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WINDOW PERFORMANCE ANALYSIS IN A SINGLE-FAMILY RESIDENCE

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ABSTRACT

This paper presents the results of a parametric study of fenestration in a single-family residential prototype. The DOE-2.1B energy analysis program was used to analyze the variation in heating and cooling energy requirements and resultant costs due to changes in the following fenestration characteristics: orientation, size, conductance, and shading coefficient. Incremental energy use changes due to the effects of night insulation, shade management, and overhangs were also examined. Climate sensitivity was established by considering results from four distinct climate zones representative of warm and humid (Lake Charles, LA), hot and dry (Phoenix, AZ), temperate (Washington, DC), and cold (Madison, WI). The analysis of the effects of hypothetical fenestration systems on building energy use was made viable by development of an algebraic expression through the use of multiple regression procedures. Such techniques also permitted the definition and isolation of those window characteristics which minimize residential energy use and/or cost.

INTRODUCTION

Windows systems play a major role in determining residential energy requirements. They influence the thermal environment of buildings in a manner characterized by convective and conductive heat transfer, radiant transfer, and mass transfer. Such mechanisims represent viable areas of investigation if one is to better understand and reduce residential energy consumption. Research and development in new window systems concerns itself with affecting changes to one or more of these properties. The introduction of double- and triple-pane glazing is an example in which both the conductive and radiative characteristics are affected. Another example is the use of windows having extremely low U-values, on the order of 0.1 Btu/hr$\cdot$ft$^2\cdot$F (0.6 W/m$^2\cdot{}^\circ$C), plus high solar and visual transmission (Arasteh and Selkowitz 1985 and Keller, Grether, and Broder 1984). In this system, double-pane glass is used with low-emittance coatings on two plastic interlayers and different gas mixtures in the air gap. Low emissivity coatings are used to reduce the radiative component of the thermal losses while maintaining high solar transmission. Control of optical and thermal characteristics and mass transfer can also be provided by insulating shutters and movable insulation (Selkowitz and Bazjanac 1979).

Selection of appropriate window systems for a building is based on the relationship between the window and the particular climatic variable driving the heat transfer. Aesthetics, of course, also play a major role in design decisions, and they indirectly affect energy use. In cold climates, glass conduction and solar transmittance as well as air tightness determines a system's contribution to annual energy use. In warm locations, the major contributors are solar transmission and ventilation capability.

It is essential to study the annual performance of window systems within the framework of overall residential building performance. However, once appropriate simulations have been completed, it is feasible to analytically isolate the window system from the other building components such as envelope insulation levels, infiltration, and internal heat gains as was shown in recent studies accomplished by research groups of the Applied Science Division at Lawrence Berkeley Laboratory, (Energy Analysis Program 1983 and Sullivan and Selkowitz 1985). These references document the independence of the major fenestration components to residential thermal loads and energy use by relating changes caused by varying configuration properties. The Sullivan and Selkowitz 1985 work showed the development of a regression expression derived from a large data base of DOE-2 (Lawrence Berkeley Laboratory and Los Alamos Scientific Laboratory 1981) computer simulations of a single-family residential prototype. The expression showed that comparative fenestration performance could be analyzed by considering only those factors directly related to the windows. The work reported in this document represents a continuation of this past work and takes the form of an analysis related to specific fenestration properties. Through the use of solar gain and conductance loss information, residential energy use and cost trends are conveniently established.

RESIDENCE DESCRIPTION

The prototypical single-family ranch style house selected for analysis consisted of a 55 ft (16.67 m) by 28 ft (8.53 m), one zone structure of wood frame construction with window sizes fixed on three sides at 15% of the wall area, Figure 1. The size of the fourth or primary side provided the parametric variation on window size which varied from 0% to 60% of the wall area (0% to 17.1% floor area). Typical conductance values for single, double, triple, and high-resistive (U=0.1 $Btu/hr \cdot ft^2 \cdot F$, 0.534 $W/m^{2} \cdot {}^{o}C$) glazings as well as shading coefficient values of 0.4, 0.7, and 1.0 served as the window property parametrics. Results were obtained for eight orientations covering a complete 360^o rotation in 45^o increments. More details of the thermal and operational characteristics of the prototype are provided in the Sullivan and Selkowitz 1985 report.

