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LIFE-CYCLE COST AND ENERGY-USE ANALYSIS OF SUN-CONTROL AND DAYLIGHTING OPTIONS IN A HIGH-RISE OFFICE BUILDING

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ABSTRACT

The DOE-2 building energy analysis computer program has been used to study the life-cycle cost and annual energy use for a wide range of glazing and sun-control options in a 25-story office building with 50% glazing. Four climates in the U.S. have been analyzed: Miami, Los Angeles, Washington, D.C., and Chicago. The impact of daylighting in the perimeter zones for the various sun-control options has also been investigated. Double glazing was found to have little effect on energy use in Miami and Los Angeles, but reduced energy use 11 - 23% in Washington, D.C., and 16 - 32% in Chicago. Daylighting reduced energy use 10 - 22% and had a simple payback period of 3.7 - 8.9 years depending on climate and type of fenestration. Of the alternatives considered, the lowest life-cycle cost and energy use were obtained with daylighting coupled with clear glazing and exterior sun-control blinds.

KEYWORDS

Life-cycle cost, energy conservation, energy use in buildings, daylighting, sun control

INTRODUCTION

The choice of fenestration for a building can significantly affect its thermal performance as well as its construction and operating costs. This is particularly true of office buildings, which typically have large window areas. To quantify the effect of fenestration on energy use and life-cycle cost, the DOE-2 building energy analysis computer program has been used to compare different glazing, sun-control, and daylighting options in a high-rise office building. The same prototype building was studied in four different locations: Miami, Los Angeles, Washington, D.C., and Chicago. The following fenestration options have been analyzed for both single and double glazing:

- clear glass with operable interior blinds;
- clear glass with operable exterior blinds;
- tinted (heat-absorbing) glass with and without interior blinds;
- tinted glass with reflective coating.

The effect of perimeter-zone daylighting in conjunction with the above options has also been considered.

For each alternative, the peak electrical demand, the annual energy use, and the present value of the life-cycle cost have been determined. The life-cycle cost includes the initial cost of blinds, if present, and glazing; the cost of the plant equipment needed to meet the heating and cooling requirements of the building; the cost of daylighting controls, if present; the cost for maintenance of blinds and plant equipment; and the cost of energy.

The energy-use calculations were carried out with Version 2.1 of the DOE-2 building energy analysis computer program [1]. This program determines the annual energy use (for heating, cooling and lighting) and energy cost, taking into account such factors as geometry and construction of the building envelope, hourly-varying weather conditions, building operating schedules, and the efficiency of primary HVAC equipment.

This paper is organized as follows. First, the architecture, HVAC system, and operating schedules of the building model are described. This section is followed by a discussion of the weather data, a description of the various glazing and sun-control options, a discussion of the daylighting analysis approach, and an overview of the economics calculation methodology. Results are given in two sections, one for the components of the annual heating and cooling load and the annual energy use, and a second for the life-cycle cost and annual energy use for each fenestration option. A complete set of results is presented in tabular form in the appendix.

DESCRIPTION OF THE BUILDING MODEL

The building chosen for this study is typical of high-rise office buildings currently being constructed in the U.S. Figure 1 shows a perspective view of the building and of a typical floor.

For the thermal analysis, each floor was divided into four perimeter zones served by a four-pipe induction system, and a central core zone served by a variable air volume system. The major features of the building's envelope, HVAC systems, and operating schedules are summarized below.

Envelope. The building is rectangular, 79.25 m by 19.8 m (260 ft by 65 ft), with the narrow facades facing north and south.* There are 25 stories, with a floor-to-floor height of 3.96 m (13 ft). The gross floor area is 39,250 m^2 (422,500 ft^2). Exterior walls have an overall U-value of 0.74 W/m^2-^oC (0.13 Btu/hr-ft^2-^oF), and consist of 0.64 cm (1/4 in) spandrel glass, 5.1 cm (2 in) of rigid insulation, and steel siding. The roof has an overall U-value of 0.57 W/m^2-^oC (0.10 Btu/hr-ft^2-^oF), and consists of gravel, built-up roofing, 3 in (7.6 cm) of preformed insulation, and 4 in (10.2 cm) of standard-weight concrete.

Windows cover 50% of the wall area and are flush with the outer wall surface.

Each floor of the building has five zones: a core zone and four 4.57 m (15 ft) deep perimeter zones. Partitions between zones have an overall U-value of 8.52 W/m^2-^oC (1.5 Btu/ft^2-hr-^oF). Interior floors are 10.2 cm (4 in) standard weight concrete.

Internal Loads. The lighting is recessed fluorescent, 32.3 W/m^2 (3 W/ft^2) peak intensity, with 20% of the heat from lights going into the return air plenum and 80% into the conditioned space.

Office equipment produces 1.94 W/m^2 (0.18 W/ft^2) of heat. Peak occupancy is 9.29 m^2 (100 ft^2) per person in perimeter zones, and 18.57 m^2 (200 ft^2) per person in interior zones. The building is occupied on weekdays only, from 8 A.M. to 5 P.M.

Infiltration. The infiltration rate is 0.1 air changes per hour when fans are on and 0.5 air changes per hour when fans are off.

Secondary HVAC System. A variable air volume (VAV) system with terminal reheat serves the interior zones. A four-pipe induction system serves the perimeter zones. The five zones on each floor are individually thermostatted. Thermostat control is proportional, with a throttling range of 1.1 ^oC (2 ^oF). Fans are off nights, weekends, and holidays except to maintain the 10.0 ^oC (50 ^oF) and 37.2^oC (99 ^oF) setback temperatures.

The VAV system has a minimum supply-air temperature of 12.8 ^oC (55 ^oF) and a minimum relative-humidity setpoint of 30%. The reheat ΔT is 22.2 ^oC (40 ^oF). The system has a temperature-controlled economizer cycle. Minimum outside air per person is 3.3 liters/s (7 cfm). Heating and

*The orientation of the building had a negligible effect on its energy use. For example, rotating the building by 90^o produced less than a 2.5% change in annual energy use for all cities and fenestration options studied.

cooling are available year-round. From 7 A.M. to 6 P.M. on weekdays the thermostat setpoint for heating is 21.1 °C (70 °F) and for cooling, 25.6 °C (78 °F). At night, and on weekends and holidays, the setpoint for heating is 10.0 °C (50 °F) and for cooling, 37.2 °C (99 °F).

The four-pipe induction system has an induction ratio of 2.5 and a maximum supply-air temperature of 35.0 °C (95 °F) during heating. The supply air temperature for cooling is controlled by an outside-air temperature reset schedule. The minimum ratio of outside air to supply air flow rate is 0.3. The minimum and maximum relative humidity setpoints are 30% and 60%, respectively. The system has a temperature-controlled economizer cycle. The thermostat heating and cooling setpoint schedules are the same as those given above for the VAV system.

Sizing of air-flow rates and coil capacities, which is automatically done by the DOE-2 program, is based on peak heating and cooling loads and outside air requirements for each zone, and for each climate/fenestration/daylighting option.

Primary HVAC System. There are two gas-fired hot-water boilers, two open-centrifugal chillers, and a cooling tower. The capacities of these components are automatically determined by DOE-2 to meet the peak heating and cooling demands of the secondary systems. For the range of climates and fenestration/daylighting options studied, the seasonal efficiency of the boilers varied from 0.64 to 0.71; the seasonal coefficient of performance of the chillers varied from 3.5 to 4.0.

WEATHER DATA

For the energy-use analyses, one year of hourly weather data was used for four different cities: Miami, Los Angeles, Washington, D.C., and Chicago. As shown in Table 1, these cities represent a wide range of heating and cooling degree days. The specific years chosen were the ASHRAE "Test Reference Years" [2]. The intensity of direct and diffuse incident solar radiation was calculated from hourly values of cloud type and sky coverage [1].

GLAZING AND SUN-CONTROL OPTIONS

The glazing and sun-control options considered in this study were chosen to cover a wide range of shading coefficient [3] and conductance (overall heat transfer coefficient). The shading coefficients studied range from 0.95 for clear single-pane float glass to 0.16 for clear double glazing with exterior horizontal blinds. The conductances, for 3.4 m/s (7.5 mph) windspeed, vary from 5.9 W/m^2-°C (1.02 Btu/ft^2-h-°F) for single glazing without blinds, to 1.59 W/m^2-°C (0.28 Btu/ft^2-h-°F) for double-pane tinted glass with a low-emissivity (<=0.05) reflective coating. (In DOE-2, conductance values are calculated hourly using an outside air-film resistance which depends on windspeed.)

Table 2 and Figure 2 summarize the values of shading coefficient, conductance, and initial cost (in 1980 U.S. dollars per unit window area) of the different options. Footnotes to Table 2 list the sources from which thermal and cost data were obtained.

For options with blinds, either exterior or interior, the blinds were operated differently in the cooling and heating seasons, excluding sun in the cooling season, and accepting it in the heating season. More precisely, the "cooling season" corresponds to the months in each location when the cooling demand on the perimeter-zone system for the baseline case (clear single glazing with no sun control) exceeds the heating demand. The remainder of the year is taken to be the "heating season". From Figure 3 we find cooling seasons as follows: Miami and Los Angeles - all year; Washington, D.C. and Chicago - April to October.

A detailed description of each option follows.

(1) Clear glass with no shading. The fenestration in this case consists of one pane of clear 0.64 cm (1/4 in) float glass with a shading coefficient of 0.95 and daylight transmittance of 88%, or two panes of 0.64 cm (1/4 in) clear glass, separated by a 1.27 cm (1/2 in) air gap, with a shading coefficient of 0.82 and daylight transmittance of 78%. The single-pane case represents the extreme situation; i.e., maximum solar heat gain and maximum heat transmission by conduction.

(2) Clear glass with interior blinds. Sun control is provided by light-colored venetian blinds with horizontal slats. The blinds are located on the room side of the glass. They are operated differently in the heating season and cooling season according to the schedules shown in Figure 4.

This figure gives, as a function of time of day, the amount by which the shading coefficient of the glazing is multiplied to take into account the reduction of solar heat gain due to the blinds. The blinds are retracted (fully open) at night to give maximum window conductance for night cooling; during the day the blinds are tilted at 45^{o} to block direct sunlight but still allow daylighting. (Window conductance, excluding outside air film, is assumed to be reduced by 15% [4,9] when interior or exterior blinds are fully closed or are tilted at 45^{o}.) In the heating season (Washington, D.C. and Chicago only) the blinds are fully closed at night to reduce heat loss through the windows, and fully open during the day to allow maximum direct solar heat gain.*

*The results presented in this study are not sensitive to whether the blinds, interior or exterior, are open or closed during the day in the Chicago and Washington, D.C. heating season. Keeping the blinds closed year-round in these cities -- to prevent occupant discomfort from glare caused by direct sunlight entering the building -- gave less than a 3% increase in annual energy use relative to operating the blinds in a passive solar mode during the winter.

(3) Clear glass with exterior blinds. The blinds in this case have operable light-colored horizontal louvers located outside the window. The blinds are operated according to the same schedule as described above for interior blinds; however, because the exterior blinds reflect incident sunlight before it enters the space, they give a shading coefficient (at a louver angle of 45°) which is about one-third that of interior blinds (see Figure 4).

(4) Tinted glass. This is 0.64 cm (1/4 in) float glass which has been tinted to absorb solar radiation. Part of the absorbed heat is conducted back to the outside, thus reducing solar heat gain. For single glazing, the shading coefficient is 0.71 and daylight transmittance is 74%. For double glazing, the outer pane is tinted and the inner is clear, giving an overall shading coefficient of 0.57 and a daylight transmittance of 65%.

(5) Tinted glass with interior blinds. This option is the same as (2), above, except that clear glass is replaced by tinted glass. The net shading coefficient of the tinted-glass-plus-blinds combination is 0.45 for single glazing and 0.36 for double glazing.

(6) Tinted glass with reflective coating. For single glazing, this option has a high-emissivity reflective coating located on the outside of 0.64 cm (1/4 in) heat-absorbing glass. In order to minimize solar gain, a shading coefficient of 0.28 was chosen to approximate the smallest value commercially available for glass of this type. The daylight transmittance is 8%. For double glazing, a low-emissivity reflective coating is located on the inside of the outer pane, giving a shading coefficient of 0.23, again close to the lowest commercially available. The daylight transmittance is 7%. The low-emissivity coating suppresses radiative heat transfer between panes, thereby lowering the overall conductance of the window to 1.59 W/m^2-°C (0.28 Btu/ft^2-h-°F), a value characteristic of uncoated triple glazing. For comparison, uncoated double glazing has a conductance of 2.78 W/m^2-°C (0.49 Btu/ft^2-h-°F).

DAYLIGHTING METHODOLOGY

Because the present version of the DOE-2 program does not explicitly calculate hourly daylighting levels, a simplified procedure was used to simulate the time-averaged effect of daylighting of the perimeter zones. In this procedure, the intensity of artificial lighting between 7 A.M. and 5 P.M. was decreased by a reduction factor of 50% or 100%, depending on time of year and the fenestration option. The same reduction factors were used for all perimeter zones, independent of orientation. (This procedure gives a daylighting potential which is lower than could be achieved with a system in which artificial lighting can be continuously dimmed from 100% to 0% independently for each zone.)

