) were on the order of 9 cents in Los Angeles, 8 cents in Atlanta, and 18 cents in New York. These figures are representative but only approximate since the effective cost per kilowatt-hour (including demand charges) will depend on the blend of consumption and peak demand, which varies with the building configuration being simulated. In all cases, the HVAC equipment was sized for the specific building configuration being simulated.

†For the base-case building (with no roof apertures) the fraction of the total energy operating cost that was expended for heating was about 2% in Los Angeles, 7% in Atlanta, and 10% in New York. Comparing Figure 6 with Figures 4 and 5, it is clear that the percent variation in heating

In examining Figure 7, the most significant observation is the striking similarity of the three cost curves. The differences relate to fine details. As expected, the Los Angeles curve reaches its minimum at a slightly lower aperture area than for New York or Atlanta, which reflects the generally sunny character of the Los Angeles climate. However, this does not appear to be a significant design issue, since the minimum in all cases is generally broad, and slight oversizing of the aperture will probably be the appropriate design approach for all three climates. In other words, an effective roof aperture area of 3% to 4% would appear to be reasonable and conservative in all three climates.

The maximum reduction in energy operating cost that can be achieved by incorporating this roof aperture configuration is higher for Los Angeles than for Atlanta, which results primarily from the superior daylighting resource in Los Angeles. On the other hand, the maximum reduction in energy operating cost is higher in New York than in Los Angeles, because the very high utility rates in New York overwhelm the energy benefits of the superior Los Angeles daylighting resource.

This raises a more general point: utility rates vary across the United States by more than a factor of 10, which is far more extreme and significant than the variation in daylighting resource across the range of U.S. climates. The range of U.S. climates has, in fact, been reasonably well represented by the three locations examined in this study, and research in the near future should logically focus more on effects of utility rates than on climatic effects. Variations in utility rates will have a much stronger effect on the maximum reductions in energy operating costs than on the effective roof aperture area at which the maximum reductions are realized. In other words, the utility rate will have a stronger effect on the decision to use or not to use roof apertures than it will on the design optimum.

The shapes of the energy cost curves in Figure 7 were influenced by two important assumptions in the study:

1. The COP of the cooling system may have been somewhat higher than normal, since 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 simulation were performed again with a lower COP for the cooling system, the cooling consumption curves (in Figure 5) would rise more rapidly for large aperture areas. Furthermore, the peak-power demand charges, which are highly sensitive to cooling loads (ASHRAE 1985), would also rise rapidly at large aperture areas. Both effects would tend to make the cost curves in Figure 7 rise more rapidly for effective roof aperture areas above about 3%.

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energy consumption (over the wide range of aperture ratios shown) is relatively small compared with the percent variations in lighting and cooling electricity consumption. Hence, we are talking about small percentage variations in a quantity that is already small. Therefore, the effect of heating energy variations on the shape of the energy operating cost curve is very small in all cases.

The assumption that control of the building's thermal conditions is based solely on air temperature also tends to underestimate the rate of rise of the cost curves for aperture areas beyond the minimum point. In a real situation, the larger aperture areas 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. (Although the admitted solar radiation is assumed to be dispersed by diffusing glazing, there is still significant heat content in this diffuse radiation, particularly for large aperture areas where the amount of radiation admitted is high.) The effect would be that the occupants of a building with a large aperture area would want a lower air temperature to compensate for the warmer radiant environment. Lower air temperature 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% effective aperture area, but the shape of the curve would change in a manner to make the minimum more apparent. The effects of more sophisticated comfort controls are currently being studied and will be the subject of a future paper. In the meantime, some caution should be exercised in oversizing the aperture.

Figures 4, 5, and 6 suggest that properly controlled, movable, external shading (or movable insulation) would facilitate significant additional reductions in both energy consumption and energy costs. The optimal area for uncontrolled glazing is primarily limited by excess solar gains during the cooling season. Using movable, external shading makes it possible to use larger apertures without aggravating the cooling problem. In fact, by properly controlling the amount of sunlight admitted during the summer, it would be possible to produce further reductions in both the cooling electricity consumption and peak electricity demand charges. The larger aperture has the obvious advantage of allowing the collection of more daylight with consequent reductions in lighting electricity consumption and peak electricity demand charges.

Using an oversized aperture also has the economic advantage of facilitating simplifications in the electric lighting system; the oversized apertures will collect enough sunlight during almost all daylight hours to allow the electric lights to be completely off, thereby permitting the use of simple digital switching, rather than continuous dimming controls. Since digital switching permits the entire electric lighting system to be fully switched off, it is even possible to save more energy with digital switching (in conjunction with properly controlled, oversized apertures) than with continuous electric lighting controllers, which have the drawback of imposing a lower limit to the allowable electric lighting power level.

The oversized apertures may also permit the use of inexpensive (and inefficient) fixtures and ballasts, since the lights would be on only infrequently. Using dynamic aperture control also has the potential to substantially reduce the capacity of the cooling system. Movable insulation would also reduce heat loss during the wintertime, but this is a second-order economic effect for this particular building in the climates examined. Finally, aperture controls also provide a mechanism for the occupants to control the interior lighting environment, which is crucial to certain activities, such as using computer terminals or audio-visual equipment.

BLAST simulations similar to the ones described above for linear roof apertures (tilted, south-facing glazing) have also been made for localized roof apertures in the same three climates (New York, Atlanta, and Los Angeles). For the localized roof apertures examined, the general climatic effects were essentially identical to those for the linear roof aperture described above (Fontoynont et al. 1984).

Comparisons of Various Glazing Orientations and Tilts in a Single Climate

In the following section, simulation results are presented for 11 different combinations of glazing orientation and tilt in Atlanta, Georgia. For clarity of presentation, we have divided the graphic results into three groups, each associated with a class of similar roof apertures. For each of these groups, graphic results are presented in a format similar to the one used in the preceding section, i.e., there are four figures showing annual predictions for (1) lighting electricity consumption, (2) cooling electricity consumption, (3) heating fuel consumption, and (4) energy operating cost.

Figures 8 through 11 compare simulation results in Atlanta, GA, for the following linear apertures with vertical glazing:

1. vertical glazing facing north;
2. vertical glazing facing south; and
3. a combination of vertical glazing facing both north and south.

Figures 12 through 15 compare simulation results in Atlanta, GA, for the following linear apertures with tilted glazing:

1. glazing tilted 60° up toward the south;
2. glazing tilted 45° up toward the north; and
3. combination of glazings tilted 60° up toward both west and east.

Figures 16 through 19 compare simulation results in Atlanta, GA, for the following localized apertures, some with vertical glazing and some with tilted glazing:

1. the combination of vertical glazings facing north, south, west and east;
2. the combination of vertical glazings facing northwest, northeast, southwest, and southeast;
3. the combination of vertical glazings facing southwest and southeast; and
4. the combination of glazings tilted 60° up toward both southwest and southeast.

For all glazing combinations, it has been assumed that the glazing area is equally divided between the various orientations. In order to facilitate visual comparisons between the three sets of results, each graphic set contains the results for horizontal glazing (skylights). Skylights have been chosen as the reference because they are a very common roof aperture configuration and because they can be considered either linear or localized, depending on the design. In each of the graphs, the curve for the horizontal glazing is drawn with short dashes, the curves for tilted glazings are drawn with long dashes, and the curves for vertical glazings are drawn with solid lines.

In Figures 8, 12 and 16, annual lighting electricity consumption at the building site is plotted as a function of the effective roof aperture area for the three groups of roof aperture configurations. For all aperture areas, the horizontal glazing displays the best potential for reducing the lighting electricity consumption, reflecting the highly effective year-round collection of both diffuse and beam sunlight. However, some of the tilted glazings are almost as effective in collecting sunlight as is the horizontal glazing. For example, glazing tilted toward the south has an annual lighting electricity consumption curve very similar to that of horizontal glazing (see Figure 12). In general, the horizontal glazing collects diffuse skylight more effectively, but glazing tilted toward the south is more effective in collecting wintertime beam sunlight.