Incremental changes to the glazing properties due to night insulation, shade management, and overhangs were also investigated. Insulation levels of R=1.0 $hr \cdot ft^{2} \cdot {}^{o}F/Btu$ (0.18 $m^{2} \cdot {}^{o}C/W$), 2.5 (0.44), and 5.0 (0.88) were implemented at night during the months of October 1 to April 30. Shade management was simulated by deploying a shade that reduced solar heat gain by 40% if the direct solar gain on a particular window exceeded 20 Btu/ft^2 (63 W/m^2). Overhangs were modeled using a fixed width of 2.5 ft (0.76 m) above each window.

Standard year (WYEC) weather profiles (Crow 1980) for Madison, WI and Lake Charles, LA were used in the analysis. Their selection was based on the expectedly large thermal load differences resulting from their geographic location. Base 65 F (18.3 °C) heating degree day values for Madison and Lake Charles were 7825 and 1717 respectively. Simulation runs were also made for configurations located in Washington, DC and Phoenix, AZ, although the number of runs was much smaller than the two primary locations. The purpose of investigating these additional climate locations was to verify the existance of a very convenient proportional relationship, reported in Sullivan and Huang et al. 1985, between building thermal loads and varying configuration parameters. The relationship was shown to be independent of climate location and covered a broad spectrum of those variables that influence a building's energy use.

DISCUSSION

The change in residential energy use due to differing fenestration characteristics was shown by the Sullivan and Selkowitz 1985 report to be very accurately predicted by an equation of the form:

$$\begin{aligned} \Delta E = {} & \beta_1(U_gA_g) + \beta_2(\Sigma U_{go}A_{go}) && \text{conduction} \\ & + \beta_3(SC_gA_g)^2 + \beta_4(SC_gA_g) + \beta_5(\Sigma SC_{go}A_{go}) && \text{solar gain} \end{aligned} \tag{1}$$

where

β = regression coefficients
U_g = primary glazing U-value
A_g = primary glazing area
SC_g = primary glazing shading coefficient
U_{go} = off-primary glazing U-value
A_{go} = off-primary glazing U-value
SC_{go} = off-primary glazing U-value

The off-primary glazing values represent the sum of the three sides that were fixed in size. The regression coefficients were revised by multipliers to account for the effects of night insulation, shade management, and overhangs. Such an expression can be used to derive convenient graphical techniques for presenting residential energy comparisons as a function of glass conductance and shading coefficient.

Figures 2, 3, and 4 use this equation form to define the net useful flux during the heating season in Madison, WI. The net useful flux for a particular orientation is defined as the difference in annual energy usage caused by a change in one or more of the primary window's characteristics. These figures show the differences between the primary orientations of south, east, and north for two window sizes both with and without the use of night insulation. Typical glazing products are located in the figures based on their U-value and shading coefficient defined in Table 1.

The general variation of net flux with shading coefficient is as one would expect: for a fixed U-value, the net flux increases with increased shading coefficient, indicating larger net useful solar gains. For a fixed shading coefficient, the net flux increases with decreasing U-value, indicating smaller conductance losses. The range of net flux values vary from a low of -176 Kbtu/yr$\cdot$ft^2 (-2 GJ/yr$\cdot$m^2) for a north orientation using low resistance glass, i.e. single-pane, to a high of 70 Kbtu/yr$\cdot$ft^2 (0.8 GJ/yr$\cdot$m^2) for a south facing, high resistive glass, i.e. triple-pane.

Window area changes cause a large variation in the curves shown on the figures. With the exception of a north primary orientation, the window conductance value for the crossover from net savings to net losses is reduced with increasing window area. In Figure 2, for the smaller window with a shading coefficient value of 1.0, a conductance as high as 0.79 Btu/hr$\cdot$ft$^2\cdot$F (4.5 W/m$^2\cdot$°C) provides a net positive energy flow; whereas, for the larger window, a conductance of 0.53 Bt/hr$\cdot$ft$^2\cdot$F (3.1 W/m$^2\cdot$°C) is required. As the shading coefficient decreases, the effect of window area also decreases and at SC´s less that 0.4, the U-values at crossover would be the same regardless of window size.

