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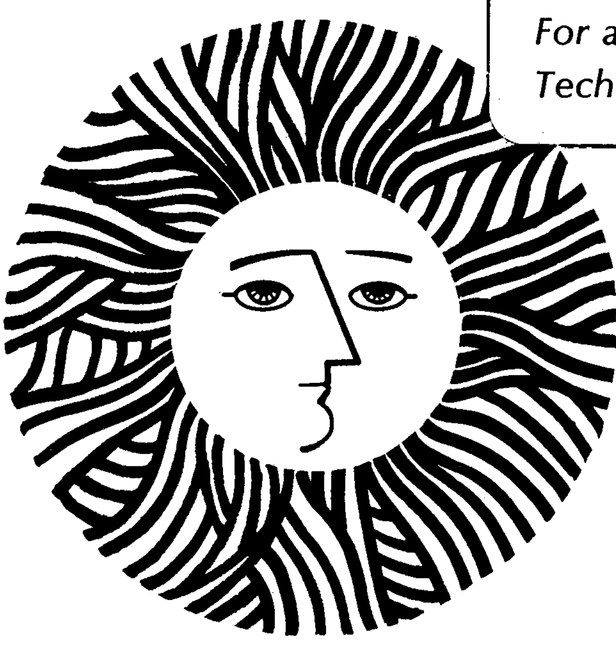

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COMMERCIAL BUILDING DAYLIGHTING*

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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 commercial building. Experimental scale models have been used to determine the fraction of the solar radiation entering the aperture which reaches the work plane as useful illumination. This information is used in a developmental version of the building energy analysis computer program BLAST-3.0§ to predict reductions in lighting electricity and the impacts on energy consumption for heating and cooling the building. It is found in general that the lighting electricity reductions are more significant than the heating and cooling impacts in a properly designed system. In an improperly designed daylighting system, where reduction of lighting electricity is the only design criterion, deleterious thermal impacts can negate the lighting electricity benefits.

1. INTRODUCTION

Lighting accounts for about one-quarter of the total primary energy use in the existing American commercial building stock [1]. For office buildings constructed with current practice thermal envelope integrity and HVAC efficiency, this fraction is closer to one-half [2]. Providing illumination in buildings using sunlight as a substitute for electric light is attractive for several reasons:

- During most working hours, the solar illumination incident on a building is several times greater than that required to illuminate the building interior, indicating that it should be possible to design solar apertures that provide enough illumination to offset most of the lighting electricity consumption.
- The luminous efficacy of natural light is generally higher than that of commercially available electric lamps, which means that sunlight has the potential for reducing cooling loads by replacing electric light of higher heat content.
- Reductions in site electricity (for both cooling and lighting) result in substantially larger savings in primary energy, owing to utility generating inefficiencies and network losses.
- Sunlight is normally plentiful during the hottest summer periods when many utilities experience their peak demand, suggesting that there is potential for reducing demand for both cooling and lighting electricity, with consequent demand-charge savings for the building owners and the potential for reduced capacity requirements for the utility.

2. PROBLEM APPROACH

The purpose of this study is to make a preliminary assessment of the maximum potential for reducing energy consumption in a commercial building using simple daylighting apertures constructed with current technology. Although daylight can be admitted through any aperture in the building, achieving the most effective interior illumination with sunlight

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

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

requires care in the placement and design of the illumination glazing. To achieve the maximum potential energy savings without reducing illumination effectiveness, the following conditions must be satisfied:

- The sunlight admitted through the apertures must be delivered to the task surface in an efficient and effective manner. In the case of the office building under study, this means delivering as much of the admitted sunlight as possible, as uniformly as possible, to the plane of the desk tops.
- The room must be free of glare which diminishes the effectiveness of the illumination system.

These conditions can be achieved in a single-story building (or on the top floor of a multi-story building) by

- using closely-spaced illumination apertures in the roof, thereby producing uniform illumination on the work plane and minimizing visual discomfort by keeping the light sources outside the field of view of people involved in tasks at the work surface (see Fig. 1);
- using reflective view glazing in the walls, thereby eliminating a bright source in the field of view of an occupant involved in the primary task;
- using light-colored interior surfaces, thereby increasing the amount of light reaching the work plane from the apertures and reducing contrasts between the light sources and opaque surfaces within the space.

This paper presents BLAST predictions of the lighting electricity reductions and heating and cooling energy impacts of daylighting in a single-story office building designed according to the rules outlined above.