The combination of glazings tilted up toward the southwest and southeast has an annual lighting electricity consumption curve even closer to that of horizontal glazing (see Figure 16). Although the horizontal glazing is more effective in collecting diffuse skylight, the glazing tilted up toward the southwest and southeast is more effective in collecting beam sunlight during the wintertime, and early in the morning and late in the afternoon during the summertime, i.e., it collects well during those periods when the solar resource tends to be weak, and effective collection is therefore important.

The combination of glazings tilted up toward both west and east also produces fairly low annual lighting electricity consumption, particularly for effective aperture areas above about 2% (see Figure 12). The major virtue of this glazing configuration is its effectiveness in collecting early morning and late afternoon beam sunlight. Of all the tilted glazings shown, north-facing glazing has by far the highest annual lighting electricity consumption, because tilting glazing toward the north reduces the collection of both diffuse skylight and beam sunlight (see Figure 12). As a general rule, we can say that tilted glazings can work essentially as well as horizontal glazing in reducing lighting electricity consumption, if the tilt is toward the solar resource, rather than away from it.

In general, vertical glazings are less effective, per unit of glazing area, in reducing annual lighting electricity consumption than are horizontal glazing or properly oriented tilted glazings, since the vertical glazings face only half the skydome and are generally not as effective in the annual collection of beam sunlight. The effect of changing from tilted glazing to vertical glazing is illustrated by comparing the two combinations of glazings facing both southwest and southeast (see Figure 16).

The vertical glazing least effective in reducing annual lighting electricity consumption faces toward the north (see Figure 8). This results from the fact that vertical glazing facing north collects essentially no beam sunlight at any time during the year. The annual lighting electricity consumption curve for vertical glazing facing south lies approximately halfway between the curve for vertical glazing facing north and the curve for horizontal glazing (see Figure 8). In between the curves for vertical glazing facing north and vertical glazing facing south is the curve for the combination of vertical glazings facing both north and south (see Figure 8). At very small apertures, the curve for the combination of north and south glazings is essentially halfway between the curve for north glazing and the curve for south glazing, reflecting the importance of beam sunlight for small apertures and the fact that only half of the glazing in the combination is effective in collecting beam sunlight. At larger apertures, the curve for the combination of glazings facing both north and south becomes essentially identical to the curve for glazing facing only south. This reflects the fact that at larger aperture areas the combination of glazings accepts more than enough beam sunlight when beam sunlight is available, and when it is not available (e.g., with overcast conditions), the combination of vertical glazings is just as effective in collecting diffuse skylight as is pure, south-facing glazing.

Per unit of glazing area, localized apertures with vertical glazings seem to be comparable with or slightly better than linear apertures with vertical glazings in reducing annual lighting electricity consumption. For example, the combination of vertical glazings facing both southwest and southeast has generally lower annual lighting electricity consumption (see Figure 16) than vertical glazing facing south (see Figure 12). This reflects the superior collection of beam sunlight in the early morning and late afternoon by the combination of vertical glazings facing southwest and southeast.

There are two other localized apertures of interest in Figure 16: (1) vertical glazings facing north, south, west, and east, and (2) vertical glazings facing northwest, northeast, southwest, and southeast. These two configurations produced annual lighting electricity curves so close to each other that in Figure 16 they are indistinguishable. The degree of similarity in these curves suggests that we can speak about a "single configuration with vertical glazing facing in four directions," without worrying too much about the exact orientation of that unit. From a design point of view, this is a very significant result; it suggests that we can safely use this roof aperture on any building, without regard to the building orientation.

For small aperture areas, the annual lighting electricity consumption curve for vertical glazing facing in four directions is higher than for vertical glazing facing south (see Figure 8). This reflects the importance of beam sunlight for very small apertures and the effectiveness of south-facing glazing in collecting beam sunlight. At effective aperture areas above about 2%, the annual lighting electricity curve for vertical glazing facing in four directions is lower than for vertical glazing facing south. This reflects the superior collection of early morning and late afternoon beam sunlight by the glazing facing in four directions.

In Figures 9, 13, and 17, annual cooling electricity consumption at the site (direct expansion cooling unit plus fans) is plotted versus effective roof aperture area for the three groups of roof aperture configurations. At small aperture areas (effective roof aperture areas less than 1%), the lowest cooling electricity consumption curves correspond to the orientations that collect the most sunlight during the cooling season (e.g., horizontal glazing). This result is explained by the fact that for small aperture areas, all the sunlight collected is useful in displacing electric lighting of higher heat content. At higher aperture areas, the order of the curves is reversed, in the sense that low cooling electricity consumption is produced by the orientations that collect less sunlight during the cooling season. The higher cooling electricity consumption at large aperture areas results from excess solar gains, which do nothing to offset lighting electricity consumption, but which do contribute to the cooling load.

At large aperture areas, horizontal glazing has the highest cooling penalty, followed by the tilted glazings, which tend to cluster together (see Figures 13 and 17), and then by the vertical glazings, which also tend to cluster together (see Figures 9 and 17). Even at a 6% effective aperture area, no significant cooling problem is seen for any of the combinations of vertical glazings. As mentioned earlier in this paper, if we were accounting properly for all the comfort impacts of excess solar radiation gains during the summertime (e.g., increased mean radiant temperature and solar radiation impinging directly on the building occupants), the differences in the cooling penalties identified above would be accentuated. In other words, the cooling penalty for horizontal glazing would be substantially increased, the cooling penalty for the tilted glazings would be significantly increased, and the cooling penalty for the vertical glazings would be relatively unaffected.

In Figures 10, 14, and 18, boiler fuel consumption is plotted as a function of effective roof aperture area for the three groups of roof aperture configurations. At small aperture areas (effective aperture areas less than 1%), the heating consumption increases moderately as the electric lighting is replaced by daylighting of lower heat content. These increases in heating fuel consumption are most rapid for those orientations that collect beam radiation most effectively during the wintertime—e.g., tilted glazing facing south (see Figure 14) and vertical glazing facing south (see Figure 10). At larger effective aperture areas (above 2%), these glazing orientations collect sufficient excess solar gains (beyond those required for illuminating the building) to offset the loss of internal heat generation from the electric lights, resulting in heating fuel consumption slightly lower than for the base-case building (0% aperture area).

For those orientations that collect solar radiation poorly during the wintertime (e.g., vertical glazing facing north [see Figure 10] and tilted glazing facing north [see Figure 14]), the heating fuel consumption increases steadily with increasing aperture area. (Tilted glazing facing north has an even worse heating penalty than vertical glazing facing north, since it not only collects no beam radiation during the wintertime, but it also faces toward the cold winter sky.)

The various glazing configurations can be listed in approximate order of decreasing heating performance: tilted facing south; vertical facing south; tilted facing southwest and southeast; vertical facing southwest and southeast; vertical facing north and south; horizontal; vertical facing north, south, west and east; vertical facing northwest, northeast, southwest, and southeast; tilted facing west and east; vertical facing north; and tilted facing north.

As in the case of cooling, the differences in heating performance of these various glazing configurations would be accentuated if we accounted for all of the comfort parameters affecting the building occupants. For example, tilted, north-facing glazing, which requires relatively large areas to significantly reduce lighting electricity consumption and which faces the cold winter sky, would have a significant detrimental impact on the mean radiant temperature experienced by the building occupants.