To determine the allowable reduction factors for the various options, the lumen method of daylighting analysis [10,11] was used to calculate manually the level of daylight illumination on a desk-height reference surface 3.05 m (10 ft) from the window. This calculation was carried out for each window orientation for representative hours on March 21, June 21, and December 21, at latitude 40°N (Chicago), under clear and overcast conditions. The parameters used in the calculation were:

room depth	4.57 m (15 ft)
room length	6.10 m (20 ft)
ceiling height	3.66 m (12 ft)
sill height	0.91 m (3 ft)
window area	12.10 m^2 (130 ft^2)

daylight transmittance of window	clear, single pane	88%
	clear, double pane	78%
	tinted, single pane	74%
	tinted, double pane	5%
	reflective, single pane	8%
	reflective, double pane	7%

louver angle for interior and exterior blinds	45°
wall reflectance	70%
ceiling reflectance	80%
floor reflectance	30%
ground reflectance	10%

It was assumed that artificial lighting at peak intensity produced an illumination of 538 lx (50 fc) on the reference surface; thus, lights could be reduced 50% if the daylight illumination over an entire time period (7 A.M. to 5 P.M. for summer, winter, or spring/fall season) exceeded 269 lx (25 fc) for each zone orientation, and could be reduced 100% if the daylight illumination exceeded 538 lx (50 fc). The reduction factors resulting from this analysis are summarized in Table 3; the lighting schedules used in the DOE-2 analysis are shown in Figure 5. Note that, with the simplified procedure being used in this study, no daylighting is possible with reflective glazing since the daylight transmittance is very low for this option (8% for single glazing, 7% for double glazing).

LIFE-CYCLE COSTING METHODOLOGY

For each alternative, the life-cycle cost over a period of 25 years was calculated using the methodology described in Ref. 12. The life-cycle cost is given by

$$LCC = P - S + M + R + E$$

where

P = purchase and installation cost for glazing (plus blinds if present), primary HVAC equipment, and daylighting controls, if present.

S = salvage value
M = maintenance and repair costs
R = replacement costs
E = energy costs.

All of the above costs are discounted present values adjusted for income taxes. For comparing the various options, only those costs expected to differ from option to option were considered, i.e., costs for fenestration, primary HVAC equipment, and energy. It was assumed that material and installation costs and energy cost rates were the same in each city. Salvage value and replacement costs were assumed to be zero.

Table 2 summarizes the installed first costs for the different fenestration options and gives the sources from which these costs were obtained. The installed first cost for the various fenestration options is also shown graphically in Figure 2. The annual maintenance cost for exterior blinds per unit window area is $\$1.61/m^2$ ($\$0.15/ft^2$) [8] and for interior blinds is $\$2.91/m^2$ ($\$0.27/ft^2$) [13]. The annual maintenance cost for the glass itself — which includes periodic cleaning — is assumed to be the same for all options and, therefore, has been neglected. The cost of daylighting controls for the perimeter zones was taken to be \$9.04 per m^2 ($\$0.84$ per ft^2) of perimeter area [14].

The installed first cost of primary HVAC equipment as a function of output capacity was assigned as follows:

$$\text{boiler cost} = \$22{,}900 \left[\frac{\text{capacity in } 10^6 \text{ Btu/h}}{7.2}\right]^{0.67}$$

$$\text{chiller cost} = \$80{,}220 \left[\frac{\text{capacity in } 10^6 \text{ Btu/h}}{7.2}\right]^{0.67}$$

$$\text{cooling tower cost} = \$21{,}200 \left[\frac{\text{capacity in } 10^6 \text{ Btu/h}}{4.8}\right]^{0.67}$$

The above boiler and cooling tower costs are from Ref. 15; the chiller cost is from Ref. 6. The annual maintenance cost for plant equipment was taken as 3.5% of installed first cost. The variation in cost for the secondary HVAC system cost from option to option was not considered.

The annual cost of electrical energy was calculated on the basis of a uniform rate of \$0.049 per kWh plus \$1.50 per month for each kW of peak electrical demand in that month. The cost for natural gas was taken as \$0.35 per 100,000 Btu (29.3 kWh) of energy content. The uniform costs for electricity and natural gas are based on an average of 1980 commercial-sector energy prices [16] in U.S. Department of Energy regions 4, 5, and 9, which contain Miami, Chicago, and Los Angeles, respectively.

Table 4 lists values of other life-cycle costing parameters used. Because life-cycle cost is generally sensitive to the values of discount rate, d, and energy escalation rate, e, and because these values are usually not well defined, calculations were performed for three different combinations of values for these rates. The combinations chosen were: d = 6%, e = 2%; d = 3%, e = 2%; and d = 3%, e = 5% (relative to general inflation).

As will be evident later, the life-cycle cost of a given fenestration option varies by about a factor of two for this range of values of d and e. This variation is due primarily to the effect of d and e on the life-cycle energy cost, LCC_E, which is given by

$$LCC_E = (1 - t) \sum_{n=1}^{25} C_E \left[\frac{1 + e}{1 + d}\right]^n$$

$$\begin{aligned} &= 15.7\ C_E \quad \text{for } d = 0.06,\ e = 0.02 \\ &= 22.0\ C_E \quad \text{for } d = 0.03,\ e = 0.02 \\ &= 32.2\ C_E \quad \text{for } d = 0.03,\ e = 0.05, \end{aligned}$$

where C_E is the annual energy cost in constant dollars, and t is the corporate income tax rate (0.46 in the present analysis). In general, the higher e is with respect to d, the larger the contribution of energy cost to the overall life-cycle cost, and the larger the difference in life-cycle costs among fenestration/daylighting options.

RESULTS AND DISCUSSION

Load and Energy-Use Components

A useful way of understanding how sun control and daylighting affect the thermal performance of a building is to display the constituents of the annual heating and cooling loads and the constitutents of the annual energy use. This is done in Figure 6 for three of the twelve options considered in this study: clear single glazing with no sun control (referred to below as the "baseline"); clear single glazing with exterior blinds; and clear single glazing with exterior blinds and daylighting. These alternatives were chosen for display to illustrate the extreme cases of no sun control vs. the large reduction in solar heat gain achievable with exterior blinds, and to illustrate the impact on load and energy-use components of daylighting.

Components of annual cooling load. From Figure 6a we see that:

(1) The largest component of the baseline cooling load is solar heat gain. Adding exterior blinds reduces this component by 74 - 85%, depending on the city.

(2) The second largest component of the baseline cooling load is heat from lights. This component is reduced approximately 25% with daylighting.

Components of annual heating load. From Figure 6b we see that:

(1) In Los Angeles, Washington, D.C., and Chicago, approximately 75% of the heat loss is due to conduction through windows; the rest is due to infiltration and to heat loss through walls and roof.

(2) The heat losses are offset by heat gain from lights, occupants, and solar radiation, with the last predominating. Sun control reduces solar gain, thereby raising the net heating load. Daylighting, by reducing heat from lights, also raises the net heating load.

Components of annual energy use. From Figure 6c we see that:

(1) For the baseline case, 43 - 62% of the energy use, depending on location, is electricity for lighting.

(2) The second largest component of energy use is electricity for cooling in Miami and Los Angeles, and gas for heating in Washington, D.C. and Chicago.

(3) Sun control via exterior blinds reduces electricity for cooling 42 - 61%. Daylighting further reduces electricity for cooling 12 - 19% due to reduction in heat from lights.

(4) Daylighting reduces electricity use for lights by 24% for clear glazing, and by 18% for tinted, uncoated glazing.

(5) Daylighting in Washington, D.C. and Chicago increases gas use by about 12% due to reduction of heat from lights.

A complete tabulation of the annual energy-use components for all of the fenestration/daylighting options is given in the appendix, Tables A.1 to A.4.

Life-Cycle Cost and Annual Energy Use

The annual energy use and life-cycle cost (LCC) for all of the fenestration/daylighting alternatives are compared in Figures 7 - 11. Figure 7 shows the annual energy use per unit of total floor area. Figures 8 and 9 show LCC for three different sets of values of discount rate and energy escalation rate. The correlation between cost and energy use for the different alternatives is shown in Figures 10 and 11, which give LCC vs. annual energy use for a 3% discount rate and a 5% energy escalation rate. Our main conclusions follow.

Double glazing. Figure 7 shows that double glazing produces significant energy savings in Washington, D.C. and Chicago but has little effect in the warmer climates of Miami and Los Angeles. In Washington, D.C., uncoated double glazing reduces energy use 11 - 17%; in Chicago, which has 50% more heating degree days than Washington, D.C., the corresponding reduction is 16 - 25%. For tinted double glazing with reflective coating (which has a smaller U-value than uncoated double glazing), the reductions are greater: 23% in Washington, D.C., and 32% in Chicago.

Defining as "cost-effective" any measure that reduces LCC by more than \$0.50/ft^2 (\$5.38/m^2), we see from Figure 8 that double glazing is not cost-effective in Miami or Los Angeles as would be expected from the small effect double glazing has on the energy use in these cities. At a 2% energy escalation rate, double glazing is not cost-effective in Washington, D.C. (Figure 9) for any of the sun-control options. Even at a 5% energy escalation rate (and 3% discount rate) only one double-glazed option is cost-effective; viz., tinted glass with reflective coating, which has an LCC of \$171.79/m^2 (\$15.96/ft^2) for single glazing vs. \$164.37/m^2 (\$15.27/ft^2) for double glazing.

In Chicago (Figure 9), the only double-glazed option that is cost-effective for a 2% energy escalation rate is tinted glass with reflective coating. For a 5% energy escalation rate (and 3% discount rate), however, most of the double-glazed options are cost-effective relative to their single-glazed counterparts.

Daylighting. Daylighting is found to be cost-effective in all four cities. The effects of daylighting on energy use and LCC are summarized in Table 5, which is a condensation of the results shown in Figures 7 - 11. This table gives the reduction in annual lighting energy, reduction in annual overall energy use, reduction in LCC (for 3% discount rate and 5% energy escalation rate), and the simple payback period (increase in first cost with daylighting divided by after-tax annual energy and maintenance cost savings).

Without daylighting, the perimeter zones use 56.2 kWh/m^2 (17.8 Btu/ft^2) annually for lighting. Daylighting reduces this figure by 46% for options with clear glass (i.e., for clear single or double glazing, with or without blinds), and by 34% for options with uncoated tinted glass. There is no reduction for tinted glass with reflective coating because of its low daylight transmittance.

For the building as a whole, the reduction in overall annual energy use due to daylighting ranges from 24.6 - 34.1 kWh/m^2 (7.8 - 10.8 Btu/ft^2) in Miami, to 12.3 - 26.5 kWh/m^2 (3.9 - 8.4 Btu/ft^2) in Chicago. The reduction is smaller in the colder climates because the decrease in electricity use for lighting and cooling is offset by an increase in heating demand.

In addition to reducing energy use, daylighting decreases peak electrical demand. As shown in Tables A.1 - A.4, the decrease is 9.7 - 16.2 W/m^2 (0.9 - 1.5 W/ft^2), or 11 - 22%, depending on fenestration option and city.

Sun control. Table 6 summarizes the optimum sun-control alternatives according to three different selection criteria — lowest first cost, lowest LCC, and lowest energy use. (The option of clear glass without blinds has not been considered in this summary). The first-cost includes cost of glazing, primary HVAC equipment (boilers, chillers, and cooling tower), blinds (if present) and daylighting controls (if present), as given in Tables A.5 - A.8. The LCC here is based on a 3% discount rate and a 5% energy escalation rate. From this table we see that

- In all four cities, the alternative with lowest first cost is single-pane tinted glass without daylighting.

- In Miami and Los Angeles, the alternative with lowest LCC is clear single-pane glass with exterior blinds and daylighting; in Washington, D.C., clear double-pane glass with exterior blinds and daylighting; and, in Chicago, clear double-pane glass with interior blinds and daylighting.

- In all four cities, the alternative with lowest energy use is clear double-pane glass with exterior blinds and daylighting.

We also see that, relative to the option with lowest first cost,

- The option with lowest LCC saves 24.55 - 46.82 $\$/m^2$ (2.28 - 3.89 $\$/ft^2$) in LCC and 45.4 - 80.5 kWh/m^2 (14.4 - 25.5 $KBtu/ft^2$) in annual energy use.

- The option with lowest energy use saves 24.55 - 41.87 $\$/m^2$ (2.28 - 4.35 $\$/ft^2$) in LCC and 14.4 - 25.5 kWh/m^2 (16.4 - 25.9 $KBtu/ft^2$) in annual energy use.

CONCLUSIONS

We have shown that intelligent choice of fenestration in a high-rise office building can lead to substantial savings in both life-cycle cost and annual energy use. Of the alternatives considered here, the lowest life-cycle cost and energy use are obtained with perimeter-zone daylighting coupled with clear glazing and exterior sun-control blinds.

Several areas of further study are worth pursuing: Our analysis could be extended to take into account the effect of window size and to include other sun-control alternatives, such as selective transmittance coatings, solar-control screens, vertical interior blinds, and fixed external shading devices. The economics of heat mirrors (single glazing coated to reflect instead of absorb thermal radiation) as a substitute for double glazing should be investigated. A better determination of the effects of daylighting on artificial lighting levels and heating/cooling loads could be obtained by calculating daylighting levels hourly. Finally, the restriction of having the same fenestration on each exposure could be relaxed and a study made to determine optimal glazing and sun-control alternatives as a function of facade orientation.

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9. John I. Yellott, Effect of Louvered Sun Screens Upon Fenestration Heat Loss, ASHRAE Transactions, Vol. 78, Part I, p. 199, January 1972.

10. Libbey-Owens-Ford Company, How to Predict Interior Daylight Illumination, Toledo, Ohio, 1976

11. Illumination Engineering Society Daylighting Committee, Recommended Practice of Daylighting, Lighting Design and Application, Vol. 9, No. 2, February 1979, p. 45.