3. BUILDING DESCRIPTION

The floor plan of the building chosen for analysis is shown in Fig. 2. For simulation purposes, the square, 10,000 ft^2 building was divided into five thermal zones: four perimeter zones and one larger core zone. The 12-ft high external walls contained 12%-transmissivity, double-pane view glazing 3.5 ft high, extending the full length of each wall. A more complete description of the building's thermal envelope, internal loads, operating schedules, and HVAC system can be found in Ref. [2].

The daylighting system consists of roof monitors fitted with south-facing, double-pane glass tilted 60 degrees up from the horizontal and extending the full width of the building. Figure 1 shows the roof aperture configuration, the roof structural elements, and the arrangement of ducts and electric light fixtures. The illumination glazing consists of two panes of .25-in thick glass with an overall normal solar transmissivity of 0.624. The inner glass pane is assumed to be an excellent diffuser. Simulations were performed for a range of aperture ratios from 1.25% to 10.0%. (Aperture ratio is defined here as the ratio of the total illumination glazing area to the total building floor area.) Both experiments and analysis were used to estimate the appropriate spacing between roof monitors to achieve satisfactory uniformity of the illumination on the work plane.

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 50 footcandles on the work plane. From this calculation, a power level of about 2.5 W/ft^2 for the lights was deduced. The lighting hardware and the daily 12-hour operating schedule were chosen to be representative of current practice rather than the current state-of-the-art. Controls are provided to adjust the electric lighting power level in response to the presence of sunlight.

4. 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.

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

(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 fifty footcandles on the work plane (unless constrained by assumption (4) below).

(4) Power to the lights cannot be reduced below 20% of full power. (This assumption is based on current limitations of the technology for continuous control of fluorescent bulbs. Further power reductions could be achieved by combinations of continuous controllers and on-off switches, but that topic is not treated in this paper.)

Each hour BLAST keeps track of the lighting electricity savings associated with reductions in power to the lights. At the same time, BLAST also accounts for the heating and cooling impacts of solar gains and conductive losses associated with the illumination glazing and reduced lamp heat output. To perform a BLAST daylighting analysis, the user must specify the following two parameters of the daylighting and electric lighting systems:

(1) The luminous efficacy of the radiation as a ratio of light content to energy content. The simulations described in this paper assume the luminous efficacy of both beam and diffuse sunlight to be 100 lumens/W. The luminous efficacy of light from the cool white fluorescent lamps was assumed to be 62 lumens/W [3].

(2) The fraction of the radiation from the emitting surface which reaches the workplane, expressed as a dimensionless quantity called the coefficient of utilization (CU). Based on both small-scale experiments and analytic information, a CU of 0.72 was selected for the light emitted from the interior surface of the illumination glazing. The CU for light emitted from the surface of the fluorescent bulbs is 0.61 [3]. In this case, the predominant reason for the superior CU of the solar system is that much of the light emitted by the interior surface of the illumination glazing can go directly to the work plane; this is in contrast to the electric lighting system which has a cover plate on the luminaire.

Using the luminous efficacies of sunlight and electric light and the coefficients of utilization for the daylighting and the electric lighting systems, BLAST calculates the reduction in electric lighting power as a function of the solar power admitted through the illumination glazing.

5. RESULTS

A number of annual and design day BLAST simulations of the prototype building were performed with TMY weather data from New York, Atlanta, and Los Angeles. The results from some of these simulations are presented below.

Figure 3 shows the hourly variations in lighting requirements in Atlanta on July 10th for two design conditions: one clear day (maximum beam = 877 W/m^2, maximum diffuse = 118 W/m^2) and one overcast day (maximum beam = 15 W/m^2, maximum diffuse = 120 W/m^2). An aperture ratio of 2.5% was used for both simulations. The plots indicate that the illumination apertures work much better near midday than in the morning and afternoon--a result of diurnal variations of solar radiation direction and intensity, reinforced by the directional selectivity of the illumination glazing. The diurnal variation in the direction of beam sunlight can be addressed by using glazing of more than one aperture orientation.

The annual energy consumption for lighting electricity (at the site) is plotted in Fig. 4 as a function of the aperture ratio. (The consumption of primary energy at the utility power plant would be on the order of 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 has clearer weather.

The annual energy consumption for cooling electricity (at the site) is plotted vs. aperture ratio in Fig. 5. 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.

The annual energy consumption in boiler fuel is plotted versus aperture ratio in Fig. 6. 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 at large aperture areas, 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 limit summer gains to the level needed for illumination and controlled to maximize winter gains when heating is required and the glazing is a net gainer.