Again, the reader is cautioned against attaching too much significance to the variations in heating fuel consumption, since they are still smaller than either cooling electricity consumption or lighting electricity consumption, and the cost per unit of heating energy is lower than the cost per unit of electricity at the site. Heating is a relatively small part of the total energy cost of operating the prototypical building, and variations of the heating cost with glazing area are inconsequential.*

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*On the other hand, the overall heating issue is not completely inconsequential. From a primary energy point of view, heating fuel consumption is a significantly larger part of the problem. This

In Figures 11, 15, and 19, annual operating energy costs are plotted versus effective roof aperture area, for the three groups of aperture configurations. At very small effective aperture areas (less than 1%), horizontal glazing has the lowest annual energy cost, reflecting the highly effective annual collection of sunlight. By going to slightly higher effective aperture areas (2% to 3%) and using tilted glazings facing south or facing both southwest and southeast, we can achieve even lower annual operating energy costs. This superior performance of these tilted glazings is a reflection of their generally good annual collection of daylight and their good balance between summertime and wintertime collection. At even larger effective aperture areas (3% to 6%), even lower annual energy operating costs can be achieved with vertical glazings facing in any of the following orientations: south; north and south; north, south, west, and east; southwest and southeast; or northwest, northeast, southwest, and southeast.

Glazings facing north (either tilted or vertical) do not have superior performance at any effective aperture area.[†] The minimum annual operating energy cost for either of these two orientations occurs at large effective aperture areas (about 6% or above). At these large areas, both glazings will tend to seriously reduce the mean radiant temperature during the winter, and the tilted glazing facing north will also have a deleterious effect on comfort conditions during the summer, by increasing the mean radiant temperature and subjecting the occupants to excessive amounts of solar radiation impinging directly on their bodies.

In addition to the energy cost and thermal comfort impacts of the various glazing configurations, there is a psychological factor, which, although difficult to quantify, is probably very important: people tend to prefer spaces that are brighter during the wintertime than during the summertime. This criterion favors glazings that are generally oriented toward the south, makes horizontal glazing somewhat less desirable, and puts in serious doubt any merits of tilted glazing facing north.

For the glazing orientations examined in this paper, the highest annual energy cost savings per unit of building floor area are achieved by vertical glazing with any of the following combinations of orientations: south; north and south; north, south, west, and east; southwest and southeast; or northwest, northeast, southwest, and southeast. For effective aperture areas on the order of 4% to 6%, the annual operating energy cost savings are about $4 per square meter of floor area per year ($.40 per square foot of floor area per year).

These savings may not seem large to building designers who are accustomed to initial constructions about one hundred times larger than these annual cost savings. However, two points should be made. To begin with, these energy cost savings will accrue throughout the life of the building. Secondly, it is probably more meaningful to evaluate

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is particularly true of more northerly climates (see again Figures 4-7 for New York data). Also, the relative importance of heating energy consumption will increase, as daylighting and more efficient electric lighting systems become more widely used . Finally, in this study, we have not specifically addressed serious strategies for reducing heating energy consumption, such as using thermal storage or low-conductance glazings.

[†] This issue may be highly climate-sensitive. For example, vertical glazings facing north may work well in very warm climates, such as would be encountered in Florida and the Gulf states.

the energy cost savings relative to the required area of roof aperture glazing, rather than relative to the floor area of the building, since, to first order, the required area of roof glazing is an indicator of the incremental cost to achieve the indicated energy cost savings. At an actual aperture area of 8%, the annual energy cost savings can be about $50 per square meter of glazing per year ($5.00 per square foot of glazing per year).

If a designer is interested in "skimming the cream" of the energy benefits, the highest annual energy cost savings per unit of glazing area is achieved by horizontal glazing at very small effective aperture areas (less than 1%). For the combination of building type, climate, and electric lighting system examined in this paper, these savings will be on the order of $200 per square meter of glazing area per year ($18 per square foot of glazing area per year). If we assume that the initial cost per unit of roof glazing is roughly independent of the amount of glazing installed, then the "apparent benefit/cost ratio" for skimming the cream is very compelling; i.e., the results suggest strongly that we should install a small amount of horizontal glazing and forget about the other options.

However, the assumption of constant cost per increment of glazing area may be highly inaccurate. In some designs, there will be a quantum jump in construction cost associated with simply introducing the glazing, i.e., the first small increment of glazing may be by far the most expensive and adding more glazing, even up to fairly large actual aperture areas (5% to 10%), may still prove to be cost effective. Clearly the economics of the roof system depend strongly on the structural concept and the roofing details, and a detailed analysis of the economics would have to occur on a case-by-case basis. The purpose of this paper is to give the reader a sense of the energy operating costs and the relative performance of various combinations of glazing orientation and tilt, so that the information can be folded into a more detailed design process.

In performing that design process, the unquantified but still very important issues related to human comfort and psychological response should not be forgotten. Tilted and vertical glazings that are oriented in a manner to accept more solar radiation during the winter than during the summer will have substantial benefits over horizontal glazing with respect to both of these issues. The reader is also reminded that the predicted savings will be sensitive to various assumptions in the analysis, particularly the efficiency of the electric lighting system (Fontoynont et al. 1984; Place and Siminovitch 1984; Siminovitch et al. 1985).

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 the glazing configurations examined in this paper:

   A. The highest annual energy cost savings per unit of floor area are achieved by vertical glazings having any of the following orientations: south; north and south; north, south, west, and east; southwest and southeast; or northwest, northeast, southwest, and southeast. For the combination of building type, climate, and electric lighting system examined in this paper, these savings will be on the order of $0.40 per square foot of floor per year ($4 per square meter of floor area per year), for actual aperture areas in the range of 6% to 10%. At 8% actual aperture area, these figures translate to about $5.00 per square foot of glazing per year ($50 per square meter of glazing per year).*

   B. The next highest annual energy cost savings per unit of floor area are achieved by tilted glazings facing south or facing both southwest and southeast. For the combination of building type, climate, and electric lighting system examined in this paper, these savings will be on the order of $0.33 per square foot of floor per year, ($3.50 per square meter of floor area per year) for actual aperture areas in the range of 2% to 4%. At 3% actual aperture area, these figures translate to about $10.00 per square foot of glazing per year ($120 per square meter of glazing per year).

   C. The highest annual energy cost savings per unit of glazing area is achieved by horizontal glazing at very small actual aperture areas (less than 2%). For the combination of building type, climate, and electric lighting system examined in this paper, these savings will be on the order of $18 per square foot of glazing per year ($200 per square meter of glazing per year).

5. Utility rates have a very significant effect on the energy cost benefits from the daylighting system and therefore a significant influence on the decision to incorporate the daylighting system. The influence of utility rates on the optimal roof aperture design is much less pronounced than their influence on the decision to use roof apertures.

6. Movable external shading (or movable insulation), which properly controls the solar gains through the illumination glazing, could enable the daylighting system to eliminate most of the lighting electricity consumption while reducing the cooling electricity consumption.

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*The predicted savings will be sensitive to various assumptions in the analysis, particularly the efficiency of the electric lighting system (Fontoynont et al. 1984; Siminovitch et al. 1985).

