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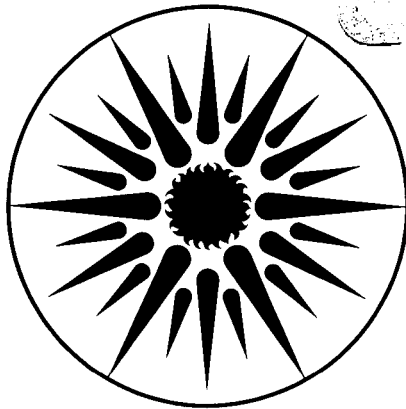
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ON THE ENERGY PERFORMANCE OF OFFICE BUILDINGS

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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. It reports results of scale-model experiments investigating lighting electricity reductions and associated thermal impacts from replacing electric light with sunlight admitted through rooftop glazing on a single-story, prototypical office building.

THE PREDICTED IMPACT OF LINEAR ROOF APERTURES  
ON THE ENERGY PERFORMANCE OF OFFICE BUILDINGS\*

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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<sup>§</sup> 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.

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<sup>#</sup>Synergetics, Inc., P.O. Box 33422 Method Station, Raleigh, North Carolina 27606.

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

INTRODUCTION

Approximately 5 percent of the United States' primary energy is consumed providing illumination in commercial and industrial buildings. Roughly another three percent is consumed for cooling these buildings. Furthermore, buildings account for a substantial fraction of the peak electricity demand on U.S. utilities [1,2]. 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:

- o During most working hours, the solar illumination on a building is several times greater than that required to illuminate the interior, indicating that it should be possible to design solar apertures that provide enough illumination to offset most of the lighting electricity consumption.
- o The luminous efficacy and color rendering of sunlight is generally superior to that of commercially available electric lamps, which means that sunlight has the potential for reducing building cooling loads by replacing electric light of higher heat content.
- o 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.

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. In this study, a clear distinction has been drawn between view glazing and illumination glazing. For purposes of view, the prototype office building has vertical glazing mounted in the walls. In order to reduce cooling loads and glare, this view glazing is assumed to have a transmissivity of only 15%. For purposes

of illumination, another type of glazing is mounted in the roof. The use of roof apertures allows highly uniform light penetration into the building and also allows the selection of any glazing orientation (or combination of orientations) which is favorable to the energy needs of the building. In this study, diffusing illumination glazing is assumed for all orientations other than north-facing, in order to disperse direct-beam sunlight over the workplane. In the analyses reported in this paper, no illumination benefit is attributed to daylight admitted through the view glazing.

The emphasis of the work reported in this paper is on estimating the impact of roof aperture area and orientation on the total energy consumption and energy cost of operating a prototypical office building. All the results presented in this paper deal with glazing configurations which are compatible with linear roof structures, i.e., roofs with penetrations which are substantially elongated in one direction. Figure 1 shows such a system with tilted, south-facing, roof glazing. The glazing orientations evaluated in this study are: 1) horizontal, 2) north-facing vertical, 3) south-facing vertical, 4) south-facing tilted 60 degrees up from horizontal, 5) the combination of east-facing and west-facing, both tilted 60 degrees up from horizontal. A future paper will deal with glazing configurations compatible with two-dimensional roof structures, i.e., roofs with localized penetrations; or island sources (see Fig. 2).

#### BUILDING DESCRIPTION

The floor plan of the building chosen for analysis is shown in Fig. 3. 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 illumination glazing in the roof 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 analysis and experiments under a range of solar conditions have been used to estimate the appropriate spacing between roof monitors for achieving satisfactory uniformity of the illumination on the work plane. Another paper currently being written will describe the experimental scale 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 lighting hardware and the daily 12-hour operating schedule were chosen as representative of current 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 is examined in another paper [4]. 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. 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.

#### 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 540 lux (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 under a range of solar conditions. 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 BLAST simulations of the prototype 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 [5]. Figs. 4-7 show results from some of these simulations for south-facing glazing tilted up 60 degrees from the horizontal.

In Fig. 4, the annual energy consumption for lighting electricity (at the site) is plotted as a function of the aperture ratio, defined as the ratio of roof glazing area to building 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 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. 5, 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. 6, 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 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 4, 5, and 6 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 net

gains during the heating season.

Figure 7 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 4%. Reductions in both lighting and cooling electricity consumption contribute to these utility cost decreases (see Figs. 6 and 7). Beyond an aperture ratio of about 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. 7 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. Furthermore, 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. 7 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 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 4% aperture ratio, but the shape of the curve would change in a manner to make the minimum more pronounced. The effects of more sophisticated comfort controls are currently being studied and will be the subject of a future paper.

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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.