Orientation changes to an off-south direction reduce the conductance at crossover, with a limit being approached at 0.09 Btu/hr$\cdot$ft$^2\cdot$F (0.5 W/m$^2\cdot$°C) for a large primary north window with a shading coefficient equal to 0.4. Table 2 shows the crossover values for all orientations as well as showing the changes resulting from the use of night insulation. Use of night insulation has a dramatic effect on all aspects of the net flux variations shown on the figures, especially for the south and east orientations. Night insulation permits a window system to achieve a net positive energy flow at a much higher glass conductance value. Effective use of night insulation would thus permit use of more standard window products without penalty. For example, the U-value at crossover for a primary window area of 66 ft^2 (6.13 m^2) using a south orientation and a shading coefficient of 1.0 is 1.23 Btu/hr$\cdot$ft$^2\cdot$F (7.0 W/m$^2\cdot$°C), a value higher than the published ASHRAE standard U-value for single glazing for winter conditions. The major practical obstacle to realizing energy savings is the uncertainty in consistent operation of the night insulation options.

The relative position of the conductance and shading coefficient values of the various glazing products annotated on Figures 2 through 4 is quite informative. For a south orientation, Figure 2, all glazing types listed, with the exception of single-pane, yield a net positive flux for both the small and large window sizes without night insulation (double-pane glass yields a zero value for the large window). With night insulation, even the single-pane glass gives a net positive value.

As an easterly orientation is approached, only the highly resistive products such as triple-pane glass are positive for the small window size without night insulation. However, using night insulation changes the gain/loss crossover so that double-pane is positive. For the large window facing east, night insulation is also required with the highly resistive glass in order to yield a net positive flux. A north primary orientation reduces the amount of solar gain so appreciably that the glazing product values shown yield negative fluxes. However, new window systems incorporating low emissive coatings, low conductance gas fills in the air gap of multiple glazing layers can show net positive benefits.

Another interesting fact resulting from the use of night insulation is that the change in net flux due to a glass conductance change is approximately half the value present without night insulation. Night insulation modifies the influence of glass conductance levels and reduces the significance of major conductance changes. This is true for all orientations, but is especially obvious for the north orientation in Figure 4.

For the case of heating only, in a cold climate, the energy values shown in Figures 2 to 4 can be directly converted to annual heating costs using an appropriate seasonal heating efficiency. For a house that is heated and cooled, the fenestration performance is more complex. However, equation (1) can be used to generate the heating and cooling energy requirements, and then the results can be multiplied by appropriate energy cost values. These results are shown in Figure 5 which presents, for a south primary orientation, the summed heating and cooling energy net cost curves.

Heating cost was based on \$.60/therm (\$6.00/Mbtu, \$5.69/GJ) and cooling was \$.07/kwh (\$20.50/Mbtu, \$19.43/GJ). These curves can be compared directly with Figure 2 which shows only heating energy. A significant change is apparent resulting from the greater relative cooling energy cost. Cooling energy in Madison is small, varying from about 21% of heating for a large, unshaded window to 4% for a small, heavily shaded window. However, the cost of electricity, in the example used, is 3.4 times the cost of gas. Therefore, the additional solar radiation and cooling energy associated with increased shading coefficient and window area causes a large curvature and shift in the previously almost linear net flux curves.

Figure 6 shows another perspective on cost optimization. Solutions are presented for an optimum primary window area facing south in Madison for various configuration parameters and different electricity to gas cost ratios. The curves were generated by calculating the window size which minimizes energy cost by taking the derivative of equation (1) with respect to primary area and equating the result to zero:

$$A_g = [-\beta'_4 - \beta'_1 * (U_g/SC)]/(2.*\beta'_3 * SC) \qquad (2)$$

where the prime on the coefficients indicates the summed heating and cooling energy values.

The minimum energy cost solution is found by modifying the energy equation to account for the unit costs of gas and electricity. Using the same cost figures as above, the regression coefficients become (using β_1 as an example): [$\beta_1' = 19.43\ \beta_{1c} + 5.69\ \beta_{1h}$] when using SI units. It is apparent that the reduction in optimum area is associated with increased electricity cost (cooling) and/or reduced gas cost (heating), denoted by the progression from curve A through D. The use of night insulation has the same dramatic effect on all curves as was seen previously.

Residential energy consumption in cooling dominated climates, such as Lake Charles, LA is reduced mostly by solar gain control. Through proper primary window orientation and use of shading devices, both inside and outside the residence, a significant reduction in cooling loads can be obtained. Figures 7, 8, and 9 present, for primary orientations of south, east, and north, respectively, incremental cooling energy values as a function of window area and shading coefficient for the prototype residence. Also shown are the effects from using shade management and overhangs.

The general shape of the curves is the same for all orientations, with or without the sun control devices. For a particular shading coefficient, the incremental cooling energy is approximately proportional to primary window area. Likewise, for a fixed primary area, the change in energy is proportional to shading coefficient.