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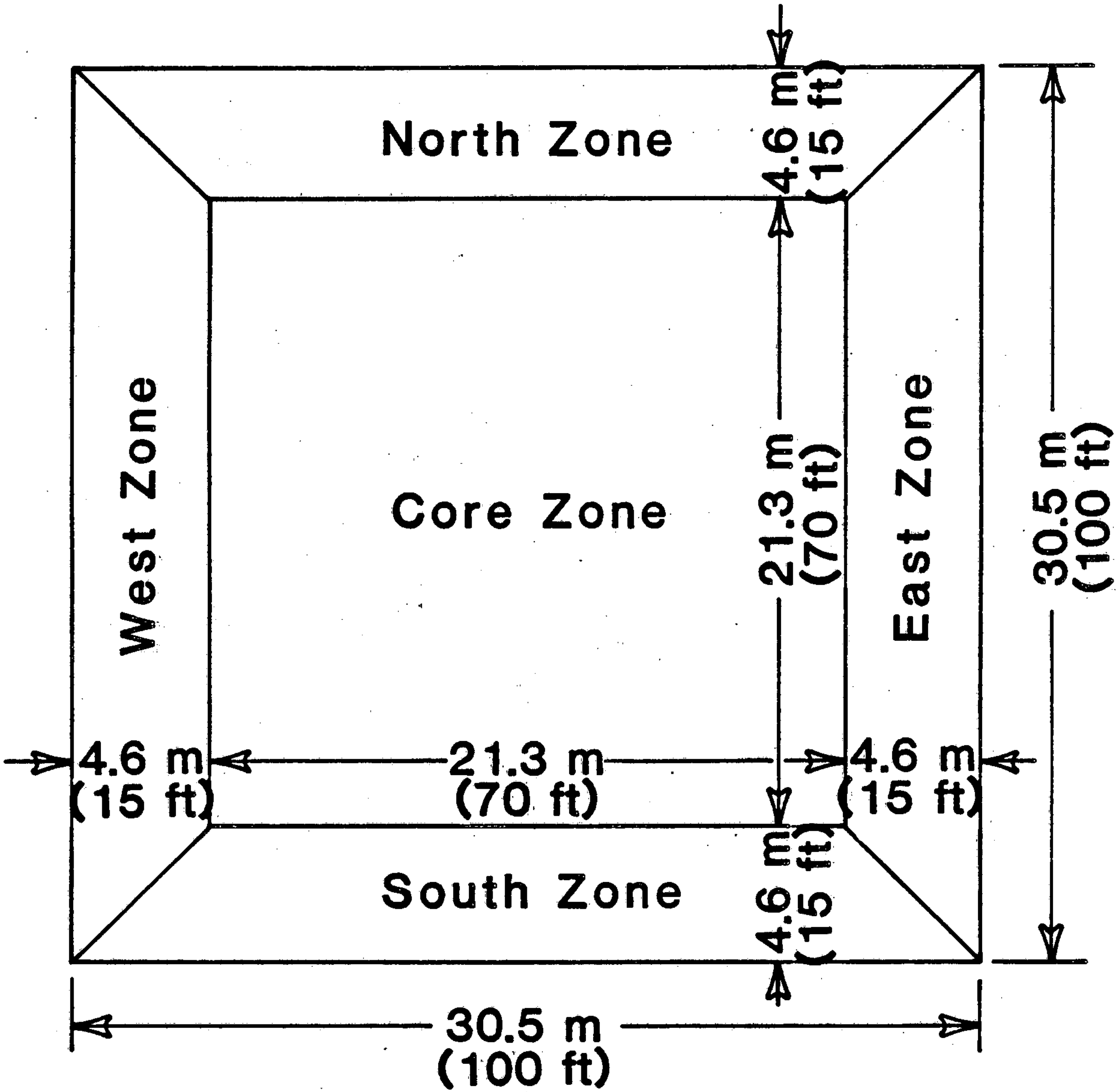