Figures 8 through 11 compare the two tilted glazing configurations just discussed to horizontal glazing, vertical glazing facing north, and vertical glazing facing south. The curves for horizontal glazing are drawn with short dashes, the curves for the tilted glazings are drawn with long dashes and the curves for the vertical glazings are drawn with solid lines. The results presented in Figs. 8 - 11 are for Atlanta, GA.

In Fig. 8, annual lighting electricity consumption at the building site is plotted as a function of the aperture ratio. (As already noted, the consumption of primary energy by the utility to generate power would be on the order of three or four times higher than the consumption at the site.) At essentially all aperture ratios, horizontal glazing has the lowest lighting electricity consumption reflecting the highly effective annual collection of both diffuse skylight and beam sunlight. At all aperture ratios, the north-facing glazing has the highest lighting electricity consumption, reflecting the negligible collection of beam sunlight and the weaker collection of diffuse skylight resulting from the fact that vertical glazing faces only half of the skydome. Lying approximately half way between the curves for horizontal glazing and vertical glazing facing north is the curve for vertical glazing facing south. This result is explained by the fact that vertical glazing facing south collects substantially more beam sunlight than vertical glazing facing north, but is substantially less effective than horizontal glazing in the annual collection of both diffuse skylight and beam sunlight.

The curves for the two tilted glazing configurations (facing south and the combination facing east and west) both lie between the curves for horizontal glazing and vertical glazing facing south. For the combination of tilted glazings facing east and west, 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. For small aperture ratios, the tilted glazing facing south displaces more lighting electricity than the combination of tilted glazings facing east and west. This result can be explained by the fact that the tilted glazing facing south collects more sunlight over the course of a year than does the combination of tilted glazings facing east and west. Consequently, at small aperture areas, where all the collected sunlight is useful in displacing lighting electricity, the tilted glazing facing south produces a lower lighting electricity consumption. For larger aperture ratios, the combination of tilted glazings facing east and west displaces more lighting electricity. This is a result of the superior collection of the combination of tilted glazings facing east and west during early morning and late afternoon hours. Monthly performance information from BLAST indicates that in December the lighting electricity consumption is lower for the tilted glazing facing south than for the combination of tilted glazings facing east and west 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 tilted glazings facing east and west than for the tilted glazing facing south, with the most pronounced difference occurring at large aperture ratios. For small aperture ratios, the superior wintertime collection of the tilted glazing facing south dominates the slightly superior summertime collection of the combination of tilted glazings facing east and west, resulting in lower annual lighting electricity consumption for the tilted glazing facing south. For large aperture ratios, the superior summertime collection of the combination of glazings facing east and west dominates the slightly superior wintertime collection of the tilted glazing facing south, resulting in lower annual lighting electricity consumption for the combination of glazings facing east and west.

In Fig. 9, annual cooling electricity consumption at the site (fans plus direct expansion cooling unit) is plotted versus aperture ratio. At small aperture ratios, the lowest cooling electricity consumption occurs for the orientations which collect the most sunlight during the cooling season (e.g., horizontal glazing, tilted glazing facing south, and tilted glazing facing east and west). This result is explained by the fact that, at small aperture ratios, all the sunlight collected is useful in displacing electric lighting of higher heat content. At higher aperture ratios, the order of the curves is reversed, in the sense that the higher cooling electricity consumption is produced by the orientations which collect the most sunlight during the cooling season. The higher cooling electricity consumption at large aperture ratios results from excess solar gains which do nothing to offset lighting electricity consumption, but which do contribute to the cooling load. At all aperture ratios, the cooling electricity consumption is higher for the tilted glazing facing south than for the combination of tilted glazings facing east and west. 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 tilted glazing facing south 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. 10, boiler fuel consumption is plotted as a function of aperture ratio. At small aperture ratios, the highest boiler fuel consumption occurs for the glazings which collect the most sunlight during the heating season (e.g., tilted and vertical glazings facing south). This result can be explained by the fact that at small aperture ratios all the admitted sunlight is useful in displacing electric light of higher heat content. At large aperture ratios, the lowest boiler fuel consumption occurs for the apertures which collect the most sunlight during the heat-

ing season, reflecting the heating benefits of solar radiation gains which exceed the illumination requirement of the building. Two important points should be made relative to heating energy requirements. To begin with, the boiler fuel consumption is less sensitive to changes in glazing area and orientation than is cooling electricity consumption, because the solar resource is weaker during the heating season. Secondly, the cost of boiler fuel is substantially less than the cost of electricity at the building boundary. In other words, for the prototype under study, both the magnitude of the heating costs and the variation in heating costs are relatively inconsequential part of the total energy costs. In fact, for Atlanta, the annual cost for boiler fuel is in the range of 5% - 10% of the total annual energy cost for operating the prototype building. However, from a primary energy point of view, boiler fuel consumption is a significantly larger part of the problem. This is particularly true of more northerly climates (see again Figs. 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. Also, in this study we have not addressed serious strategies for reducing heating energy consumption, such as using thermal storage or low-conductance glazings. These issues are currently being addressed and will be the subject of future publications.