Results for the south and east are almost identical. Within the range of the prototype configuration variables studied, the incremental cooling energy reaches an upper limit on the order of 11.4 Mbtu/yr (12 GJ/yr). At this magnitude, there is almost a constant difference in window areas between the prototype without sun control and those using shade management or overhangs. In other words, if cooling energy consumption is held constant, (e.g. the 12 GJ/yr curves on Figures 7 and 8) an increase in window area of about 24 ft^2 (2.2 m^2) is permitted if using shade management. For overhangs, the increase is 43 ft^2 (4.0 m^2). For lower cooling energy values, these area increases get progressively smaller as can be seen on Table 3.

The differences between the overhang and shade management results are not only a function of the specific model employed, but are also related to the type of sun protection afforded by each device. Overhangs protect from direct sun, whereas, shade management reduces both direct and diffuse by a certain percentage. This may somewhat explain the results shown on Figure 9 which indicates that the use of shade management for a north orientation reduces the primary window area at which the same incremental cooling energy is attained without shade management. This effect is opposite to that observed for south and east orientations. Also, the energy levels are about half the values for south and east for the same window area and shading coefficient.

Figure 10 shows the effect of climate on the heating and cooling energy of the prototype residence by comparing values of a base configuration to those values prevalent for varying window properties. The proportional relationship was verified by the Sullivan and Huang, et. al. 1985 report and was shown to be present for variations in other configurational parameters such as wall, roof, and floor insulation and mass properties, infiltration levels, etc. Understanding building energy performance is greatly simplified by a relationship of this type once a base prototype's characteristics are defined throughout a climatic range. Because the curves are linear and very nearly approach a zero value at the intercept, a percentage change in energy consumption due to a configuration variation at one geographic location would yield the same percent change at a different location.

CONCLUSIONS

This paper has discussed results of a continuing study concerned with the analysis of fenestration systems in single-family residences. Data have been presented for the heating and cooling dominated climates of Madison, WI and Lake Charles, LA. The energy related effects of varying basic window properties, i.e. area, conductance, and shading coefficient were investigated in addition to the changes resulting from use of night insulation, shade management, and overhangs. Several conclusions can be drawn from the work accomplished to date:

a. The range of net useful heating season flux values in Madison, WI varies from a low of -176 Kbtu/yr·ft^2 (-2 GJ/yr·m^2) for a north orientation using low resistive glass, i.e. single-pane, to a high of 70 Kbtu/yr·ft^2 (0.8 GJ/yr·m^2) for a south facing, high resistive glass, i.e. triple-pane.

b. Use of properly managed night insulation effectively improves window system performance, reducing the losses to -106 (-1.2) for the poorest performers and increases the benefits to about 88 (1.0) for the best performers.

c. With the exception of a north facing primary window orientation, the glass conductance value that defines the heating energy boundary between net gains and losses is reduced with increasing window area. A similar reduction is also apparent as the window orientation varies from an off-south direction.

d. The change in net flux due to a glass conductance change when using night insulation during the heating season is approximately half the value present without night insulation. This assumes that the movable insulation is effectively managed.

e. Energy cost results in heating dominated climates are influenced by cooling energy requirements due to the cost differential associated with gas (heating) and electricity (cooling), thus net energy gains can become net economic losses. Of course, the cooling required can be tempered by an appropriate natural ventilation strategy or by use of various sun control devices such as shade management and overhangs. Cost optimized solutions may lead to very different designs than those designed to minimize energy use.

f. In cooling dominated climates, the simulations suggest that overhangs result in larger reductions in cooling energy than implementation of shade management. However, these results are dependent on the specific overhang modeled, the specific shade management algorithm, and other simulation details and may not hold for other sets of assumptions.

g. For Lake Charles, LA, annual incremental cooling energy due to primary window configuration changes of size and shading coefficient were essentially the same for both the south, east, and west orientations. A north orientation resulted in about half the cooling energy required for the south and east for the same area and shading coefficient.

h. Portions of the study verified the existence of a proportional relationship among the energy quantities of different configuration parameters for varying geographic locations. This relationship will significantly simplify future studies, since a large reduction in the number of computer simulations is anticipated.

i. This study emphisized the heating and cooling load and cost implications of fenestration selection. In practice, many other considerations will influence the selection process. For example, the annual energy results suggest that single glazing with a night insulation option will produce net energy benefits in a northern climate. However, one would normally nor specify single glazing because of the condensation problems and thermal comfort effects. The night insulation and shade management results are based upon proper and consistent use of these options. The degree to which this is achieved in practice is not well documented.