12. Harold E. Marshall and Rosalie T. Ruegg, Simplified Energy Design Economics, National Bureau of Standards Special Publication No. 544, January 1980.

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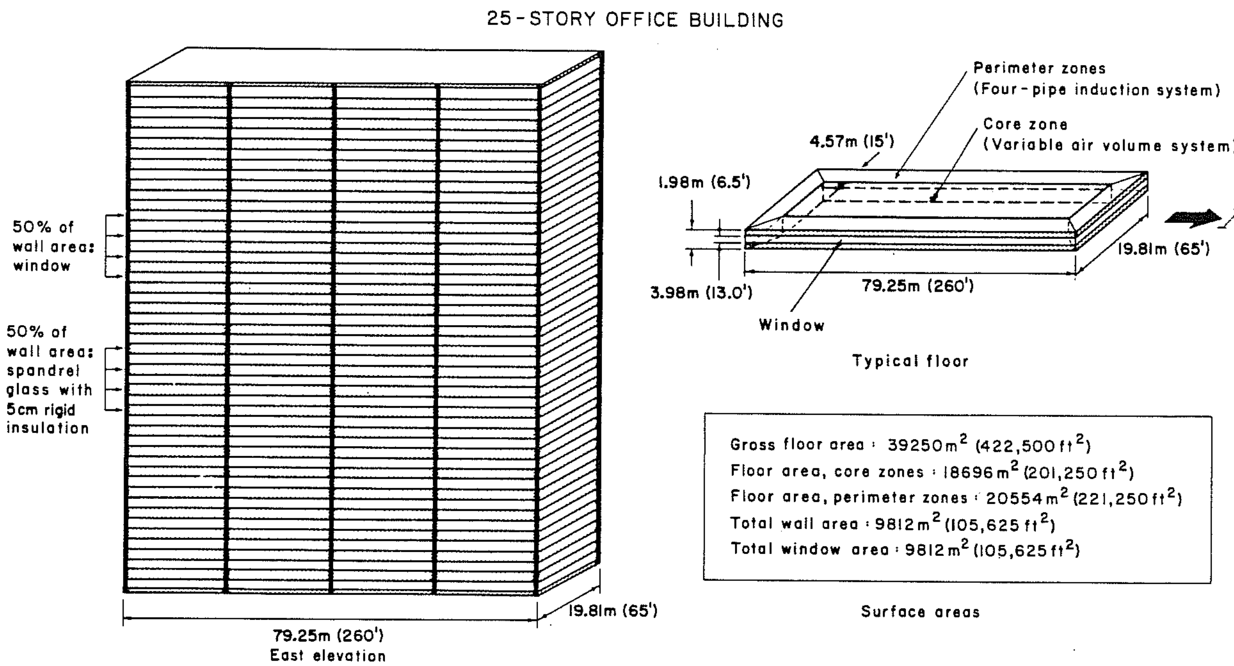
14. Daylighting control costs are based on estimates made by Francis Rubinstein, Windows and Daylighting Group, Lawrence Berkeley Laboratory, University of California, Berkeley, CA.

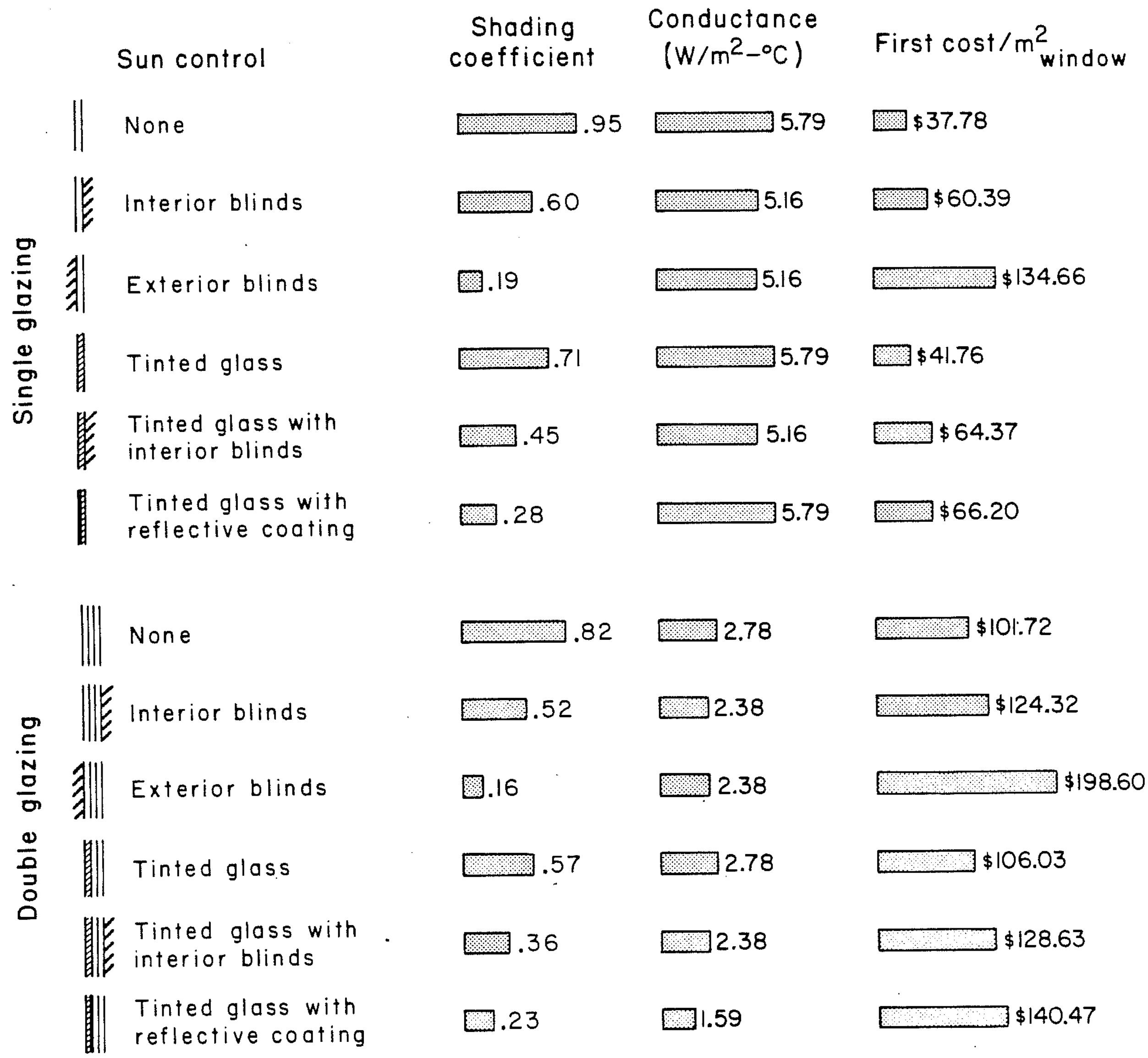
15. Robert Snow Means Co., Inc., Mechanical and Electrical Cost Data, 1980, Construction Consultants and Publishers, Kingston, MA.

16. U.S. Federal Register, No. 16, Vol. 45, p. 5639, January 23, 1980.



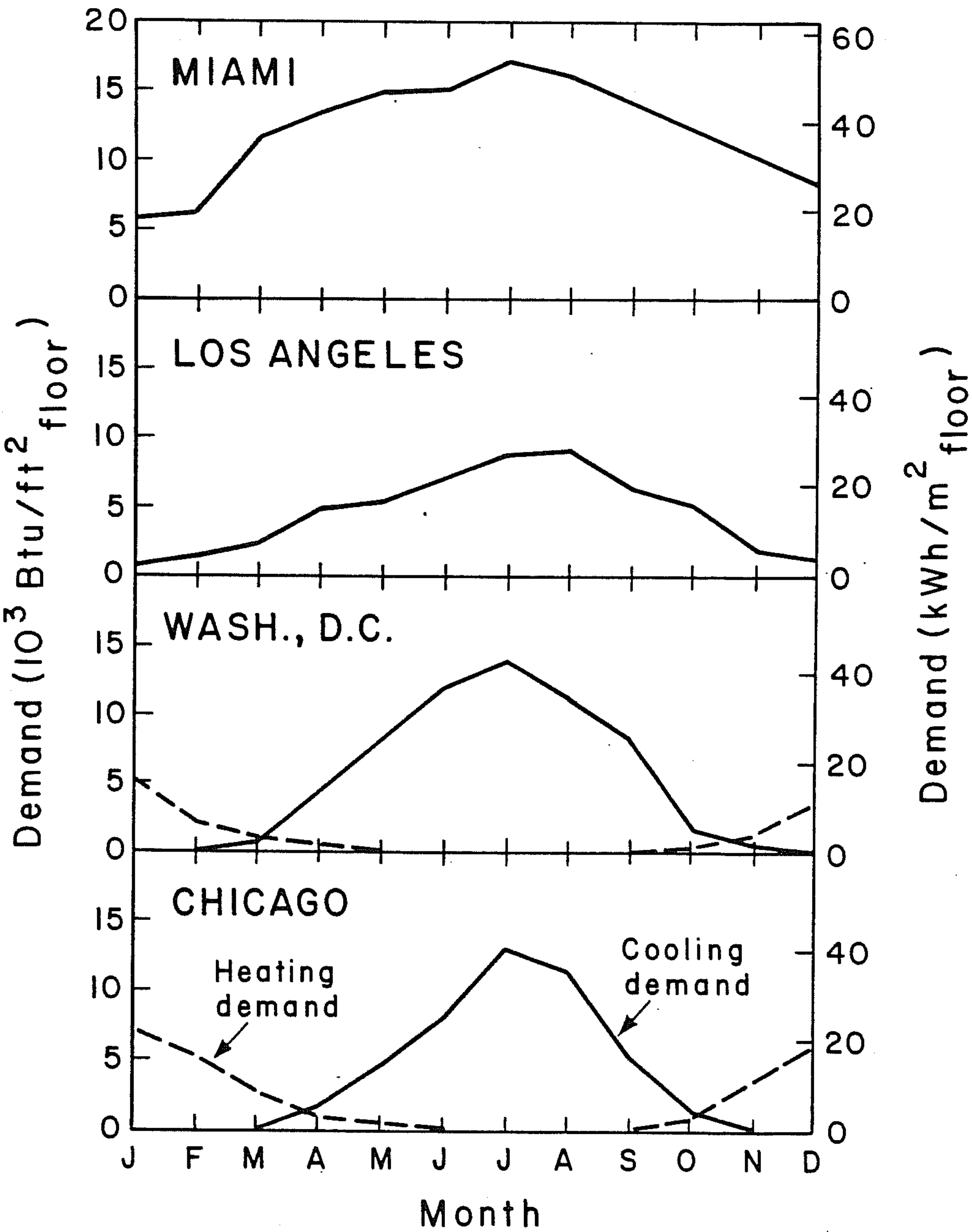
XBL 8012-2462

Figure 1. Perspective view of 25-story office building and of typical floor showing perimeter and core zones. The building is 50% glazed on all elevations.



XBL 8012-2464

Figure 2. Comparison of thermal properties and installed first cost for different fenestration options. The conductances shown correspond to a 3.4 m/s (7.5 mph) wind speed. Costs (in 1980 U.S. dollars) include blinds, if present, and glazing.



XBL 8012-2461

Figure 3. Monthly heating and cooling energy provided by the HVAC system to the perimeter zones for the baseline case (clear single glazing without sun control and without daylighting) in four cities.