In Fig. 11, annual operating costs are plotted versus aperture ratio. At very small aperture ratios, horizontal glazing has the lowest annual energy cost, reflecting the highly effective collection of sunlight. At slightly higher aperture ratios, tilted glazing facing south has the lowest annual energy cost, reflecting its good annual collection of sunlight and also its good balance between summertime and wintertime collection. At even larger aperture ratios, the combination of tilted glazings facing east and west has the lowest annual energy cost, reflecting its good early morning and late afternoon collection of sunlight. At the largest aperture ratios studied, vertical glazing facing south has the lowest annual energy cost, reflecting its excellent collection of solar radiation during the heating season, which is achieved without excessive solar gains during the cooling season.

For the glazing orientations examined in this paper, the highest annual energy cost savings per unit of floor area is achieved by vertical south-facing glazing at an aperture ratio of about 10%. For the combination of building type, climate, and electric lighting system examined in this paper, these savings will be on the order of \$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 construction costs about one hundred times larger than these annual energy cost savings. However, there are two points which should be made. To begin with, these energy cost savings will accrue throughout the life of the building. Secondly, it is prob-

ably more meaningful to evaluate 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 ten percent aperture ratio, the annual energy cost savings for the vertical, south-facing glazing is about \$40 per square meter of glazing per year (\$4.00 per square foot of glazing per year). Furthermore, 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 aperture ratios (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 \$200 per square meter of glazing area per year (\$18 per square foot of glazing area per year). Of course, the predicted savings will be sensitive to various assumptions in the analysis, particularly the efficiency of the electric lighting system [4].

A general comment can be made about the range of applicability of Figs. 3 through 11. It has been established in other studies [4,6] that 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 sunlight for electric light, 2. the thermal impact of excess solar radiation gains through the glazing, and 3. the thermal impacts of conductive gains and losses through the glazing. For the small glazing areas examined in this paper, conductive gains and losses are relatively inconsequential when compared to either lighting electricity reductions or excess solar radiation gains. This fact allows us to apply the results in Figs. 4 through 11 to glazings having transmissivities different from the 0.62 assumed in the simulations used to generate the figures. The key point is the following: for any two glazings with the same product of transmissivity and area, the transmitted illumination and radiation will be the same, and therefore the lighting electricity reductions and thermal impacts of solar radiations gains will be the same. The only difference will be in conductive gains and losses, which, as we have noted above, are relatively inconsequential. If we want to estimate the effect of a glazing with a transmissivity which is larger by a factor  $f$  than the one used in this study, then we reduce the aperture ratio of interest by the factor  $1/f$  before looking for the appropriate effect in Figs. 4 through 11. This procedure can be applied reliably to all glazing orientations simulated with the possible exception of north-facing glazing where the modest levels of solar gain make the conductive gains and losses relatively more important.

## 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) The highest annual energy cost savings per unit of floor area is achieved by vertical south-facing glazing at an aperture ratio of about 10%. For the combination of building type, climate, and electric lighting system examined in this paper, these savings will be on the order of \$4 per square meter of floor area per year (\$.40 per square foot of floor area per year). At ten percent aperture ratio, these figures translate to about \$40 per square meter of glazing (\$4.00 per square foot of glazing). (The predicted savings will be sensitive to various assumptions in the analysis, particularly the efficiency of the electric lighting system [4].)
- (5) The highest annual energy cost savings per unit of glazing area is achieved by horizontal glazing at very small aperture ratios (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 \$200 per square meter of glazing (\$18 per square foot of glazing).
- (6) Movable insulation or external shades, which properly control the solar gains 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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## REFERENCES

1. Jim McMahon, Craig Conner, Ronald C. Kammerud, and Wayne Place, "A Review and Analysis of Commercial Building Energy Consumption Studies," LBL Report LBL-10620 Draft (to be published).
2. W.L. Carroll et al., "Passive Cooling Strategies for Nonresidential Buildings: An Impact Assessment," Lawrence Berkeley Laboratory Report LBL-14558 (to be published).
3. IES Lighting Handbook, edited by J.E. Kaufman, Illumination Engineering Society of North America, New York, 1981.
4. Marc Fontoynt, Wayne Place, and Fred Bauman, "Impact of Electric Lighting Efficiency on the Energy Saving Potential of Daylighting from Roof Monitors," Lawrence Berkeley Laboratory Report LBL-15032, to be Published in Energy and Buildings.
5. Brandt Andersson, William L. Carroll, and Marlo Martin, "Aggregation of U. S. Population Centers into Climate Regions," in Proceedings, Seventh National Passive Solar Conference, Knoxville, TN, August 29-September 1, 1982. Lawrence Berkeley Laboratory Report LBL-14351.
6. S. Selkowitz, R. Johnson, R. Sullivan, and S. Choi, "The Impact of Fenestration on Energy Use and Peak Loads in Daylighting Commercial Buildings," Lawrence Berkeley Laboratory Report LBL-15889, presented at PASSIVE 83, the National Passive Solar Conference, Glorieta NM, September 7-9, 1983.
7. Arthur H. Rosenfeld and Stephen E. Selkowitz, "Beam Daylighting: An Alternative Illumination Technique," Energy and Buildings, 1 (1977) 43-50.