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TABLE 1

Performance of typical glazing products for use with Figures 2 through 5.

Type	U ($W/m^2 \cdot {}^oC$)	SC
g	6.46	1.0
g-g	2.87	0.88
g-g-g	1.80	0.80
g-eg	1.92	0.77
g-ep-g	1.32	0.67
l-l	2.87	0.97
l-l-l	1.80	0.90

g: 3.18 mm (1/8") DS float glass
l: 3.18 mm (1/8") low-iron sheet glass
e: low-emittance coating, e=0.15
p: 0.10 mm polyester

All air gaps are 12.7 mm (1/2")
U-value: Standard ASHRAE winter conditions
SC: Standard ASHRAE summer conditions

Night insulation performance:
Resistance level: 0.44 $m^2 \cdot {}^oC/W$
Active months: October - April
Active hours: 7 pm - 6 am
Outside air temperature: Less than 15.5°C
No leakage

TABLE 2

Maximum glass conductance values yielding a net positive useful flux in Madison, WI as a function of primary window orientation, area, and shading coefficient using heating energy requirements. (Units are $W/m^2 \cdot {}^oC$)

Without Night Insulation

	South		East		North	
SC	$6.13m^2$	$24.53m^2$	$6.13m^2$	$24.53m^2$	$6.13m^2$	$24.53m^2$
1.0	4.5	3.1	2.5	1.6	1.0	0.9
0.7	3.3	2.5	1.9	1.4	0.9	0.75
0.4	2.0	1.8	1.2	1.1	0.7	0.5

With Night Insulation ($R = 0.44\ m^2 \cdot {}^oC/W$)

	South		East		North	
SC	$6.13m^2$	$24.53m^2$	$6.13m^2$	$24.53m^2$	$6.13m^2$	$24.53m^2$
1.0	7.0	4.9	3.5	2.4	1.1	1.0
0.7	4.8	3.7	2.7	1.9	0.9	0.75
0.4	2.7	2.3	1.6	1.4	0.7	0.5

TABLE 3

Solar gain control effectiveness of shade management and overhangs in Lake Charles, LA using the change in primary window area (m^2) which achieves the same incremental cooling energy as the unshaded window.

Δ Cooling Energy = 4 GJ/yr

Shade Management				Overhangs			
SC	South	East	North	SC	South	East	North
1.0	0.6	0.6	-0.6	1.0	1.4	1.3	0.9
0.7	1.4	0.8	-0.6	0.7	2.4	1.9	0.9
0.4	2.6	0.8	-1.3	0.4	3.7	4.0	2.0

Δ Cooling Energy = 8 GJ/yr

Shade Management				Overhangs			
SC	South	East	North	SC	South	East	North
1.0	1.5	1.4	-1.3	1.0	2.6	2.8	1.7
0.7	2.7	1.5	-1.3	0.7	4.0	3.2	1.7
0.4	-	-	-	0.4	-	-	-

Δ Cooling Energy = 12 GJ/yr

Shade Management				Overhangs			
SC	South	East	North	SC	South	East	North
1.0	2.3	2.1	-	1.0	3.8	4.2	-
0.7	2.0	2.2	-	0.7	-	-	-
0.4	-	-	-	0.4	-	-	-

FIGURE 1 - Residential model description.