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 3%. Reductions in both lighting and cooling electricity consumption contribute to these utility cost decreases (see Figs. 4 and 5). Beyond an aperture ratio of 3%, increases in cooling electricity dominate decreases in lighting electricity, and the costs increase gradually with aperture area.

6. CONCLUSIONS

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

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

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

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

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

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

7. ACKNOWLEDGEMENT

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8. REFERENCES

(1) McMahon, J., Conner, C., Kammerud, R., and Place, W., "A Review and Analysis of Commercial Building Energy Consumption Studies," LBL Report LBL-10620 (to be published).

(2) Carroll, W.L., et al., "Passive Cooling Strategies for Nonresidential Buildings: An Impact Assessment," LBL Report LBL-14558 (to be published).

(3) IES Lighting Handbook, edited by J.E. Kaufman, Illumination Engineering Society of North America, New York (1981).

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*The rate schedules were obtained from the Johnson Environmental and Energy Center at the University of Alabama for the utilities serving each of the three cities.

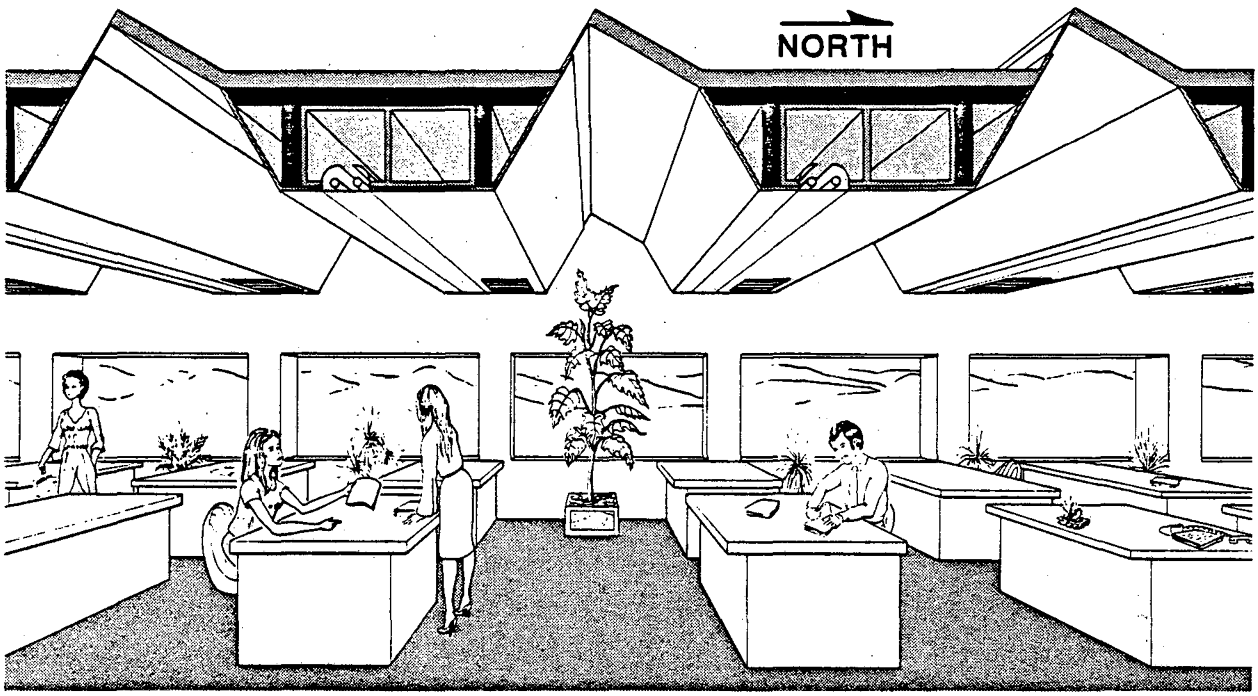

FIG. 1. PERSPECTIVE SECTION OF PROTOTYPE COMMERCIAL BUILDING.