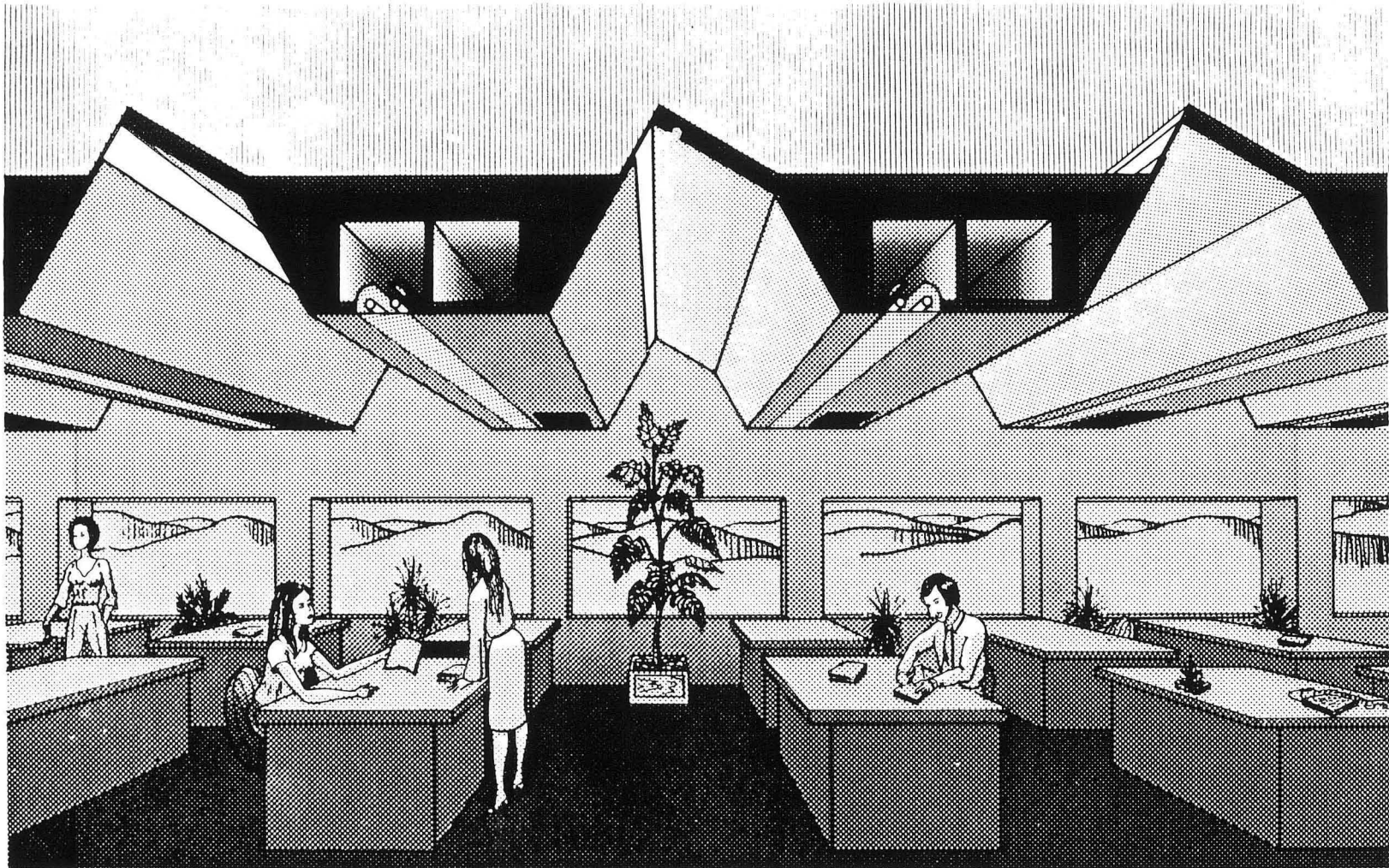
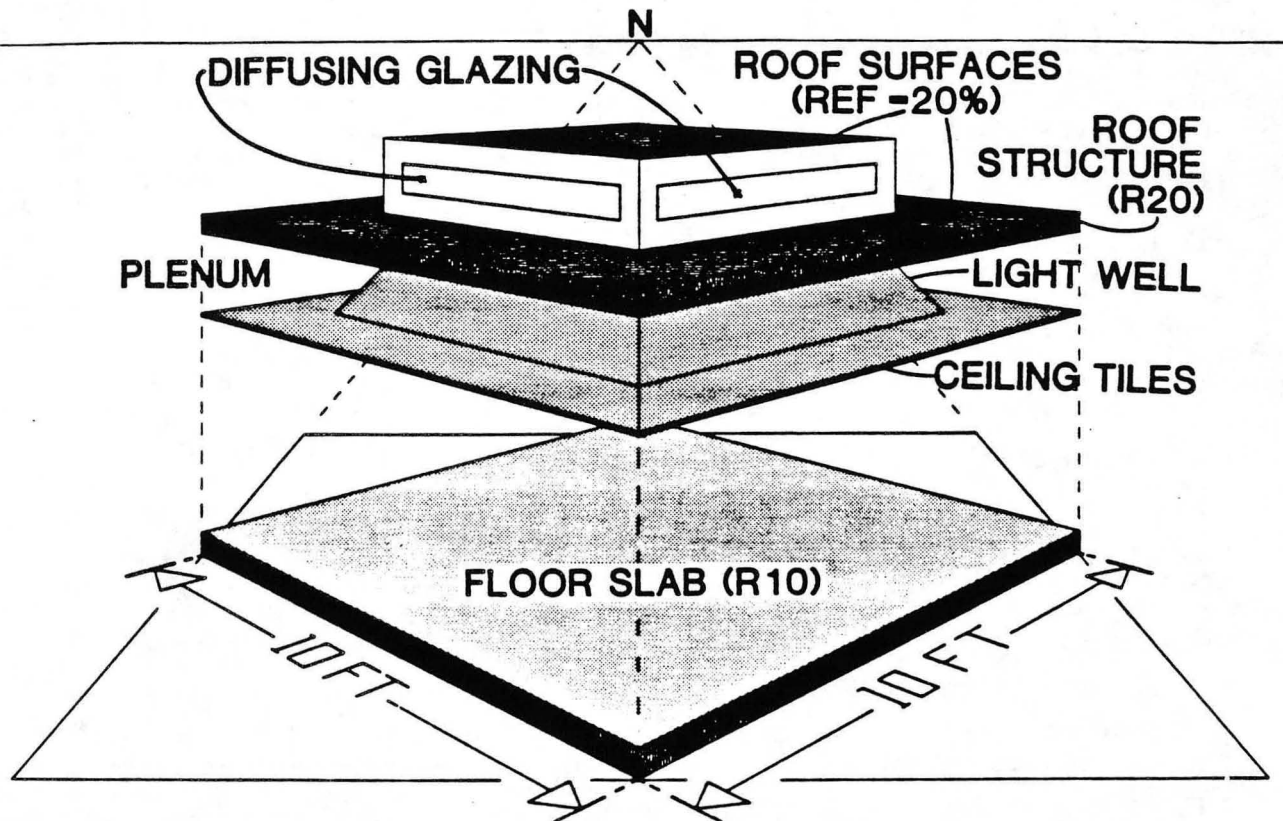