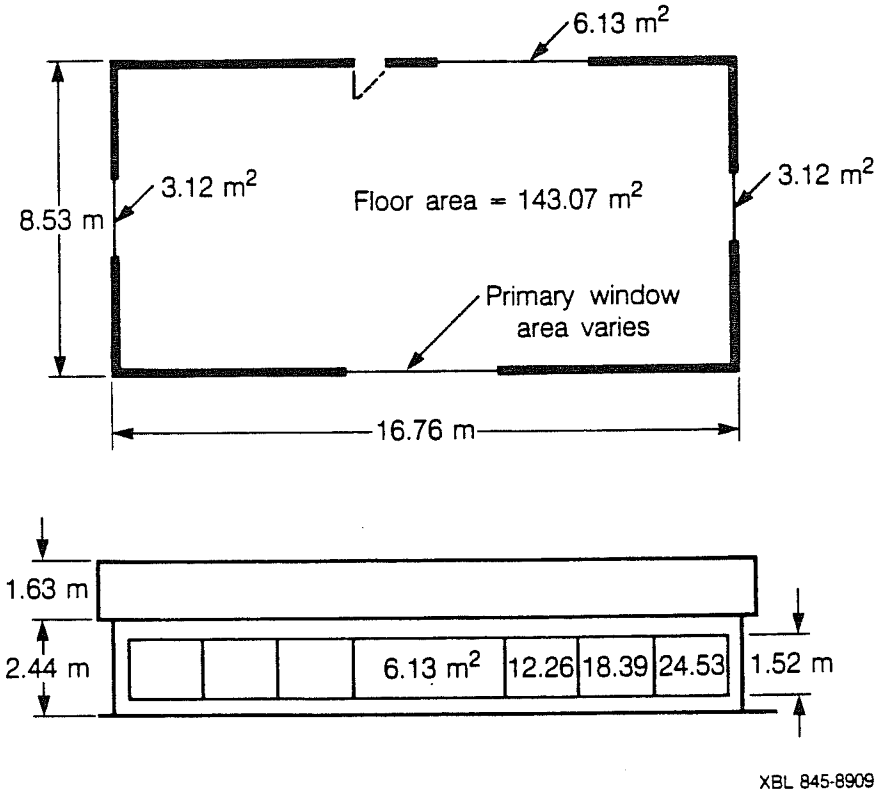

FIGURE 2a - Annual net flux in Madison, WI for a south facing primary window of area 6.13 m^2 using heating energy requirements.
(See Table 1 for glazing product information)

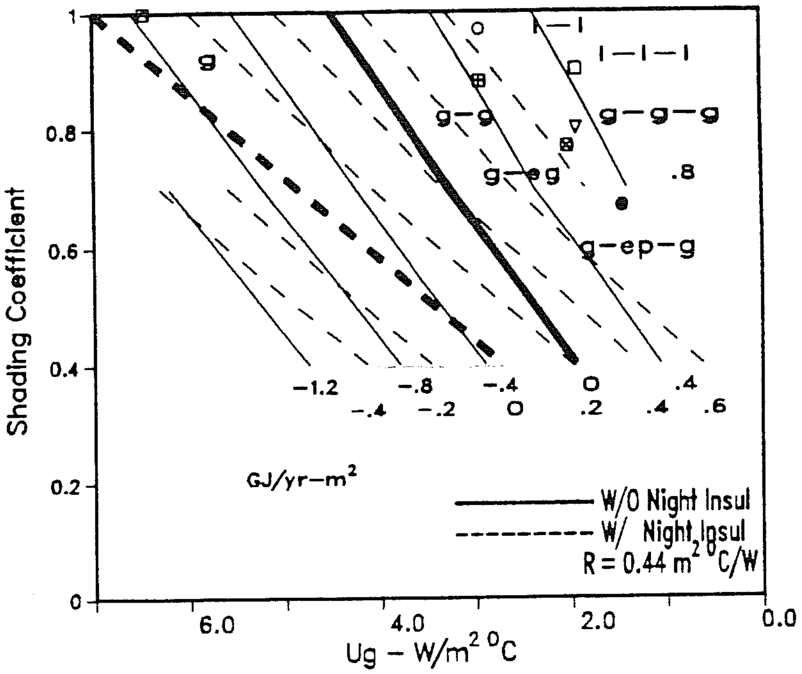

FIGURE 2b - Annual net flux in Madison, WI for a south facing primary window of area 24.53 m^2 using heating energy requirements.
(See Table 1 for glazing product information)