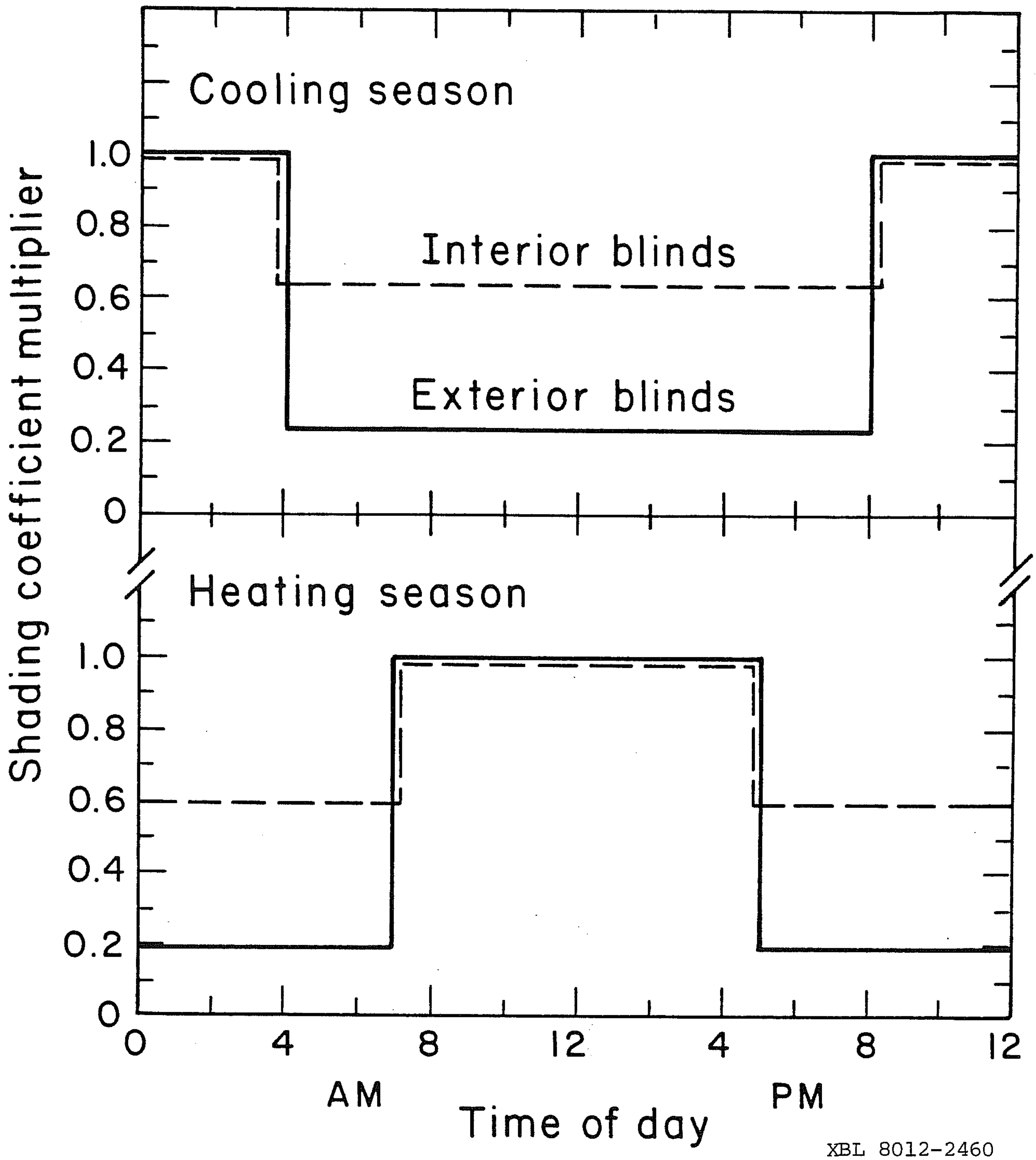


Figure 4. Amount by which shading coefficient of glazing is multiplied due to the presence of operable interior or exterior blinds. During the cooling season, the blinds are open at night to give maximum window conductance for night cooling and closed during the day (45° louver tilt) to reduce solar gain. The reverse schedule is used during the heating season.

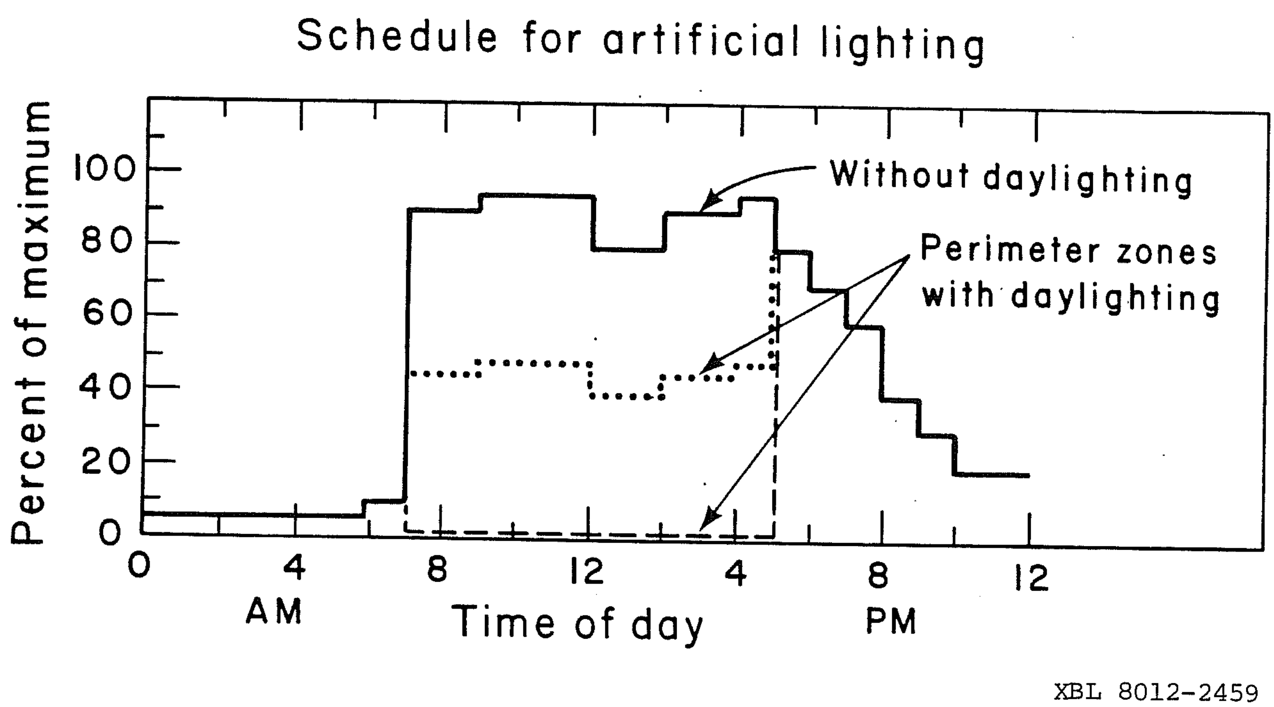


Figure 5. Hourly schedule for artificial lighting on weekdays. For daylighting, the level of artificial lighting of the perimeter zones from 7 A.M. to 5 P.M. is reduced by 50% or 100% depending on time of year and fenestration option. On weekends and holidays, the artificial lighting level is 5% of maximum for all hours.

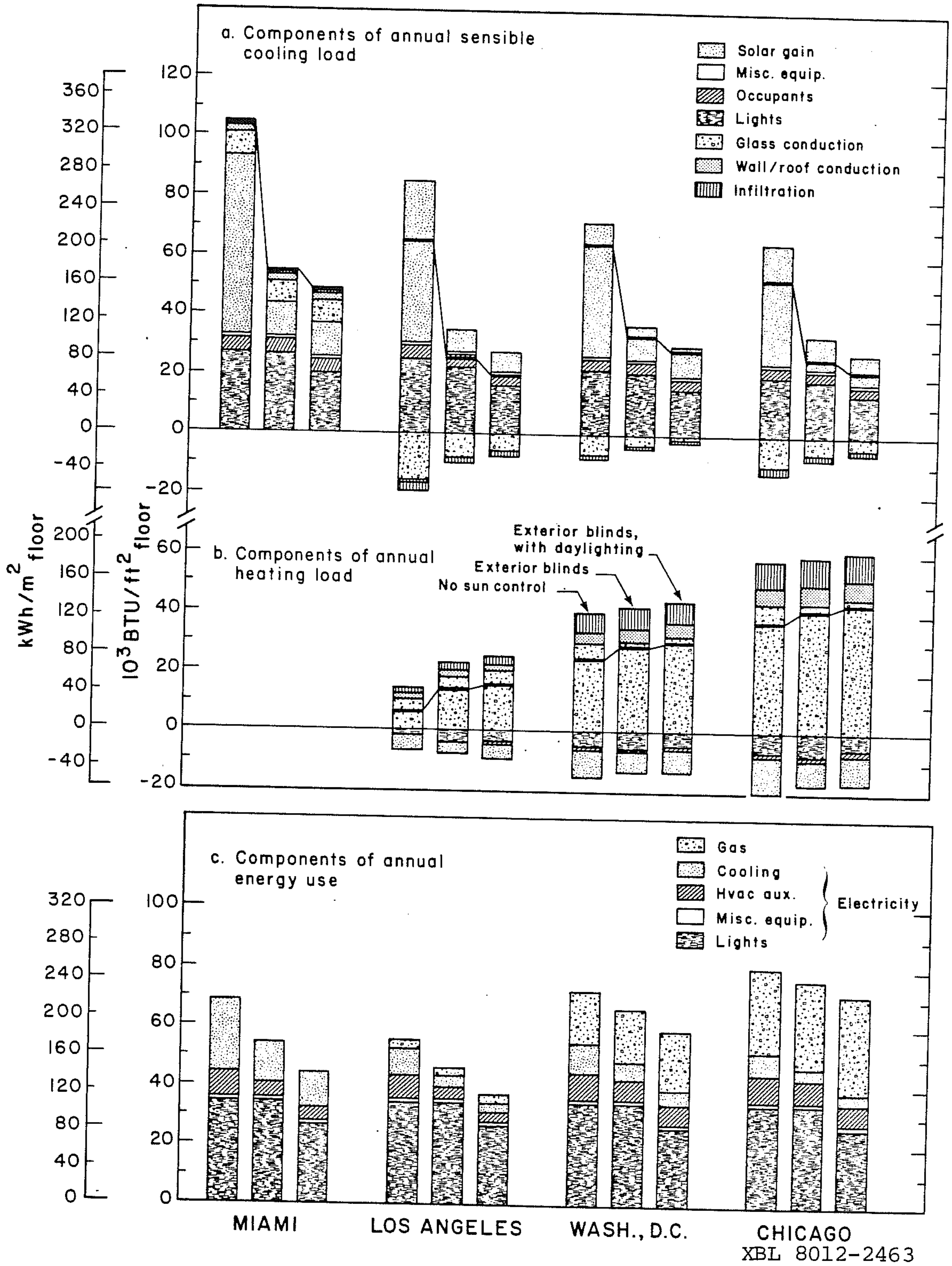
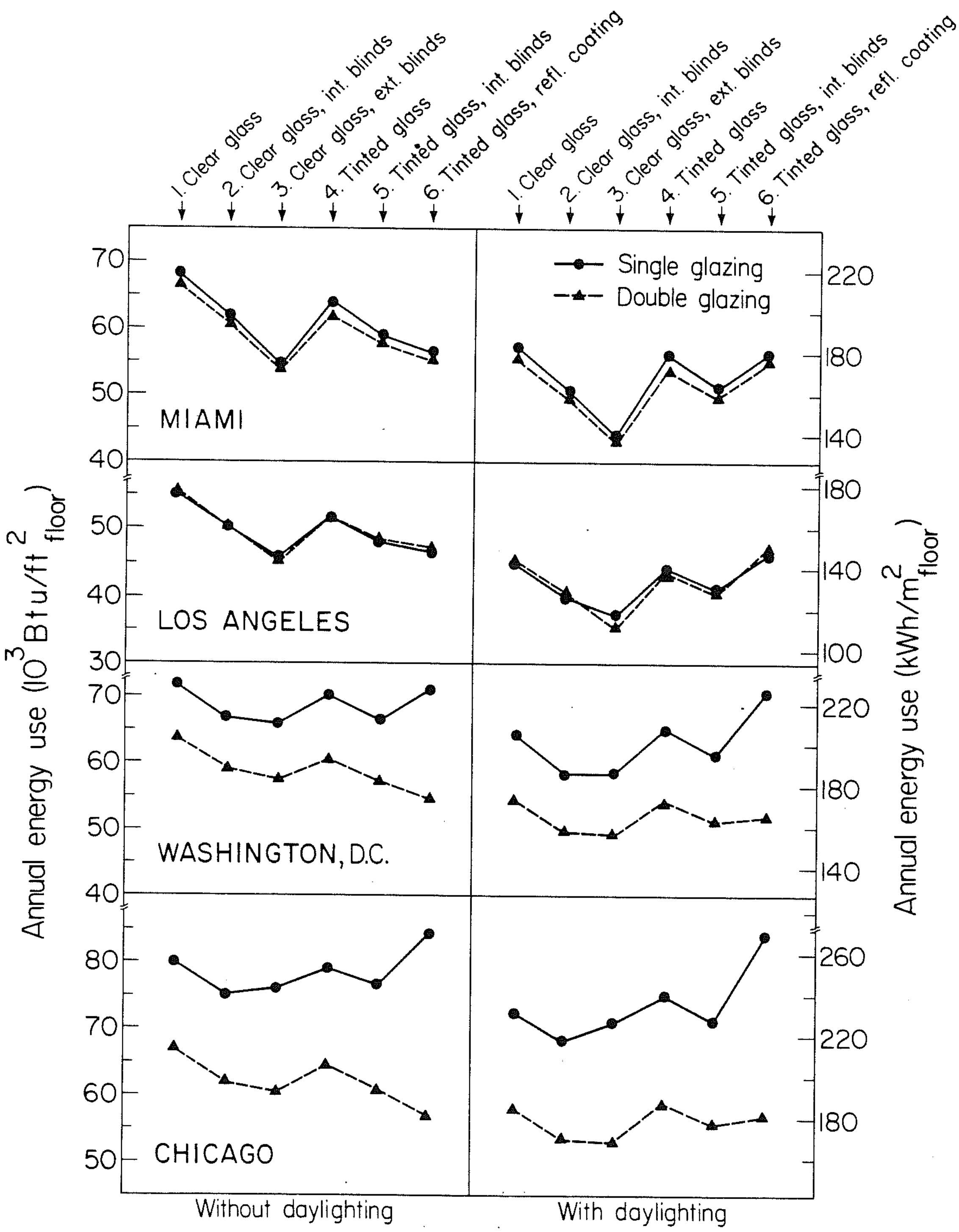
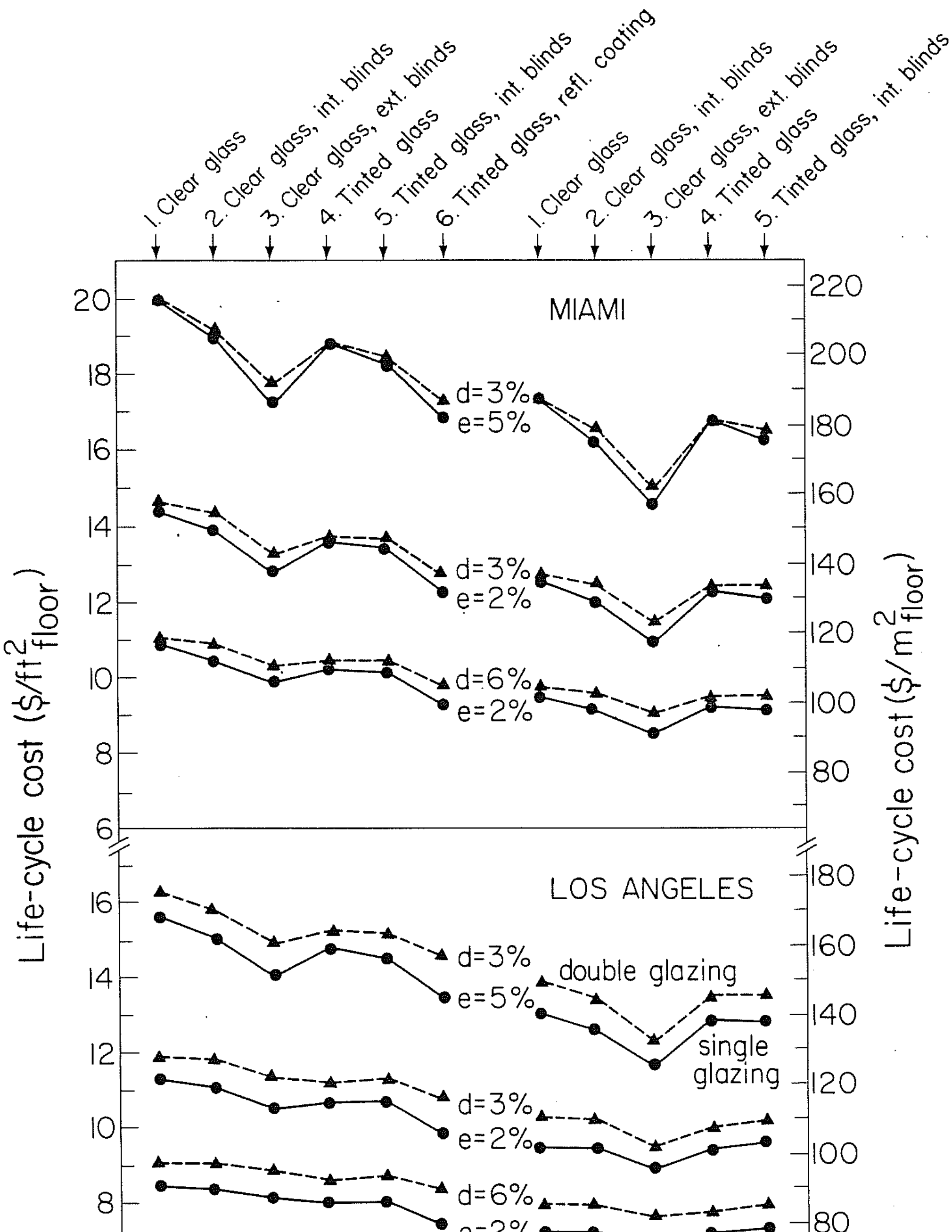