FIG. 1: SCHEMATIC FLOOR PLAN OF PROTOTYPE COMMERCIAL BUILDING

XBL 873-1141

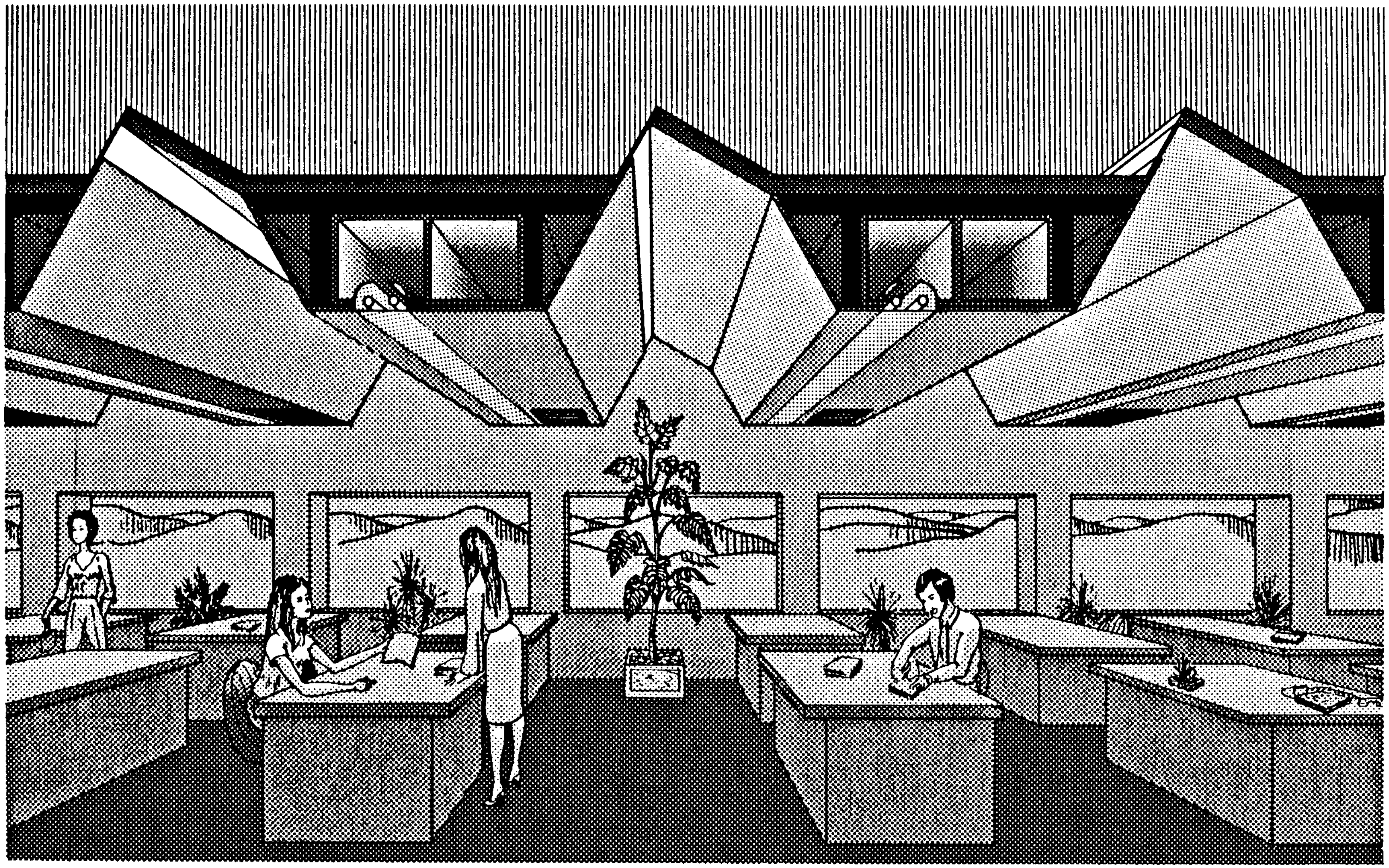

FIG. 2: A LINEAR ROOF APERTURE SYSTEM WITH DIFFUSING GLAZING TILTED TOWARD THE SOUTH

XBL 825-10228

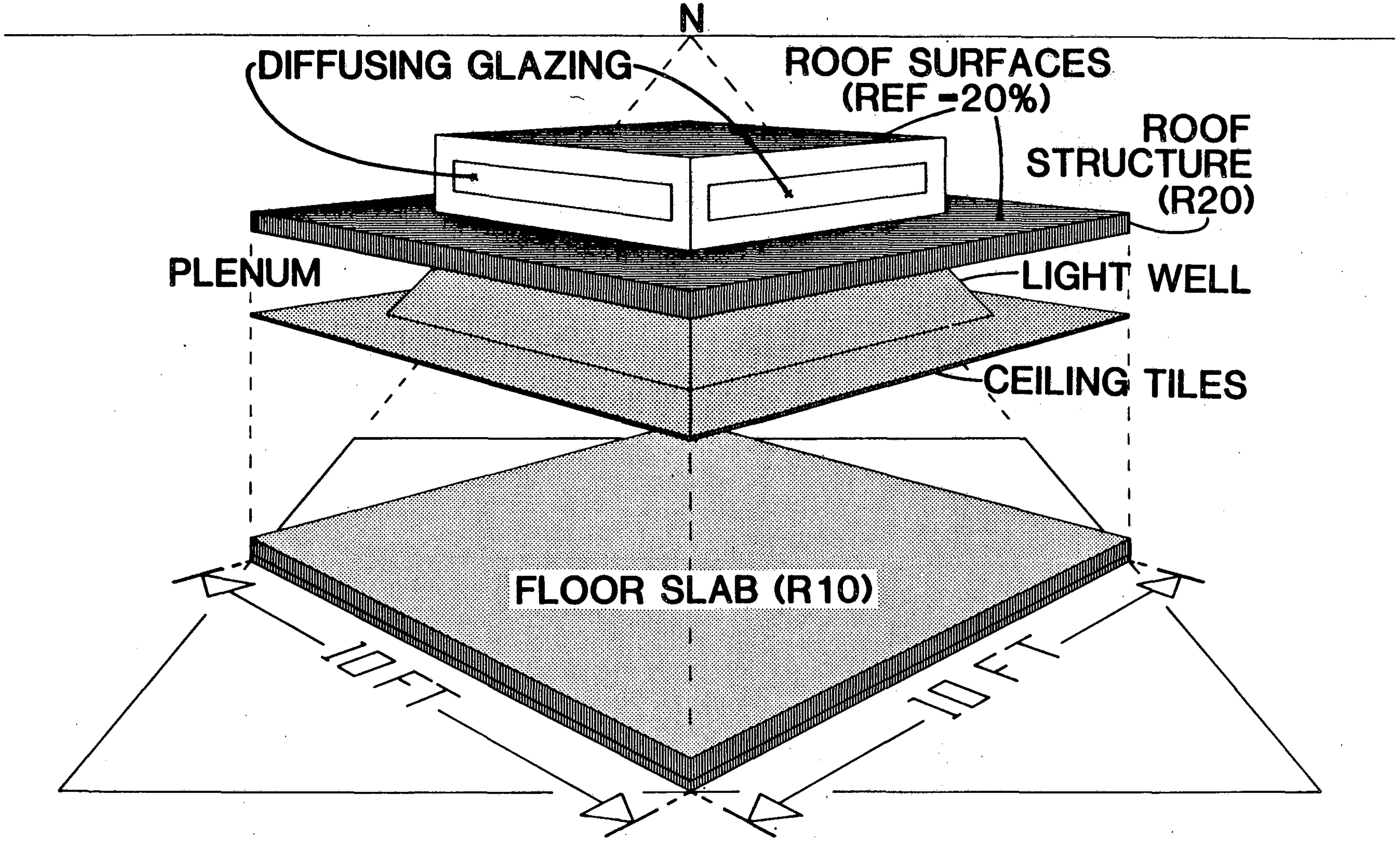

FIG. 3: TYPICAL MODULE FROM BUILDING

XBL 8310-12158

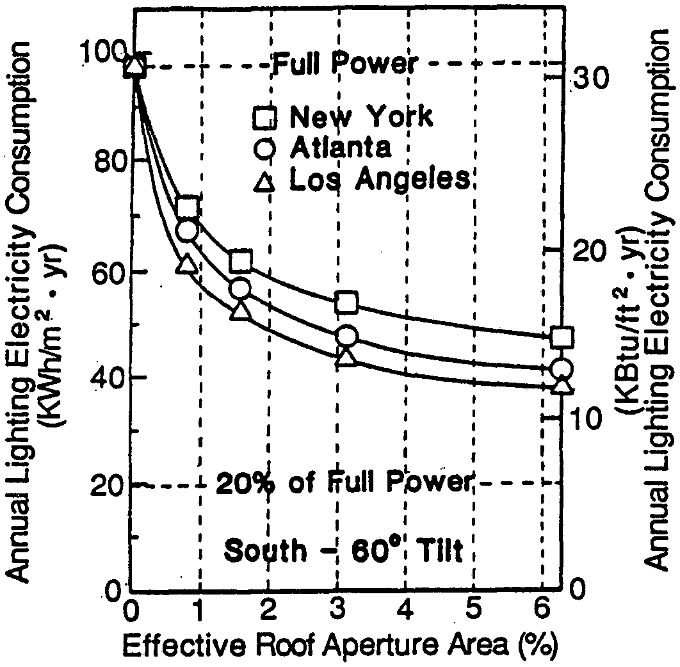

FIG. 4: ANNUAL LIGHTING ELECTRICITY

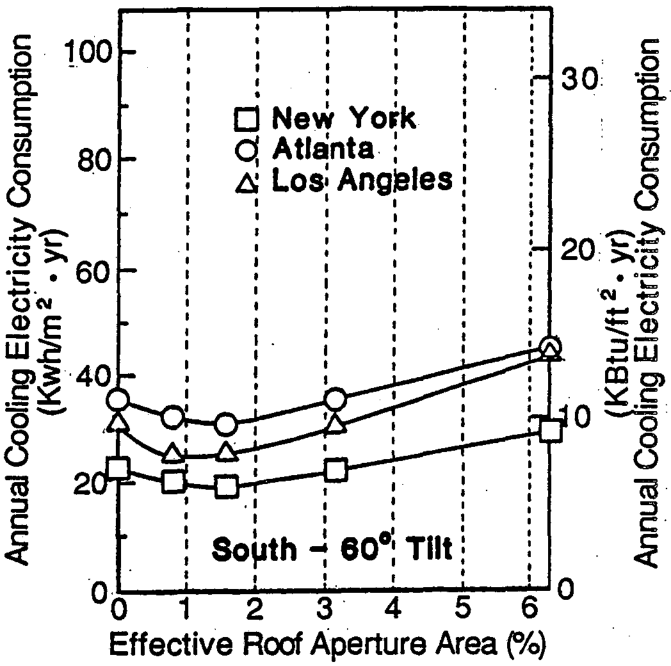

FIG. 5: ANNUAL COOLING ELECTRICITY