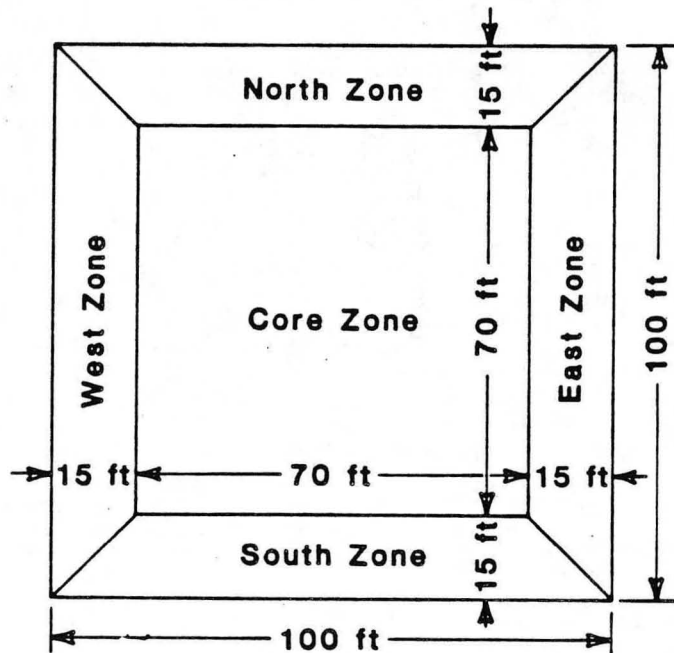