Figure 6. Components of annual cooling and heating load and of annual energy use in four cities. The options shown are: clear single glazing, no sun-control; clear single glazing with exterior blinds; and clear single glazing with exterior blinds and daylighting. In (a), a positive component is a heat gain, and a negative component, a heat loss. The reverse is true in (b). The heavy horizontal lines in (a) and (b) give the net loads. In (c), "HVAC aux." indicates electricity used for fans and pumps.



XBL 813-8384

Figure 7. Annual energy use in four cities for six fenestration options, with and without daylighting.



XBL 813-8383

Figure 8. Present value of life-cycle cost (1980 U.S. dollars) in Miami and Los Angeles for various fenestration options, with and without daylighting, for three different combinations of discount rate (d) and energy escalation rate (e). The life-cycle cost includes only the cost of fenestration, daylighting controls (if present), primary HVAC equipment, and energy.

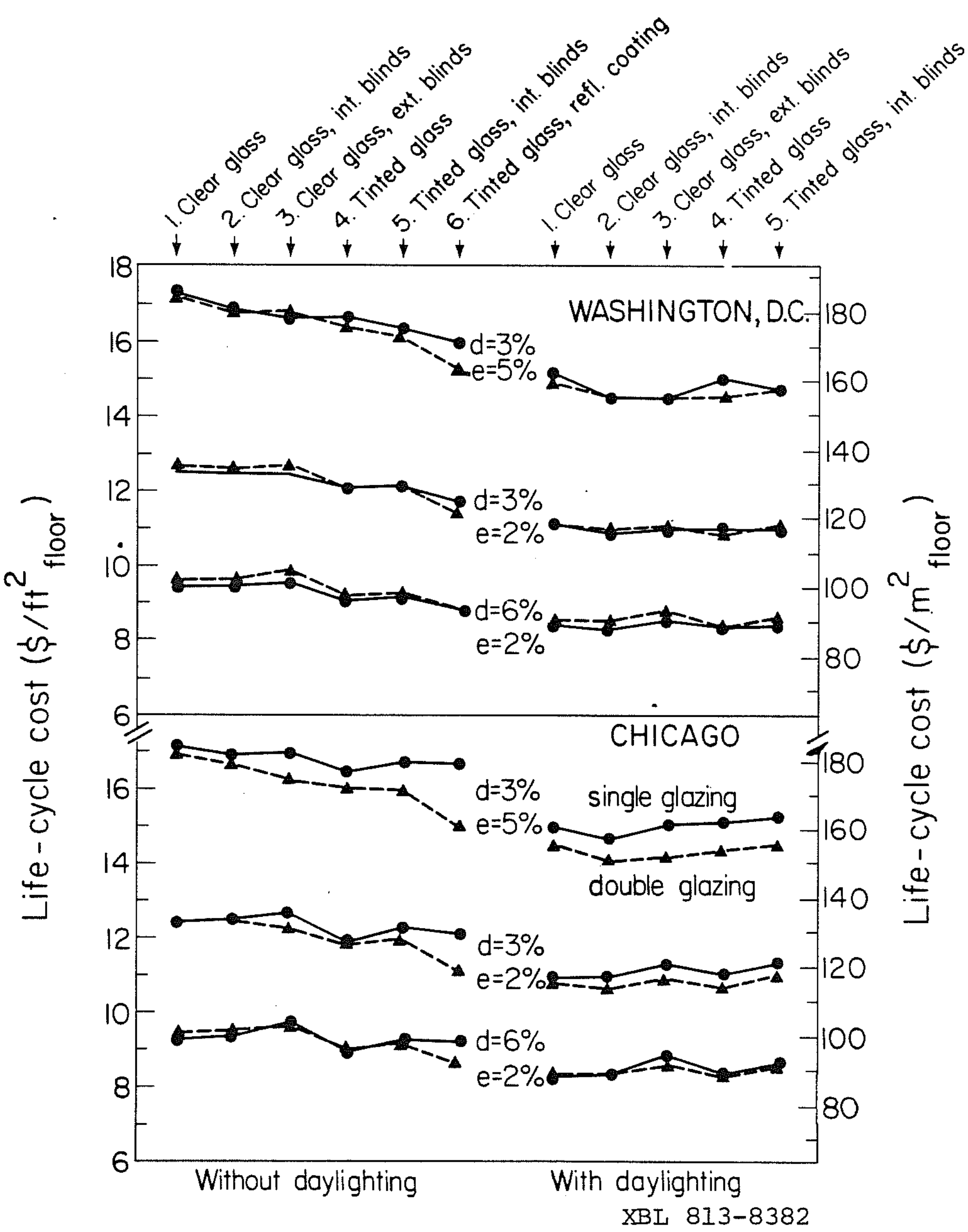


Figure 9. Present value of life-cycle cost (1980 U.S. dollars) in Washington, D.C. and Chicago for various fenestration options, with and without daylighting, for three different combinations of discount rate (d) and energy escalation rate (e). The life-cycle cost includes only the cost of fenestration, daylighting controls (if present), primary HVAC equipment, and energy.

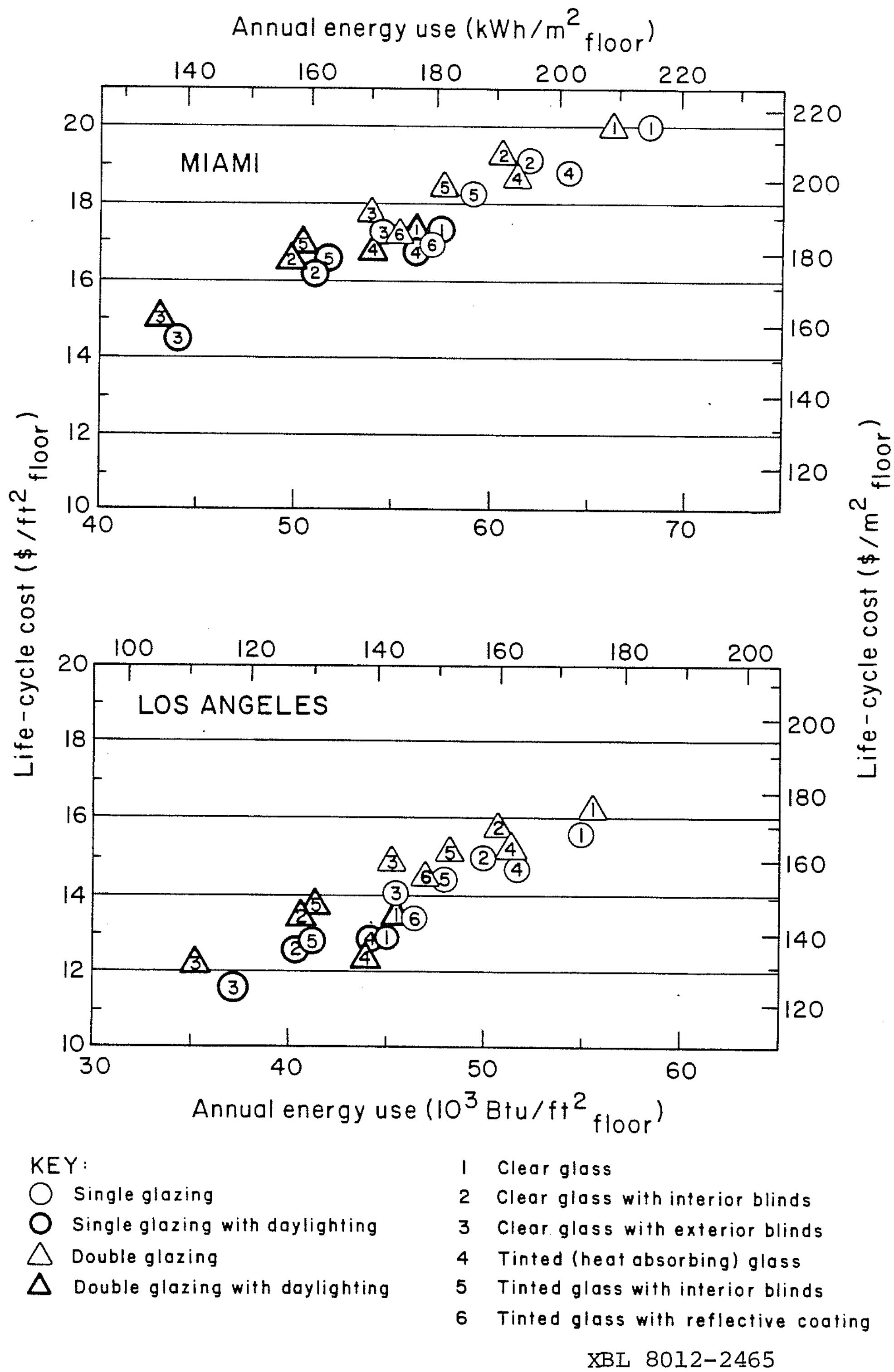
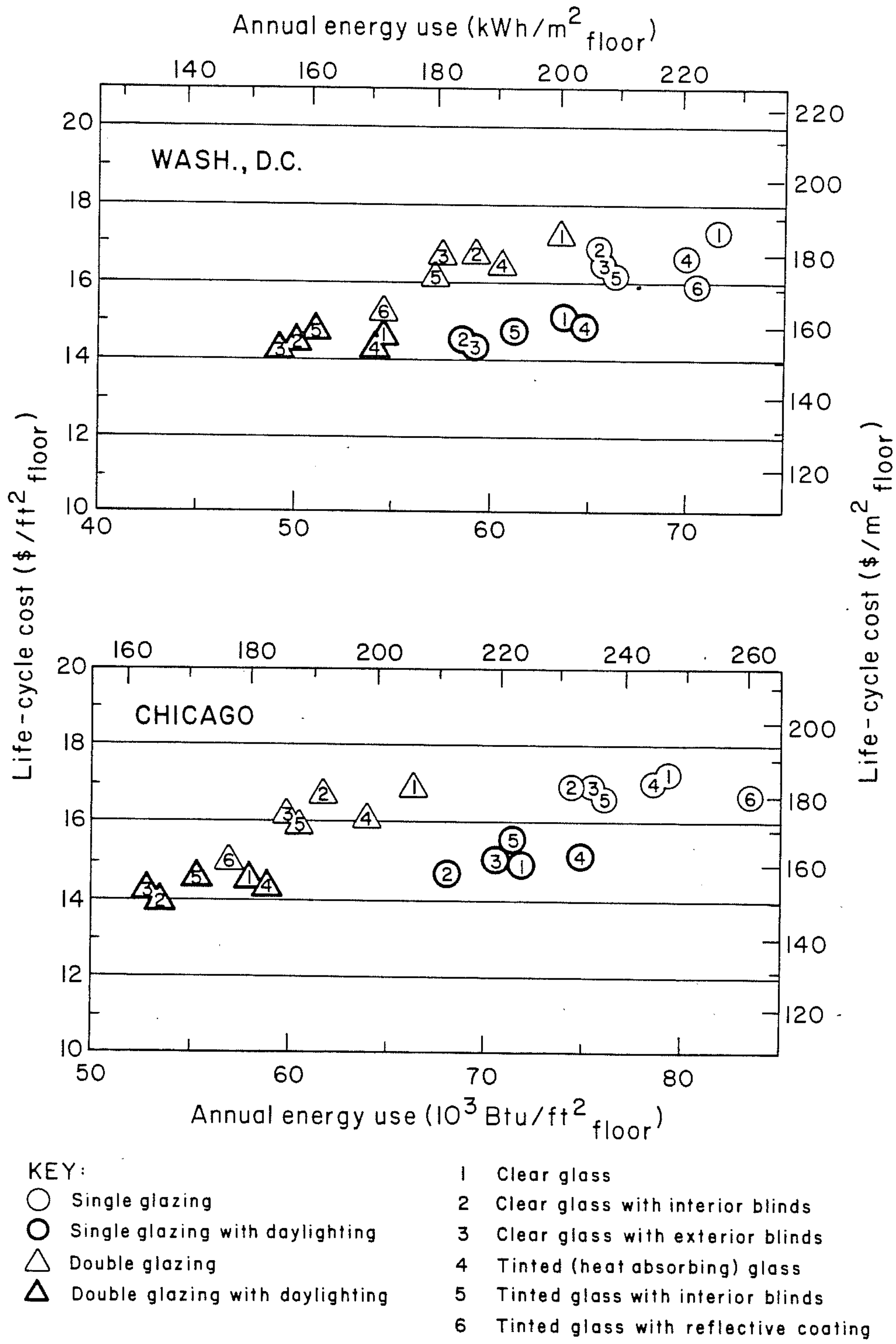