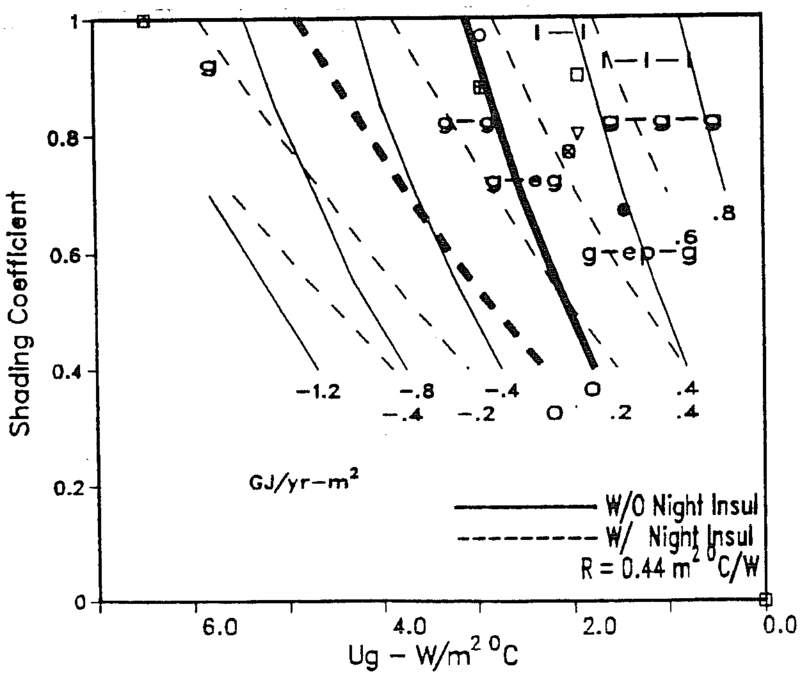

FIGURE 3a - Annual net flux in Madison, WI for an east facing primary window of area 6.13 m^2 using heating energy requirements.
(See Table 1 for glazing product information)

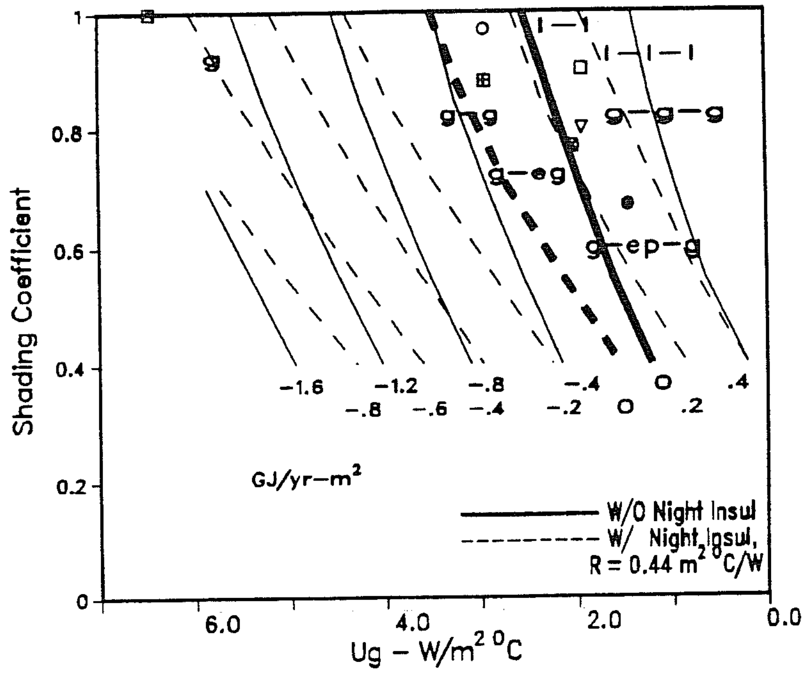

FIGURE 3b - Annual net flux in Madison, WI for an east facing primary window of area 24.53 m^2 using heating energy requirements.
(See Table 1 for glazing product information)

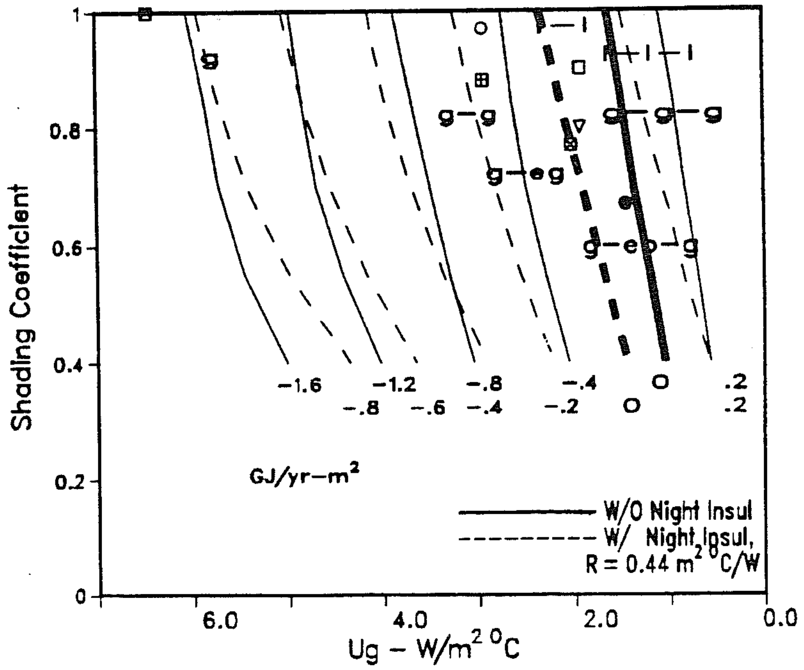

FIGURE 4a - Annual net flux in Madison, WI for a north facing primary window of area 6.13 m^2 using heating energy requirements.
(See Table 1 for glazing product information)