FIG. 1: A LINEAR ROOF APERTURE SYSTEM WITH DIFFUSING GLAZING TILTED TOWARD THE SOUTH

XBL 825-10228



**FIG. 2: A ROOF APERTURE CONFIGURATION SUITABLE FOR TWO-DIMENSIONAL GRID STRUCTURE**



**FIG. 3 SCHEMATIC FLOOR PLAN OF PROTOTYPE COMMERCIAL BUILDING.**

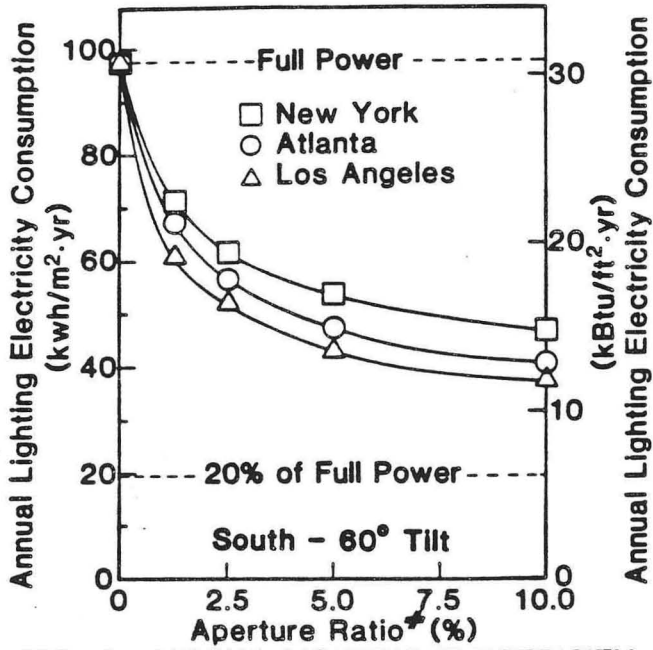


FIG. 4. ANNUAL LIGHTING ELECTRICITY

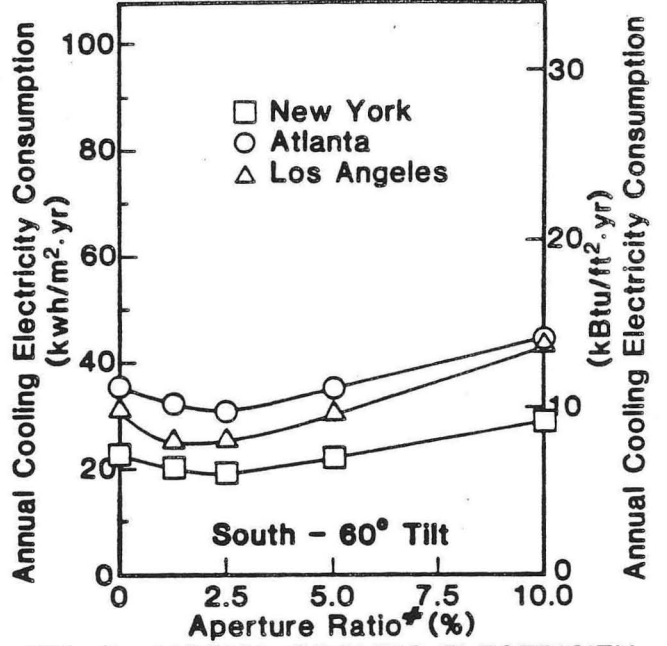


FIG. 5. ANNUAL COOLING ELECTRICITY

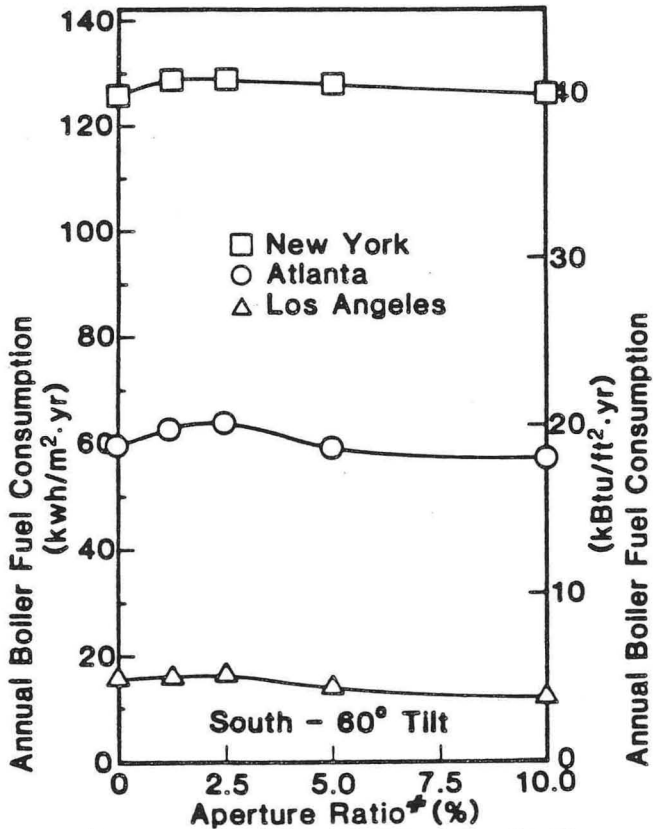


FIG. 6. ANNUAL BOILER FUEL

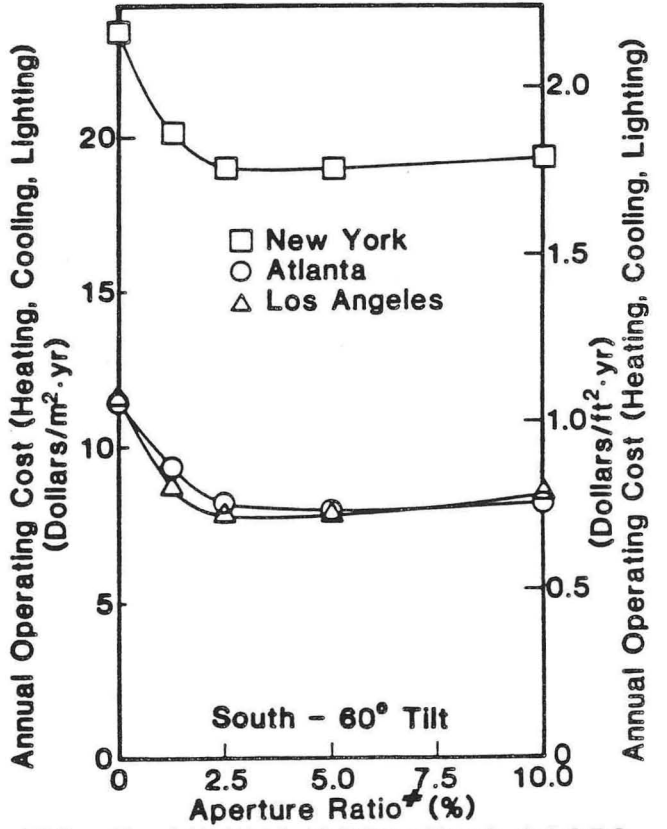


FIG. 7. ANNUAL OPERATING COSTS.