Figure 10. Present value of life-cycle cost (1980 U.S. dollars) vs. annual energy use in Miami and Los Angeles for different fenestration options, with and without daylighting. The life-cycle cost includes only the cost of fenestration, daylighting controls (if present), primary HVAC equipment, and energy.



XBL 8012-2466

Figure 11. Present value of life-cycle cost (1980 U.S. dollars) vs. annual energy use in Washington, D.C. and Chicago for different fenestration options, with and without daylighting. The life-cycle cost includes only the cost of fenestration, daylighting controls (if present), primary HVAC equipment, and energy.

Table 1. Weather data summary for Miami, Los Angeles, Washington, D.C., and Chicago.

City	Year	Latitude (deg.)	Heating Degree Days[a]		Cooling Degree Days[b]		Average Daytime Outside Temp.[c]			
			Celsius	Fahr.	Celsius	Fahr.	Winter[d]		Summer[e]	
							°C	°F	°C	°F
Miami	1964	25.8	103	186	1452	2613	22.9	73.3	27.7	81.8
Los Angeles	1973	33.9	1040	1872	84	151	15.4	59.7	19.3	66.9
Wash., D.C.	1957	38.9	2359	4247	526	947	6.5	43.7	21.7	71.1
Chicago	1974	41.8	3465	6237	255	459	1.3	34.4	18.4	65.2

[a] Base 18.3 °C (65 °F)
[b] Base 21.1 °C (65 °F)
[c] Sunrise to Sunset
[d] January-March and November-December
[e] April-October

Table 2. Comparison of costs and thermal properties of different fenestration options.

No. of Panes[a]	Sun Control	Shading Coeff[b]	Conductance[c]		Cost of Fenestration[g]	
			$W/m^2\text{-}^oC$	$Btu/ft^2\text{-}h\text{-}^oF$	$\$/m^2$	$\$/ft^2$
Single	None (clear glass)	.95	5.79	1.02	37.78	3.51[d]
	Interior Blinds	.60	5.16	.91	60.39	5.61[e]
	Exterior Blinds	.19	5.16	.91	134.66	12.51[f]
	Tinted Glass	.71	5.79	1.02	41.76	3.88[d]
	Tinted Glass, Interior Blinds	.45	5.16	.91	64.37	5.98[e]
	Tinted Glass, Reflective Coating	.28	5.79	1.02	66.20	6.15[e]
Double	None (clear glass)	.82	2.78	.49	101.72	9.45[d]
	Interior Blinds	.52	2.38	.42	124.32	11.55[e]
	Exterior Blinds	.16	2.38	.42	198.60	18.45[f]
	Tinted Glass	.57	2.78	.49	106.03	9.85[d]
	Tinted Glass, Interior Blinds	.36	2.38	.42	128.63	11.95[e]
	Tinted Glass, Reflective Coating	.23	1.59	.28	140.47	13.05[d]

[a]Glazing is assumed to be one or two panes of 0.64 cm (1/4 in) thick glass; for double glazing, panes are separated by a 1.27 cm (1/2 in) air space.

[b]Values given assume that blinds, if present, are tilted at 45°. Values for exterior blinds are from Ref. 4; other values are from product data sheets issued by U. S. glass manufacturers.

[c]For wind speed of 3.4 m/s (7.5 mph); blinds, if present, are assumed to be tilted at 45°. Conductance values for cases without blinds were calculated using the procedure described in Ref. 5.

[d]Ref. 6.

[e]Includes cost of venetian blinds at $22.60/m^2 ($2.10/ft^2), Ref. 7.

[f]Includes cost of operable exterior blinds at $96.88/m^2 ($9.00/ft^2), Ref. 8.

[g]Initial cost in 1980 U.S. dollars per unit area of window.

Table 3. Reduction in artificial lighting of perimeter zones due to daylighting, for different fenestration options.

Fenestration Option	Reduction in Artificial Lighting Level	Months
Clear glass, single or double pane, with or without blinds	100%	May-Aug
	50%	Jan-Apr Sep-Dec
Tinted glass, single or double pane, with or without blinds	50%	Jan-Dec
Tinted glass, single or double pane, with reflective coating	0%	Jan-Dec

Table 4. Life-cycle cost parameters.

Discount rate, energy escalation rate[a]	6%,2%; 3%,2%; 3%,5%
Down payment	10% [90% financing]
Mortgage rate	same as discount rate
Income tax rate	46%
Energy credits	none
Property tax rate	0%
Depreciation schedule	declining balance
Salvage value	0
Analysis period	25 years
Mortgage period	25 years
Depreciation life	25 years

[a]Relative to general inflation

Table 5. Impact of daylighting in four cities for different glazing options. Cost figures are in 1980 U.S. dollars.

City	Glass Type	Reduction in Annual Electricity Use for Lights[c]		Reduction in Annual Energy Use[c]		Reduction in Life-Cycle Cost[c,d]		Simple Payback Period
		kWh/m^2	KBtu/ft^2	kWh/m^2	KBtu/ft^2	\$/m^2	\$/ft^2	Years
Miami	Clear[a]	25.6	8.1	33.1-34.1	10.5-10.8	29.28-29.49	2.72-2.74	3.7-4.4
	Tinted, Uncoated[a]	19.2	6.1	24.6-24.9	7.8-7.9	20.67-21.96	1.92-2.04	5.7-6.5
	Tinted, Refl. Coating[b]	0	0	0	0	0	0	-
Los Angeles	Clear[a]	25.6	8.1	25.9-31.9	8.2-10.1	25.73-27.99	2.39-2.60	4.3-5.0
	Tinted, Uncoated[a]	19.2	6.1	21.5-23.7	6.8-7.5	17.87-20.24	1.66-1.88	6.1-7.0
	Tinted, Refl. Coating[b]	0	0	0	0	0	0	-
Wash., D.C.	Clear[a]	25.6	8.1	22.7-28.7	7.2-9.1	23.79-26.05	2.21-2.42	4.8-5.7
	Tinted, Uncoated[a]	19.2	6.1	15.5-19.2	4.9-6.1	14.21-20.02	1.32-1.86	6.3-7.8
	Tinted, Refl. Coating[b]	0	0	0	0	0	0	-
Chicago	Clear[a]	25.6	8.1	15.8-26.5	5.0-8.4	20.45-27.99	1.90-2.60	4.4-6.1
	Tinted, Uncoated[a]	19.2	6.1	12.3-16.4	3.9-5.2	14.42-18.30	1.34-1.70	7.0-8.9
	Tinted, Refl. Coating[b]	0	0	0	0	0	0	-

[a]Single or double glazed, with or without blinds.
[b]Single or double glazed.
[c]Per unit of total core-plus-perimeter floor area.
[d]For 3% discount rate and 5% energy escalation rate.

Table 6. Optimum fenestration/daylighting alternatives in four cities for three different criteria: lowest first cost, lowest life-cycle cost (LCC), and lowest annual energy use. Numerical entries are per unit of gross floor area.

City	Criterion	Optimum Alternative	First Cost[a]	Life-Cycle Cost[b]	Annual Energy Use
			$/m^2$ ($/ft^2$)	$/m^2$ ($/ft^2$)	kWh/m^2 (KBtu/ft^2)
Miami	Lowest first cost	Single pane, tinted glass, no dayl.	19.38 (1.80)	202.90 (18.85)	201.8 (64.0)
	Lowest LCC	Single pane, clear glass, ext. blinds, dayl.	44.78 (4.16)	156.08 (14.50)	138.8 (44.0)
	Lowest energy use	Double pane, clear glass, ext. blinds, dayl.	60.06 (5.58)	161.03 (14.96)	136.2 (43.2)
Los Angeles	Lowest first cost	Single pane, tinted glass, no dayl.	17.38 (1.61)	158.98 (14.77)	162.7 (51.6)
	Lowest LCC	Single pane, clear glass, ext. blinds, dayl.	42.95 (3.99)	125.51 (11.66)	117.3 (37.2)
	Lowest energy use	Double pane, clear glass, ext. blinds, dayl.	58.56 (5.44)	132.40 (12.30)	111.0 (35.2)
Wash., D.C.	Lowest first cost	Single pane, tinted glass, no dayl.	19.48 (1.81)	179.01 (16.63)	221.1 (70.1)
	Lowest LCC	Double pane, clear glass, ext. blinds, dayl.	61.14 (5.68)	154.46 (14.35)	155.8 (49.4)
	Lowest energy use	Double pane, clear glass, ext. blinds, dayl.	61.14 (5.68)	154.46 (14.35)	155.8 (49.4)
Chicago	Lowest first cost	Single pane, tinted glass, no dayl.	19.38 (1.80)	177.07 (16.45)	249.5 (79.1)
	Lowest LCC	Double pane, clear glass, int. blinds, dayl.	42.95 (3.99)	151.02 (14.03)	169.0 (53.6)
	Lowest energy use	Double pane, clear glass, ext. blinds, dayl.	60.49 (5.62)	152.31 (14.15)	167.8 (53.2)

[a] 1980 U.S. dollars; includes cost of fenestration, daylighting controls (if present), and primary HVAC equipment.
[b] Calculated using discount rate of 3% and energy escalation rate of 5%.

APPENDIX

This appendix contains eight tables. Tables A.1 through A.4 summarize the annual energy use in 10^3 Btu per ft^2 of gross floor area for different fenestration/daylighting options in four cities. Tables A.5 through A.8 summarize the costs associated with the various options.