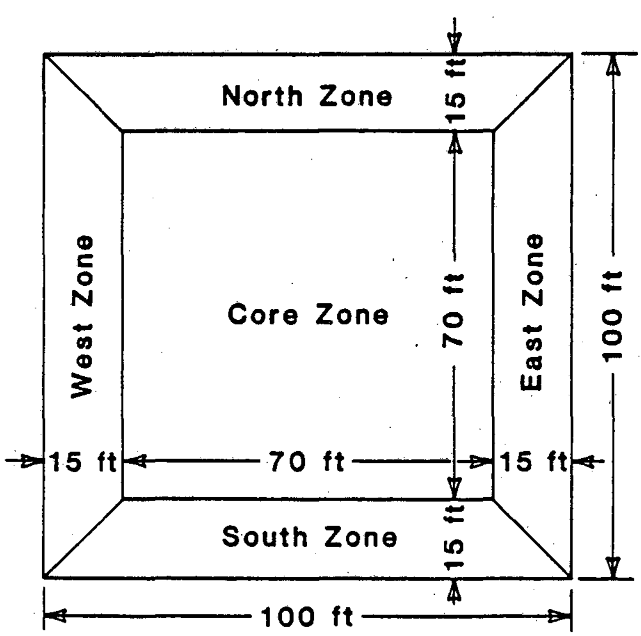

FIG. 2. SCHEMATIC FLOOR PLAN OF PROTOTYPE COMMERCIAL BUILDING.

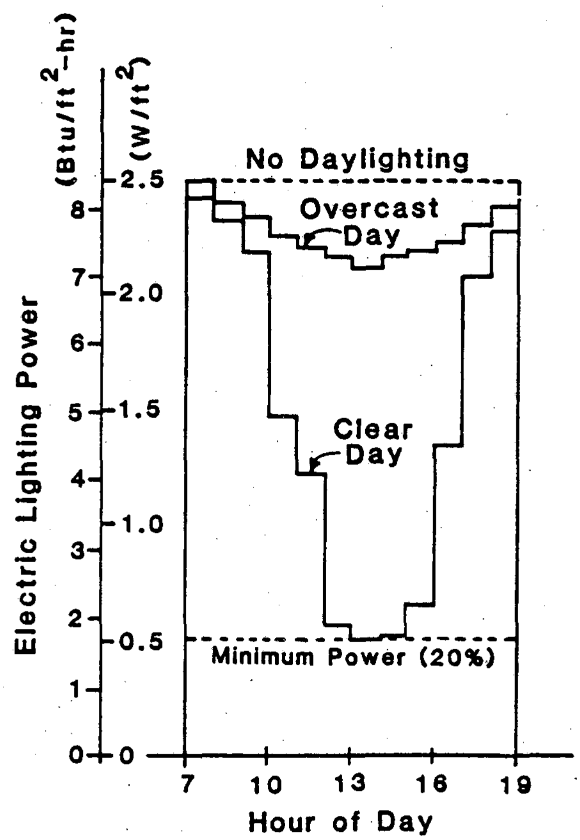

FIG. 3. HOURLY VARIATIONS OF ELECTRIC LIGHTING POWER.

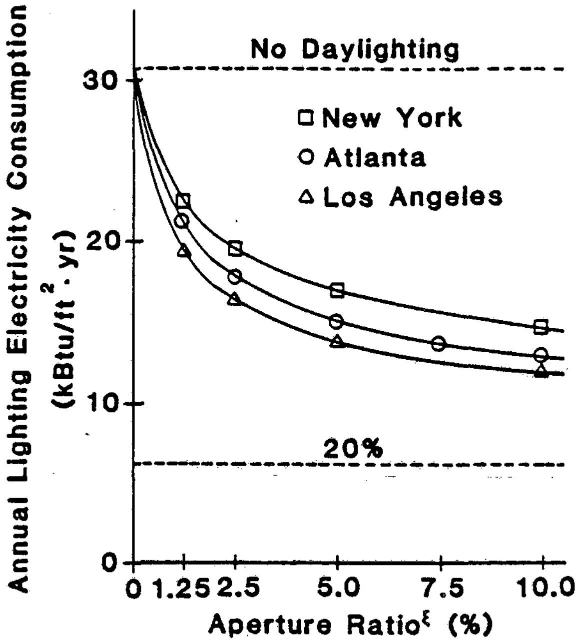

FIG. 4. ANNUAL LIGHTING ELECTRICITY.