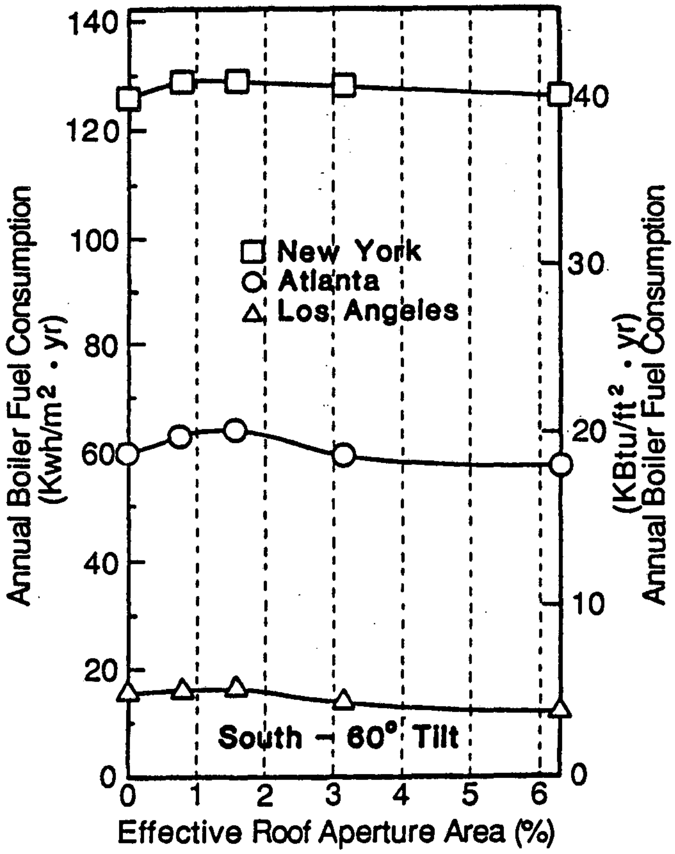

FIG. 6: ANNUAL BOILER FUEL

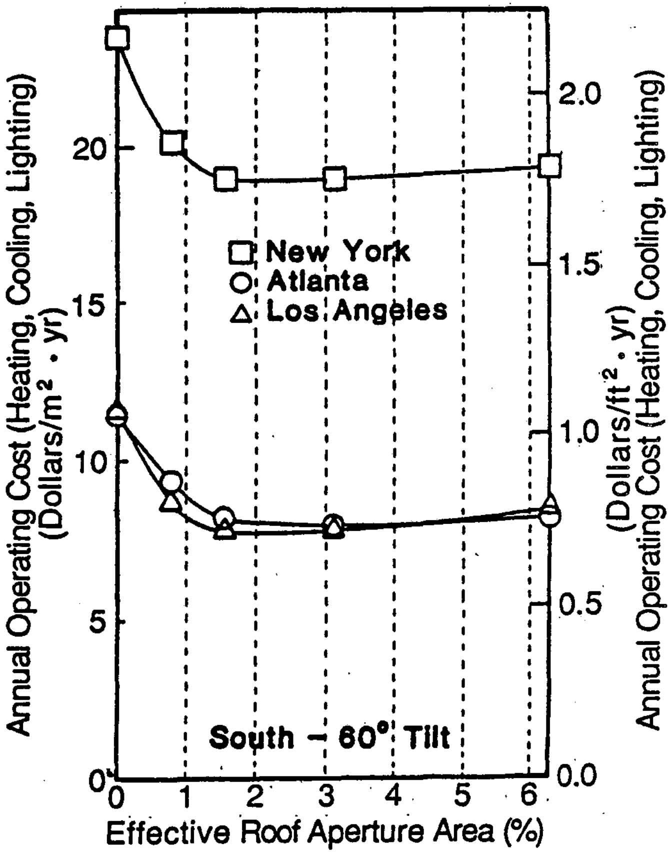

FIG. 7: ANNUAL OPERATING COSTS

XBL 873-1145

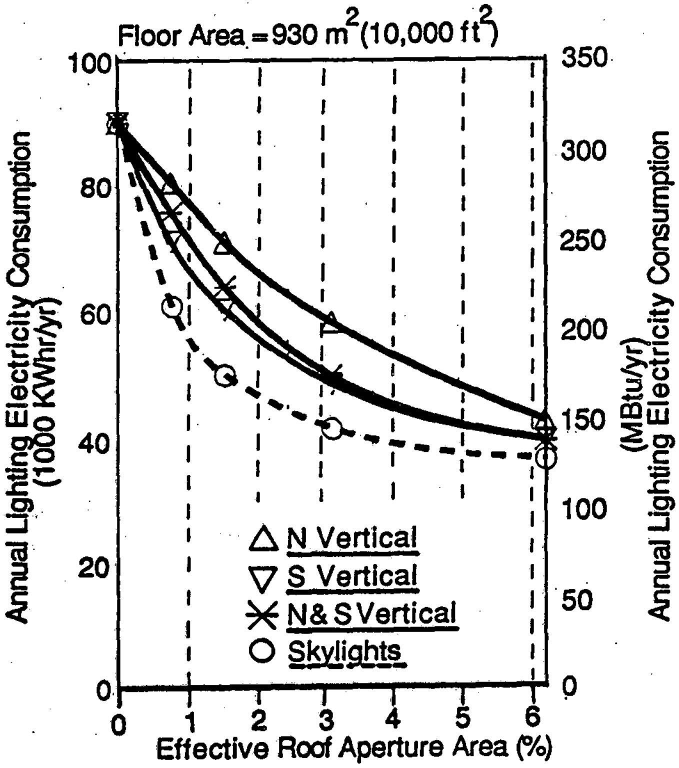

FIG. 8: ANNUAL LIGHTING ELECTRICITY CONSUMPTION IN ATLANTA

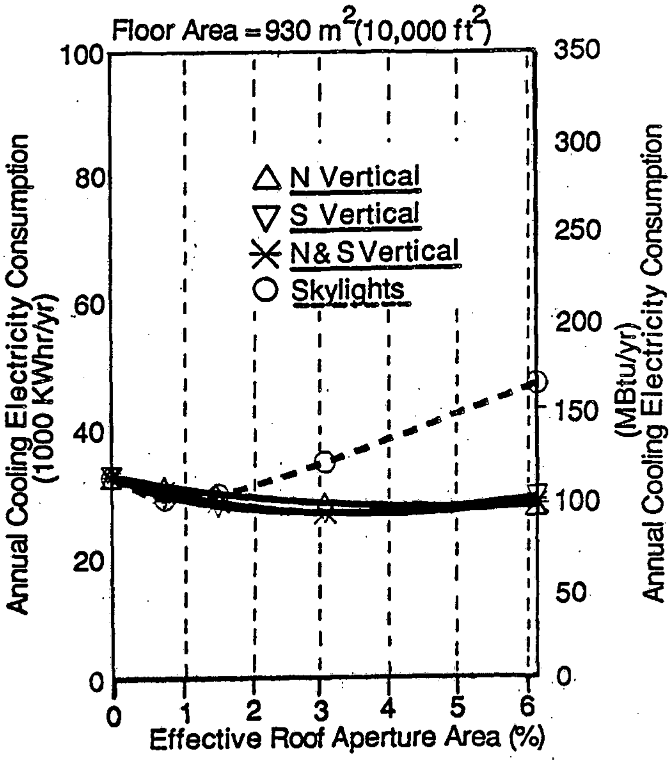

FIG 9: ANNUAL COOLING ELECTRICITY CONSUMPTION IN ATLANTA

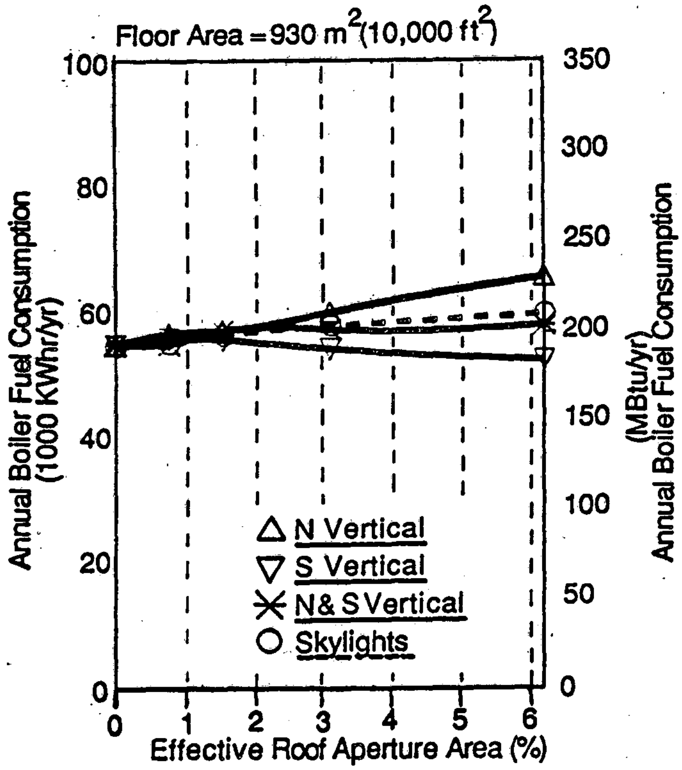

FIG. 10: ANNUAL BOILER FUEL CONSUMPTION IN ATLANTA