Table A.1
Annual energy use summary: MIAMI[a]

Glazing	Daylighting	Sun Control	Peak Elec. Demand (w/ft^2)	Electricity Use ($KBtu/ft^2$)				Total Elec. Use ($KBtu/ft^2$)	Gas Use ($KBtu/ft^2$)	Total Energy Use ($KBtu/ft^2$)	Diff. from Baseline (%)
				Lights	Misc. Equip.	HVAC Aux.	Cooling				
SINGLE	NO	None	8.9	34.0	1.1	8.5	24.4	68.0	0.2	68.2	--
		Interior Blinds	7.8	34.0	1.1	6.9	19.6	61.6	0.2	61.8	-9.4
		Exterior Blinds	6.6	34.0	1.1	5.2	14.0	54.3	0.2	54.5	-20.1
		Tinted Glass	8.3	34.0	1.1	7.5	21.2	63.8	0.2	64.0	-6.2
		Tinted Glass, Int. Blinds	7.4	34.0	1.1	6.3	17.5	58.9	0.2	59.1	-13.0
		Reflective Glass	6.9	34.0	1.1	5.6	15.3	56.1	0.3	56.3	-17.4
	YES	None	7.9	25.9	1.1	8.0	22.3	57.3	0.2	57.5	-15.7
		Interior Blinds	6.6	25.9	1.1	6.4	17.4	50.8	0.2	51.0	-25.2
		Exterior Blinds	5.6	25.9	1.1	4.7	12.0	43.7	0.3	44.0	-35.5
		Tinted Glass	7.3	27.9	1.1	7.2	19.8	56.0	0.2	56.2	-17.6
		Tinted Glass, Int. Blinds	5.8	27.9	1.1	6.0	16.1	51.1	0.2	51.3	-24.8
DOUBLE	NO	None	8.3	34.0	1.1	7.7	23.3	66.1	0.2	66.3	-2.8
		Interior Blinds	7.3	34.0	1.1	6.4	18.9	60.4	0.2	60.6	-11.1
		Exterior Blinds	6.3	34.0	1.1	4.9	13.8	53.8	0.1	53.9	-21.0
		Tinted Glass	7.6	34.0	1.1	6.7	19.7	61.5	0.2	61.7	-9.5
		Tinted Glass, Int. Blinds	6.8	34.0	1.1	5.7	16.6	57.4	0.2	57.6	-15.5
		Reflective Glass	6.4	34.0	1.1	5.0	14.9	55.0	0.2	55.2	-19.1
	YES	None	7.4	25.9	1.1	7.2	21.2	55.4	0.2	55.6	-18.5
		Interior Blinds	6.3	25.9	1.1	6.0	16.8	49.8	0.2	49.8	-27.0
		Exterior Blinds	5.3	25.9	1.1	4.4	11.7	43.1	0.1	43.2	-36.7
		Tinted Glass	6.7	27.9	1.1	6.3	18.3	53.6	0.2	53.8	-21.1
		Tinted Glass, Int. Blinds	5.6	27.9	1.1	5.5	15.2	49.7	0.1	49.8	-27.0

[a] $1.0\ w/ft^2 = 10.76\ w/m^2$; $1.0\ KBtu/ft^2 = 3.15\ kWh/m^2 = 11.35\ MJ/m^2$

Table A.2
Annual energy use summary: LOS ANGELES[a]

Glazing	Daylighting	Sun Control	Peak Elec. Demand (w/ft^2)	Electricity Use ($KBtu/ft^2$)				Total Elec. Use ($KBtu/ft^2$)	Gas Use ($KBtu/ft^2$)	Total Energy Use ($KBtu/ft^2$)	Diff. from Baseline (%)
				Lights	Misc. Equip.	HVAC Aux.	Cooling				
SINGLE	NO	None	6.9	34.0	1.1	7.7	9.3	52.1	2.9	55.0	--
		Int. Blinds	6.2	34.0	1.1	5.9	6.5	47.5	2.4	49.9	-9.3
		Ext. Blinds	5.2	34.0	1.1	4.0	3.6	42.7	2.7	45.4	-17.5
		Tinted Glass	6.4	34.0	1.1	6.6	7.3	49.0	2.6	51.6	-6.2
		Tinted Glass, Int. Blinds	5.8	34.0	1.1	5.2	5.4	45.7	2.2	47.9	-12.9
		Reflective Glass	5.4	34.0	1.1	4.4	4.2	43.7	2.7	46.4	-15.6
	YES	None	6.0	25.9	1.1	7.2	8.2	42.4	2.7	45.1	-18.0
		Int. Blinds	5.2	25.9	1.1	5.5	5.5	38.0	2.3	40.3	-26.7
		Ext. Blinds	4.4	25.9	1.1	3.7	2.9	33.6	3.6	37.2	-32.4
		Tinted Glass	5.5	27.9	1.1	6.2	6.7	41.9	2.5	44.4	-19.3
		Tinted Glass, Int. Blinds	4.6	27.9	1.1	4.9	4.8	38.7	2.4	41.1	-25.3
DOUBLE	NO	None	6.7	34.0	1.1	7.2	10.2	52.5	3.1	55.6	1.1
		Int. Blinds	5.9	34.0	1.1	5.7	7.5	48.3	2.4	50.7	-7.8
		Ext. Blinds	5.2	34.0	1.1	3.9	4.5	43.5	1.7	45.2	-17.8
		Tinted Glass	6.4	34.0	1.1	6.6	7.3	49.0	2.6	51.6	-6.2
		Tinted Glass, Int. Blinds	5.6	34.0	1.1	4.9	6.1	46.1	2.1	48.2	-12.4
		Reflective Glass	5.4	34.0	1.1	4.4	5.7	45.2	1.9	47.1	-14.4
	YES	None	5.8	25.9	1.1	6.8	9.0	42.8	2.7	45.5	-17.3
		Int. Blinds	5.0	25.9	1.1	5.2	6.3	38.5	2.1	40.6	-26.2
		Ext. Blinds	4.2	25.9	1.1	3.4	3.3	33.7	1.5	35.2	-36.0
		Tinted Glass	5.3	27.9	1.1	5.7	7.1	41.8	2.2	44.0	-20.0
		Tinted Glass, Int. Blinds	4.4	27.9	1.1	4.6	5.3	38.9	1.8	40.7	-26.0

[a]$1.0\ w/ft^2 = 10.76\ w/m^2$; $1.0\ KBtu/ft^2 = 3.15\ kWh/m^2$

Table A.3
Annual energy use summary: WASHINGTON, D.C.[a]

Glazing	Daylighting	Sun Control	Peak Elec. Demand (w/ft^2)	Electricity Use ($KBtu/ft^2$)				Total Elec. Use ($KBtu/ft^2$)	Gas Use ($KBtu/ft^2$)	Total Energy Use ($KBtu/ft^2$)	Diff. from Baseline (%)
				Lights	Misc. Equip.	HVAC Aux.	Cooling				
SINGLE	NO	None	8.4	34.0	1.1	8.8	10.2	54.1	17.7	71.8	--
SINGLE	NO	Interior Blinds	7.3	34.0	1.1	7.3	7.9	50.3	16.4	66.7	-7.1
SINGLE	NO	Exterior Blinds	6.6	34.0	1.1	6.8	5.9	47.8	18.1	65.9	-8.2
SINGLE	NO	Tinted Glass	7.7	34.0	1.1	7.7	8.5	51.3	18.8	70.1	-2.4
SINGLE	NO	Tinted Glass, Int. Blinds	6.9	34.0	1.1	6.7	6.9	48.7	17.7	66.4	-7.5
SINGLE	NO	Reflective Glass	6.7	34.0	1.1	6.7	6.0	47.8	23.0	70.8	-1.4
SINGLE	YES	None	7.5	25.9	1.1	8.5	9.3	44.8	19.1	63.9	-11.0
SINGLE	YES	Interior Blinds	6.4	25.9	1.1	6.9	7.0	40.9	17.8	58.7	-18.2
SINGLE	YES	Exterior Blinds	5.4	25.9	1.1	6.6	5.0	38.6	20.1	58.7	-18.2
SINGLE	YES	Tinted Glass	6.8	27.9	1.1	7.6	8.0	44.6	20.6	65.2	-9.2
SINGLE	YES	Tinted Glass, Int. Blinds	5.6	27.9	1.1	6.5	6.4	41.9	19.6	61.5	-14.3
DOUBLE	NO	None	8.1	34.0	1.1	7.9	10.4	53.4	10.3	63.7	-11.3
DOUBLE	NO	Interior Blinds	7.1	34.0	1.1	6.7	8.2	50.0	9.3	59.3	-17.4
DOUBLE	NO	Exterior Blinds	6.5	34.0	1.1	6.4	6.1	47.6	10.1	57.7	-19.6
DOUBLE	NO	Tinted Glass	7.7	34.0	1.1	6.7	8.3	50.1	10.4	60.5	-15.7
DOUBLE	NO	Tinted Glass, Int. Blinds	6.6	34.0	1.1	5.7	6.7	47.5	9.7	57.2	-20.3
DOUBLE	NO	Reflective Glass	6.1	34.0	1.1	5.0	5.9	46.0	8.6	54.6	-24.0
DOUBLE	YES	None	6.9	25.9	1.1	7.5	9.3	43.8	10.8	54.6	-24.0
DOUBLE	YES	Interior Blinds	6.0	25.9	1.1	6.3	7.0	40.3	9.8	50.1	-30.2
DOUBLE	YES	Exterior Blinds	5.3	25.9	1.1	6.1	5.2	38.3	11.1	49.4	-31.2
DOUBLE	YES	Tinted Glass	6.2	27.9	1.1	6.4	7.6	43.0	11.4	54.4	-24.2
DOUBLE	YES	Tinted Glass, Int. Blinds	5.2	27.9	1.1	5.5	6.1	40.6	10.7	51.3	-28.6

a $1.0\ w/ft^2 = 10.76\ w/m^2$; $1.0\ KBtu/ft^2 = 3.15\ kWh/m^2 = 11.35\ MJ/m^2$

Table A.4
Annual energy use summary: CHICAGO[a]

Glazing	Daylighting	Sun Control	Peak Elec. Demand (w/ft^2)	Electricity Use ($KBtu/ft^2$) Lights	Misc. Equip.	HVAC Aux.	Cooling	Total Elec. Use ($KBtu/ft^2$)	Gas Use ($KBtu/ft^2$)	Total Energy Use ($KBtu/ft^2$)	Diff. from Baseline (%)
SINGLE	NO	None	8.2	34.0	1.1	8.8	7.6	51.5	28.4	79.9	--
		Interior Blinds	7.0	34.0	1.1	7.6	5.8	48.5	26.4	74.9	-6.3
		Exterior Blinds	6.2	34.0	1.1	7.4	4.1	46.6	29.4	76.0	-4.9
		Tinted Glass	7.3	34.0	1.1	7.9	6.2	49.2	29.9	79.1	-1.0
		Tinted Glass, Int. Blinds	6.7	34.0	1.1	7.4	5.0	47.5	28.9	76.4	-4.4
		Reflective Glass	6.5	34.0	1.1	7.9	4.3	47.3	36.7	84.0	+5.1
	YES	None	6.7	25.9	1.1	8.4	6.8	42.2	30.1	72.3	-9.5
		Interior Blinds	5.9	25.9	1.1	7.5	5.0	39.5	29.0	68.5	-14.3
		Exterior Blinds	5.3	25.9	1.1	7.54	3.6	38.0	33.0	71.0	-11.1
		Tinted Glass	6.4	27.9	1.1	8.0	5.8	42.8	32.4	75.2	-5.9
		Tinted Glass, Int. Blinds	5.3	27.9	1.1	7.4	4.6	41.0	31.6	71.6	-10.4
DOUBLE	NO	None	7.7	34.0	1.1	7.7	8.0	50.8	16.0	66.8	-16.4
		Interior Blinds	6.8	34.0	1.1	6.4	6.2	47.7	14.4	62.1	-22.3
		Exterior Blinds	6.0	34.0	1.1	5.9	4.3	45.3	15.1	60.4	-24.4
		Tinted Glass	7.0	34.0	1.1	6.5	6.2	47.8	16.5	64.3	-19.5
		Tinted Glass, Int. Blinds	6.3	34.0	1.1	5.6	5.0	45.7	15.1	60.8	-23.9
		Reflective Glass	6.0	34.0	1.1	4.8	4.3	44.2	13.0	57.2	-28.4
	YES	None	6.4	25.9	1.1	7.3	7.1	41.4	17.0	58.4	-26.9
		Interior Blinds	5.5	25.9	1.1	6.0	5.2	38.2	15.4	53.6	-32.9
		Exterior Blinds	4.9	25.9	1.1	5.6	3.5	36.1	17.1	53.2	-33.4
		Tinted Glass	5.9	27.9	1.1	6.3	5.7	41.0	18.1	59.1	-26.0
		Tinted Glass, Int. Blinds	4.9	27.9	1.1	5.5	4.5	39.0	16.7	55.7	-30.3

[a] $1.0\ w/ft^2 = 10.76\ w/m^2$; $1.0\ KBtu/ft^2 = 3.15\ kWh/m^2$

Table A.5
Costs per square foot of gross floor area (1980 U.S. dollars): MIAMI[a]

Glazing	Daylighting	Sun Control	First Cost ($/ft²) Plant	First Cost Windows	First Cost Daylighting	First Cost Tot	Annual Maint. Cost[b] ($/ft²) Plant	Annual Maint. Windows	Annual Maint. Tot	Annual Energy Cost[b] ($/ft²) Elec	Annual Energy Gas	Annual Energy Tot	Life-Cycle Cost[c] ($/ft²) d=6% e=2%	d=3% e=2%	d=3% e=5%
SINGLE	NO	None	.90	.88	0	1.78	.03	0	.03	1.11	0	1.11	10.87	14.43	20.04
SINGLE	NO	Int. Blinds	.78	1.40	0	2.18	.03	.07	.10	1.02	0	1.02	10.42	13.88	18.93
SINGLE	NO	Ext. Blinds	.64	3.12	0	3.76	.02	.04	.06	.88	0	.88	9.80	12.79	17.22
SINGLE	NO	Tinted Glass	.83	.97	0	1.80	.03	0	.03	1.04	0	1.04	10.17	13.60	18.85
SINGLE	NO	Tinted Glass, Int. Blinds	.74	1.49	0	2.23	.03	.07	.10	.96	0	.96	10.09	13.42	18.26
SINGLE	NO	Reflective Glass	.69	1.54	0	2.23	.03	0	.03	.91	0	.91	9.22	12.23	16.82
SINGLE	YES	None	.85	.88	.44	2.17	.03	0	.03	.94	0	.94	9.45	12.56	17.30
SINGLE	YES	Int. Blinds	.72	1.40	.44	2.56	.03	.07	.10	.83	0	.83	9.09	12.01	16.19
SINGLE	YES	Ext. Blinds	.60	3.12	.44	4.16	.02	.04	.06	.71	0	.71	8.48	10.92	14.50
SINGLE	YES	Tinted Glass	.81	.97	.44	2.22	.03	0	.03	.91	0	.91	9.21	12.26	16.81
SINGLE	YES	Tinted Glass, Int. Blinds	.70	1.49	.44	2.63	.03	.07	.10	.83	0	.83	9.12	12.04	16.22
DOUBLE	NO	None	.83	2.36	0	3.19	.03	0	.03	1.07	0	1.07	11.06	14.58	19.98
DOUBLE	NO	Int. Blinds	.72	2.89	0	3.61	.03	.07	.10	.98	0	.98	10.88	14.28	19.22
DOUBLE	NO	Ext. Blinds	.58	4.61	0	5.19	.02	.04	.06	.87	0	.87	10.35	13.30	17.69
DOUBLE	NO	Tinted Glass	.75	2.46	0	3.21	.03	0	.03	1.00	0	1.00	10.45	13.75	18.79
DOUBLE	NO	Tinted Glass, Int. Blinds	.66	2.98	0	3.64	.03	.07	.10	.93	0	.93	10.45	13.69	18.38
DOUBLE	NO	Reflective Glass	.60	3.26	0	3.86	.03	0	.03	.89	0	.89	9.77	12.72	17.20
DOUBLE	YES	None	.79	2.36	.44	3.59	.03	0	.03	.90	0	.90	9.73	12.72	17.25
DOUBLE	YES	Int. Blinds	.67	2.89	.44	4.00	.03	.07	.10	.81	0	.81	9.55	12.41	16.50
DOUBLE	YES	Ext. Blinds	.53	4.61	.44	5.58	.02	.04	.06	.70	0	.70	9.02	11.43	14.96
DOUBLE	YES	Tinted Glass	.71	2.46	.44	3.61	.03	0	.03	.87	0	.87	9.48	12.36	16.75
DOUBLE	YES	Tinted Glass, Int. Blinds	.64	2.98	.44	4.06	.02	.07	.09	.81	0	.81	9.54	12.38	16.46