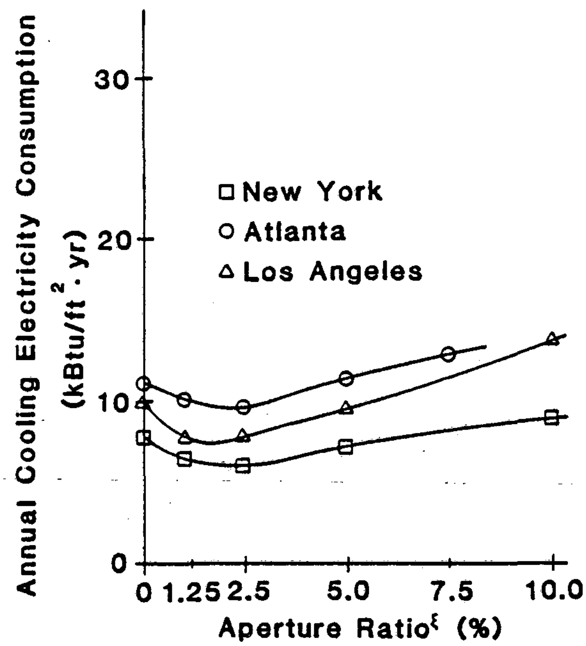

FIG. 5. ANNUAL COOLING ELECTRICITY.

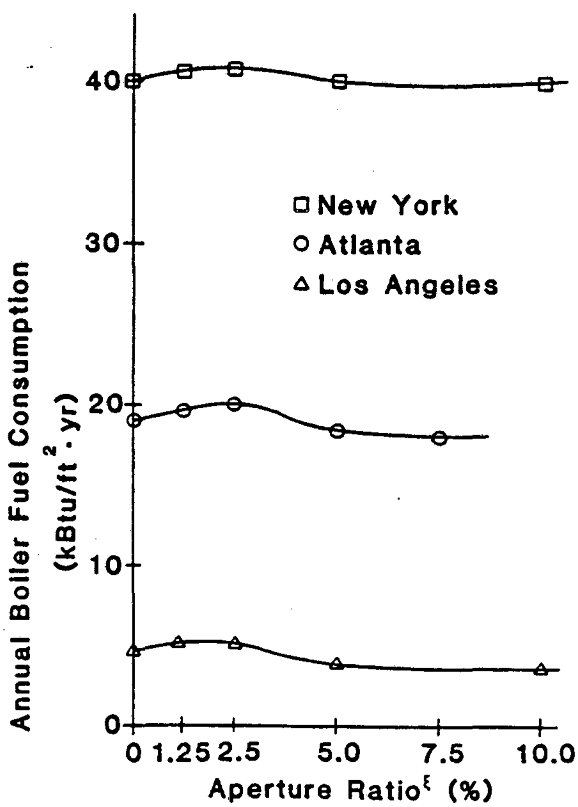

FIG. 6. ANNUAL BOILER FUEL.

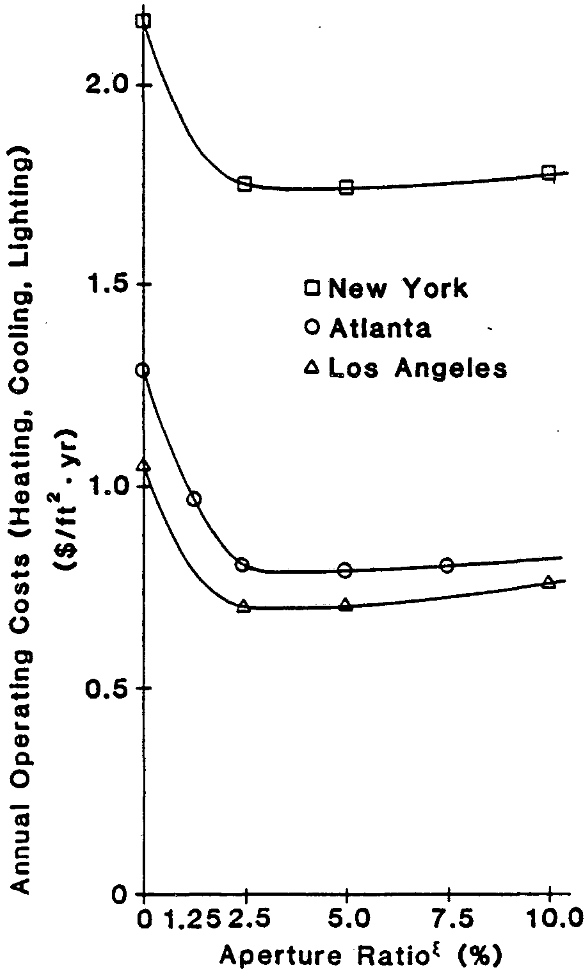

FIG. 7. ANNUAL OPERATING COSTS.

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

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