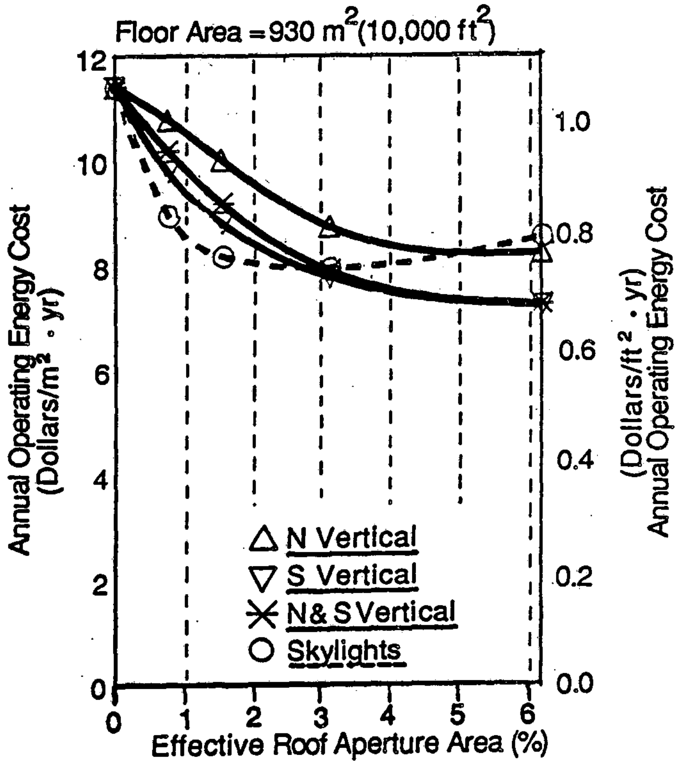

FIG. 11: ANNUAL OPERATING ENERGY COST IN ATLANTA

XBL 873-1144

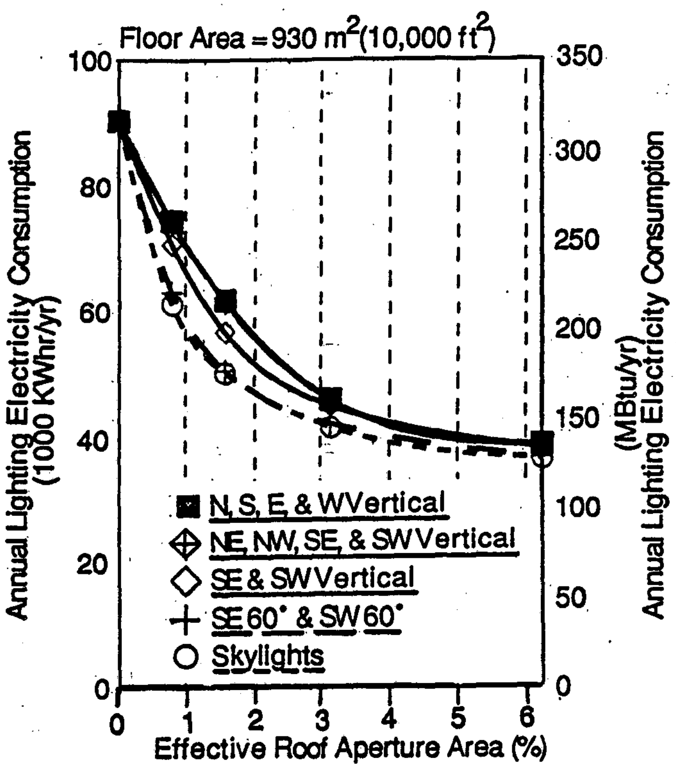

FIG. 12: ANNUAL LIGHTING ELECTRICITY CONSUMPTION IN ATLANTA

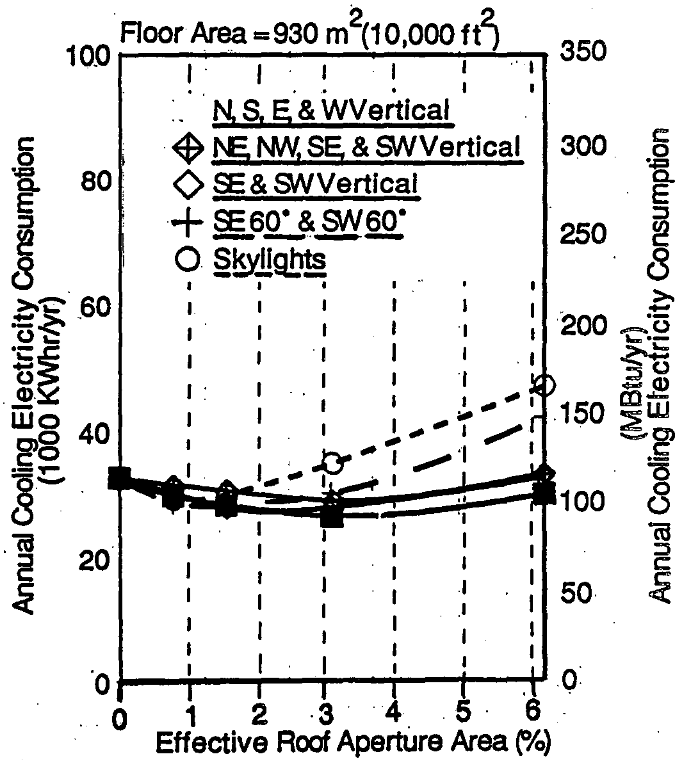

FIG. 13: ANNUAL COOLING ELECTRICITY CONSUMPTION IN ATLANTA

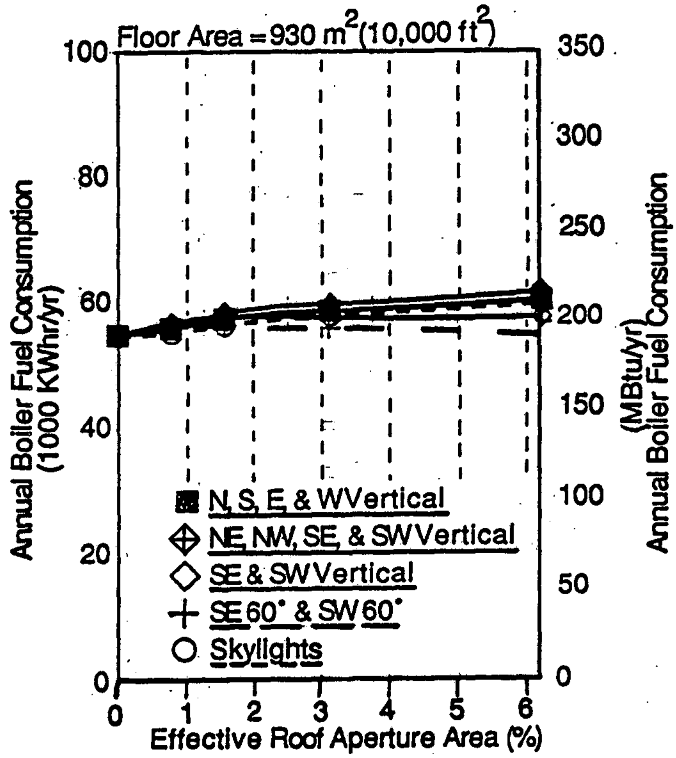

FIG. 14: ANNUAL BOILER FUEL CONSUMPTION IN ATLANTA

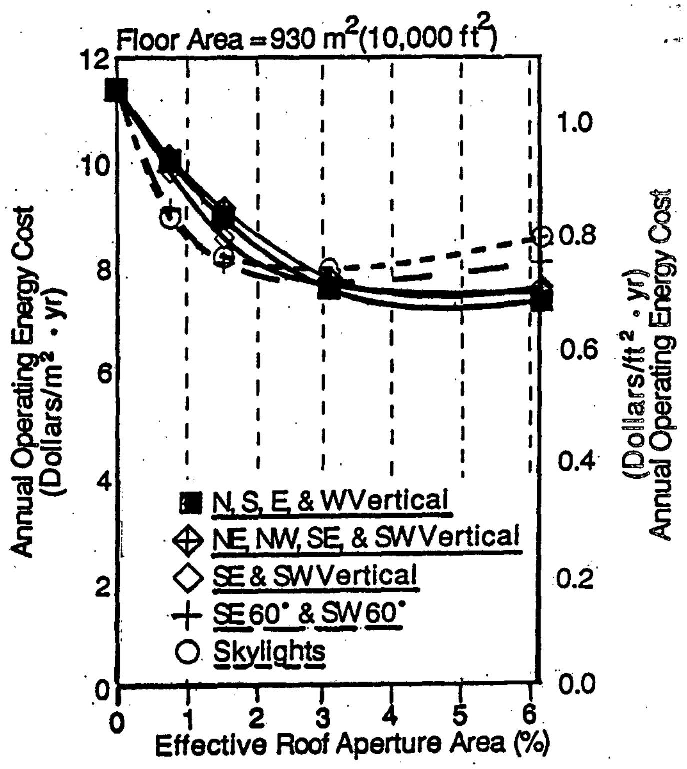