[a] $\$1.00/ft^2 = \$10.76/m^2$
[b] Before taxes
[c] For three different combinations of discount rate(d) and energy escalation rate(e)

Table A.6
Costs per square foot of gross floor area (1980 U.S. dollars): LOS ANGELES[a]

Glazing	Daylighting	Sun Control	First Cost ($/ft²) Plant	First Cost Windows	First Cost Daylighting	First Cost Tot	Annual Maint. Cost[b] ($/ft²) Plant	Annual Maint. Windows	Annual Maint. Tot	Annual Energy Cost[b] ($/ft²) Elec	Annual Energy Gas	Annual Energy Tot	Life-Cycle Cost[c] ($/ft²) d=6% e=2%	d=3% e=2%	d=3% e=5%
SINGLE	NO	None	.70	.88	0	1.58	.03	0	.03	.85	.01	.86	8.46	11.30	15.63
SINGLE	NO	Int. Blinds	.59	1.40	0	1.99	.02	.07	.09	.77	.01	.78	8.33	11.07	15.00
SINGLE	NO	Ext. Blinds	.46	3.12	0	3.58	.02	.04	.06	.69	.01	.70	8.12	10.52	14.05
SINGLE	NO	Tinted Glass	.64	.97	0	1.61	.02	0	.02	.80	.01	.81	8.02	10.68	14.77
SINGLE	NO	Tinted Glass, Int. Blinds	.55	1.49	0	2.04	.02	.07	.09	.74	.01	.75	8.08	10.72	14.50
SINGLE	NO	Reflective Glass	.50	1.54	0	2.04	.02	0	.02	.71	.01	.72	7.40	9.78	13.40
SINGLE	YES	None	.65	.88	.44	1.97	.02	0	.02	.69	.01	.70	7.21	9.53	13.06
SINGLE	YES	Int. Blinds	.54	1.40	.44	2.38	.02	.07	.09	.62	.01	.63	7.17	9.42	12.60
SINGLE	YES	Ext. Blinds	.43	3.12	.44	3.99	.02	.04	.06	.54	.01	.55	6.98	8.89	11.66
SINGLE	YES	Tinted Glass	.60	.97	.44	2.01	.02	0	.02	.68	.01	.69	7.13	9.41	12.89
SINGLE	YES	Tinted Glass, Int. Blinds	.53	1.49	.44	2.46	.02	.07	.09	.63	.01	.64	7.32	9.61	12.83
DOUBLE	NO	None	.68	2.36	0	3.04	.03	0	.03	.85	.01	.86	9.10	11.94	16.28
DOUBLE	NO	Int. Blinds	.58	2.89	0	3.47	.02	.07	.09	.78	.01	.79	9.08	11.85	15.83
DOUBLE	NO	Ext. Blinds	.47	4.61	0	5.08	.02	.04	.06	.70	.01	.71	8.88	11.32	14.90
DOUBLE	NO	Tinted Glass	.61	2.46	0	3.07	.02	0	.02	.79	.01	.80	8.57	11.21	15.24
DOUBLE	NO	Tinted Glass, Int. Blinds	.52	2.98	0	3.50	.02	.07	.09	.74	.01	.75	8.72	11.36	15.14
DOUBLE	NO	Reflective Glass	.49	3.26	0	3.75	.02	0	.02	.73	.01	.74	8.32	10.75	14.48
DOUBLE	YES	None	.64	2.36	.44	3.44	.02	0	.02	.70	.01	.71	7.95	10.30	13.88
DOUBLE	YES	Int. Blinds	.53	2.89	.44	3.86	.02	.07	.09	.63	.01	.64	7.91	10.20	13.42
DOUBLE	YES	Ext. Blinds	.39	4.61	.44	5.44	.01	.04	.05	.54	.01	.55	7.61	8.52	12.30
DOUBLE	YES	Tinted Glass	.57	2.46	.44	3.47	.02	0	.02	.68	.01	.69	7.77	10.05	13.53
DOUBLE	YES	Tinted Glass, Int. Blinds	.49	2.98	.44	3.91	.02	.07	.09	.63	.01	.64	7.96	10.25	13.48

[a] $\$1.00/ft^2 = \$10.76/m^2$
[b] Before taxes
[c] For three different combinations of discount rate(d) and energy escalation rate(e)

Table A.7

Costs per square foot of gross floor area (1980 U.S. dollars): WASHINGTON, D.C.[a]

Glazing	Daylighting	Sun Control	First Cost ($/ft²) Plant	First Cost Windows	First Cost Daylighting	First Cost Tot	Annual Maint. Cost[b] ($/ft²) Plant	Annual Maint. Windows	Annual Maint. Tot	Annual Energy Cost[b] ($/ft²) Elec	Annual Energy Gas	Annual Energy Tot	Life-Cycle Cost[c] ($/ft²) d=6% e=2%	Life-Cycle d=3% e=2%	Life-Cycle d=3% e=5%
SINGLE	NO	None	.93	.88	0	1.81	.03	0	.03	.88	.06	.94	9.40	12.55	17.34
SINGLE	NO	Int. Blinds	.80	1.40	0	2.20	.03	.07	.10	.82	.06	.88	9.37	12.45	16.88
SINGLE	NO	Ext. Blinds	.71	3.12	0	3.83	.03	.04	.07	.78	.06	.84	9.52	12.39	16.63
SINGLE	NO	Tinted Glass	.84	.97	0	1.81	.03	0	.03	.84	.07	.91	9.03	12.04	16.63
SINGLE	NO	Tinted Glass, Int. Blinds	.75	1.49	0	2.24	.03	.07	.10	.79	.06	.85	9.10	12.07	16.36
SINGLE	NO	Reflective Glass	.73	1.54	0	2.29	.03	0	.03	.78	.08	.86	8.78	11.62	15.96
SINGLE	YES	None	.89	.88	.44	2.21	.03	0	.03	.74	.07	.81	8.35	11.04	15.13
SINGLE	YES	Int. Blinds	.75	1.40	.44	2.59	.03	.07	.10	.67	.06	.73	8.19	10.78	14.46
SINGLE	YES	Ext. Blinds	.66	3.12	.44	4.22	.02	.04	.06	.63	.07	.70	8.46	10.88	14.41
SINGLE	YES	Tinted Glass	.82	.97	.44	2.23	.03	0	.03	.73	.07	.80	8.25	10.90	14.94
SINGLE	YES	Tinted Glass, Int. Blinds	.73	1.49	.44	2.66	.03	.07	.10	.68	.06	.74	8.30	10.91	14.64
DOUBLE	NO	None	.85	2.36	0	3.21	.03	0	.03	.87	.04	.91	9.65	12.66	17.25
DOUBLE	NO	Int. Blinds	.74	2.89	0	3.63	.03	.07	.10	.81	.03	.84	9.63	12.57	16.81
DOUBLE	NO	Ext. Blinds	.68	4.61	0	5.29	.03	.04	.07	.77	.04	.81	9.91	12.68	16.77
DOUBLE	NO	Tinted Glass	.76	2.46	0	3.22	.03	0	.03	.82	.04	.86	9.20	12.04	16.37
DOUBLE	NO	Tinted Glass, Int. Blinds	.67	2.98	0	3.65	.03	.07	.10	.77	.03	.80	9.26	12.07	16.10
DOUBLE	NO	Reflective Glass	.62	3.26	0	3.88	.02	0	.07?	.75	.03	.78	8.76	11.34	15.27
DOUBLE	YES	None	.81	2.36	.44	3.61	.03	0	.03	.72	.04	.76	8.51	11.04	14.87
DOUBLE	YES	Int. Blinds	.69	2.89	.44	4.02	.03	.07	.10	.66	.03	.69	8.46	10.91	14.39
DOUBLE	YES	Ext. Blinds	.63	4.61	.44	5.68	.02	.04	.06	.62	.04	.66	8.74	11.02	14.35
DOUBLE	YES	Tinted Glass	.73	2.46	.44	3.63	.03	0	.03	.70	.04	.74	8.32	10.77	14.51
DOUBLE	YES	Tinted Glass, Int. Blinds	.65	2.98	.44	4.07	.03	.07	.10	.66	.04	.70	8.57	11.06	14.59

[a] $\$1.00/ft^2 = \$10.76/m^2$
[b] Before taxes
[c] For three different combinations of discount rate(d) and energy escalation rate(e)

Table A.8

Costs per square foot of gross floor area (1980 U.S. dollars): CHICAGO[a]

Glazing	Daylighting	Sun Control	First Cost ($\$/ft^2$) Plant	First Cost Windows	First Cost Daylighting	First Cost Total	Annual Maint. Cost[b] ($\$/ft^2$) Plant	Annual Maint. Windows	Annual Maint. Total	Annual Energy Cost[b] ($\$/ft^2$) Elec	Annual Energy Gas	Annual Energy Total	Life-Cycle Cost[c] ($\$/ft^2$) d=6% e=2%	Life-Cycle d=3% e=2%	Life-Cycle d=3% e=5%
SINGLE	NO	None	.93	.88	0	1.81	.03	0	.03	.84	.10	.94	9.32	12.43	17.17
		Int. Blinds	.79	1.40	0	2.19	.03	.07	.10	.79	.09	.88	9.36	12.44	16.88
		Ext. Blinds	.67	3.12	0	3.79	.03	.04	.07	.76	.10	.86	9.68	12.62	16.95
		Tinted Glass	.83	.97	0	1.80	.03	0	.03	.80	.10	.90	8.94	11.91	16.45
		Tinted Glass,Int.blinds	.75	1.49	0	2.24	.03	.07	.10	.77	.10	.87	9.27	12.31	16.70
		Reflective Glass	.72	1.54	0	2.26	.03	0	.03	.77	.13	.90	9.14	12.11	16.65
	YES	None	.87	.88	.44	2.19	.03	0	.03	.69	.11	.80	8.25	10.91	14.95
		Int. Blinds	.74	1.40	.44	2.58	.03	.07	.10	.64	.10	.74	8.28	10.90	14.63
		Ext. Blinds	.63	3.12	.44	4.19	.02	.04	.06	.62	.12	.74	8.78	11.32	15.05
		Tinted Glass	.82	.97	.44	2.23	.03	0	.03	.70	.11	.81	8.33	11.02	15.11
		Tinted Glass, Int. Blinds	.71	1.49	.44	2.64	.03	.07	.10	.67	.10	.77	8.60	11.32	15.20
DOUBLE	NO	None	.84	2.36	0	3.20	.03	0	.03	.83	.06	.89	9.47	12.42	16.91
		Int. Blinds	.72	2.89	0	3.61	.03	.07	.10	.78	.05	.83	9.53	12.44	16.63
		Ext. Blinds	.62	4.61	0	5.23	.02	.04	.06	.73	.05	.78	9.60	12.27	16.20
		Tinted Glass	.75	2.46	0	3.21	.03	0	.03	.78	.06	.84	9.01	11.79	16.03
		Tinted Glass,Int.blinds	.66	2.98	0	3.64	.02	.07	.09	.74	.05	.79	9.17	11.94	15.93
		Reflective Glass	.60	3.26	0	3.86	.02	0	.02	.71	.05	.76	8.57	11.09	14.92
	YES	None	.80	2.36	.44	3.60	.03	0	.03	.68	.06	.74	8.33	10.79	14.52
		Int. Blinds	.66	2.89	.44	3.99	.02	.07	.09	.62	.05	.67	8.27	10.65	14.03
		Ext. Blinds	.57	4.61	.44	5.62	.02	.04	.06	.59	.06	.65	8.62	10.87	14.15
		Tinted Glass	.73	2.46	.44	3.63	.03	0	.03	.67	.06	.73	8.23	10.65	14.33
		Tinted Glass, Int. Blinds	.65	2.98	.44	4.07	.03	.07	.10	.63	.06	.69	8.53	11.00	14.48

[a] $\$1.00/ft^2 = \$10.76/m^2$

[b] Before taxes

[c] For three different combinations of discount rate(d) and energy escalation rate(e)