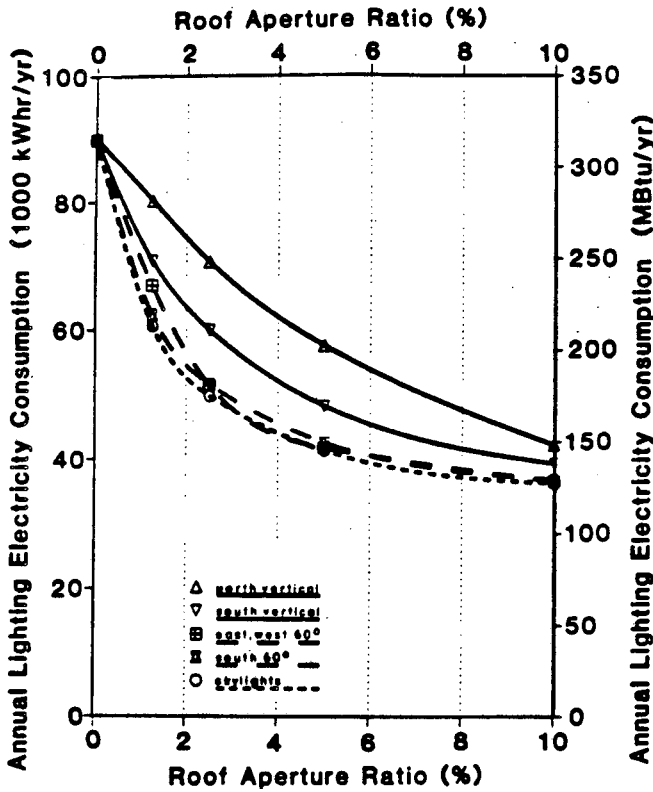


FIG. 8: ANNUAL LIGHTING ELECTRICITY CONSUMPTION IN ATLANTA

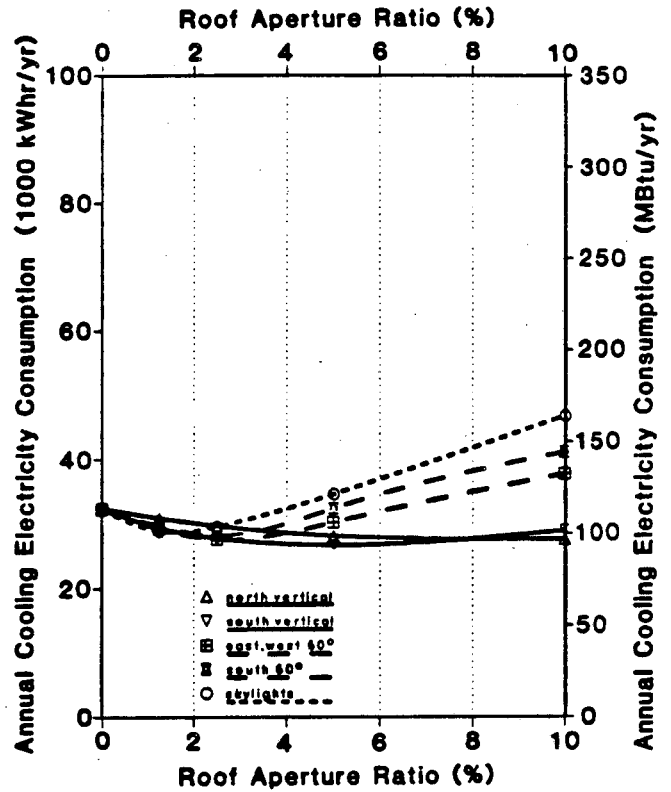


FIG. 9: ANNUAL COOLING ELECTRICITY CONSUMPTION IN ATLANTA