FIG. 15: ANNUAL OPERATING ENERGY COST IN ATLANTA

XBL 873-1143

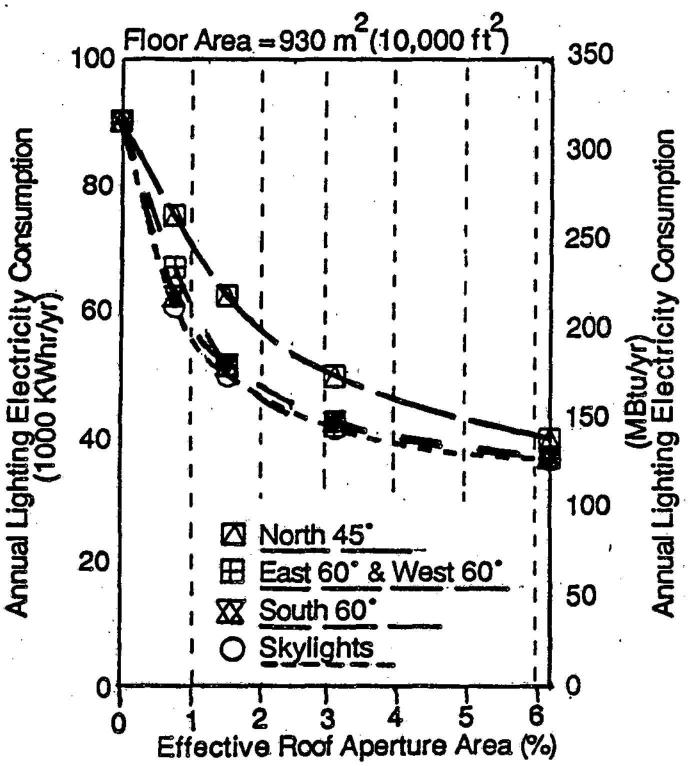

FIG. 16: ANNUAL LIGHTING ELECTRICITY CONSUMPTION IN ATLANTA

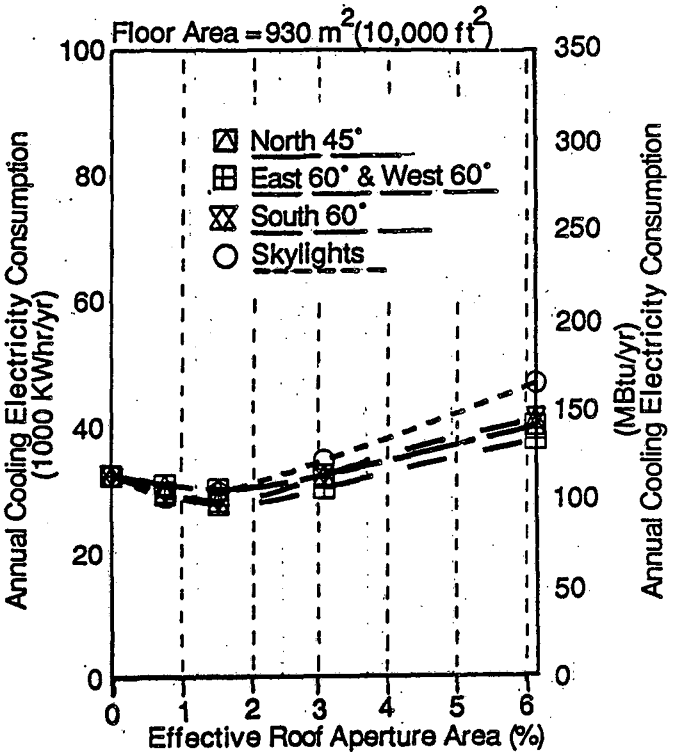

FIG. 17: ANNUAL COOLING ELECTRICITY CONSUMPTION IN ATLANTA

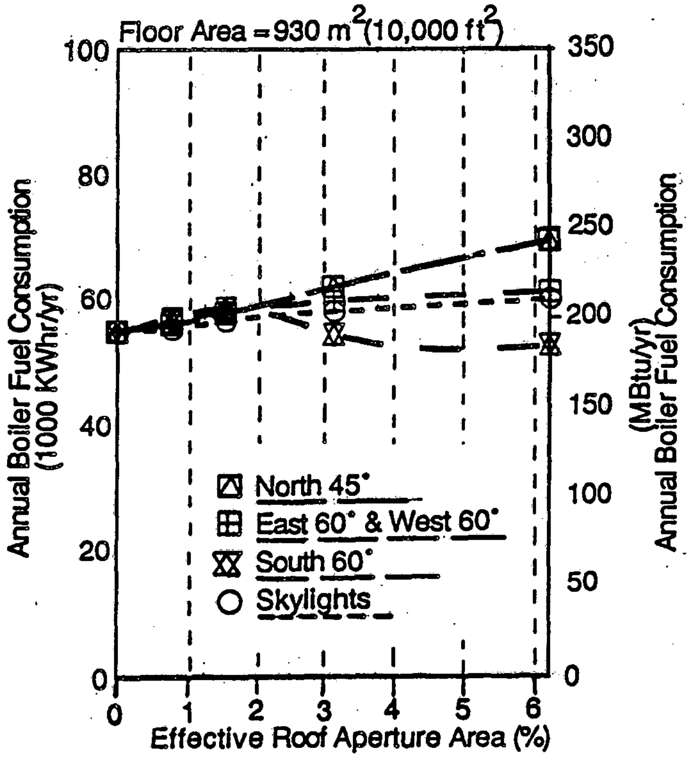

FIG. 18: ANNUAL BOILER FUEL CONSUMPTION IN ATLANTA

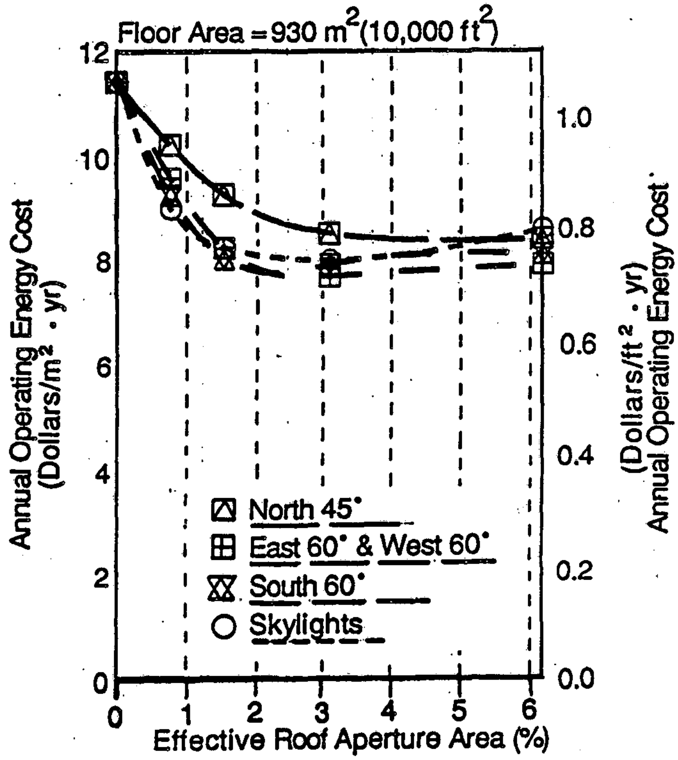

FIG. 19: ANNUAL OPERATING ENERGY COST IN ATLANTA

XBL 873-1142