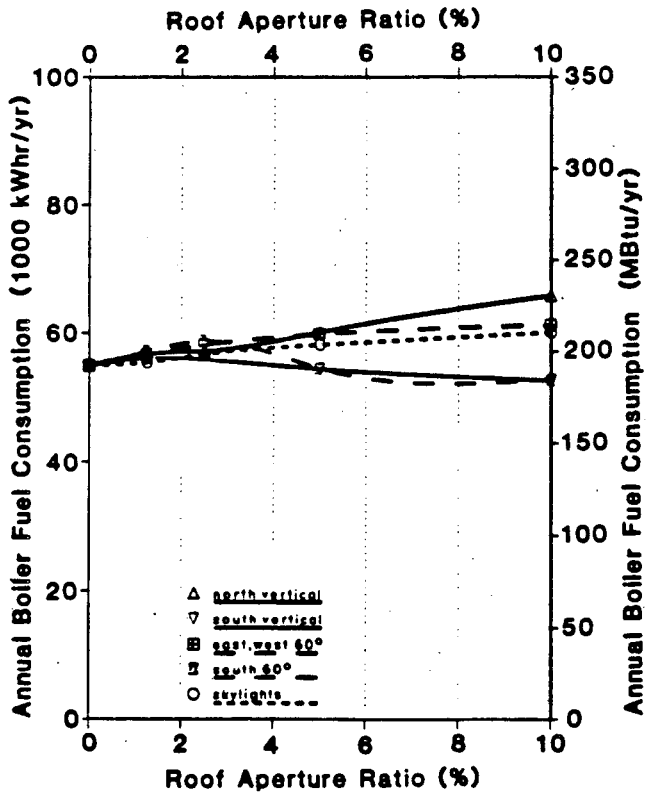


FIG. 10: ANNUAL BOILER FUEL CONSUMPTION IN ATLANTA

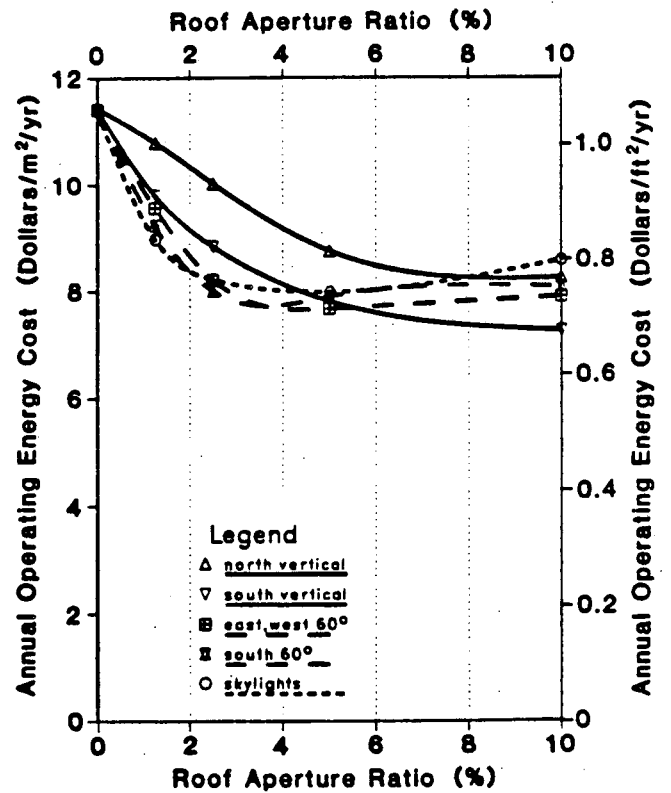


FIG. 11: ANNUAL OPERATING ENERGY COST IN ATLANTA

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