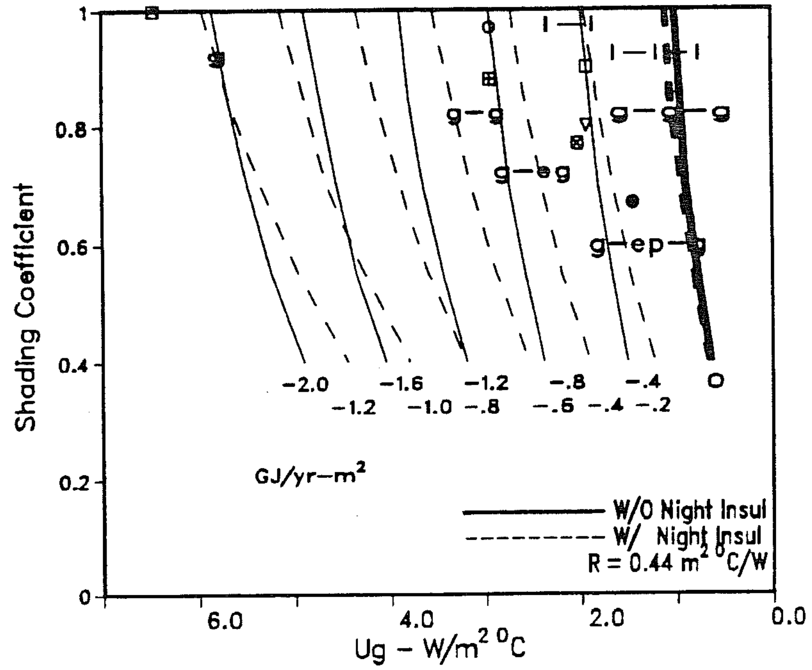

FIGURE 4b - Annual net flux in Madison, WI for a north facing primary window of area 24.53 m^2 using heating energy requirements.
(See Table 1 for glazing product information)

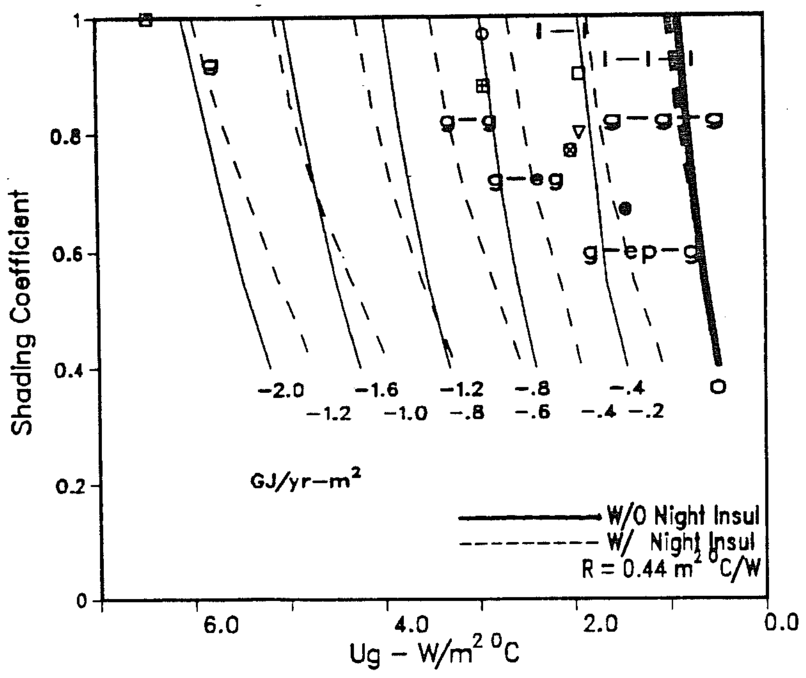

FIGURE 5a - Annual net energy costs in Madison, WI for a south facing primary window of area 6.13 m^2 using heating and cooling energy requirements.
(See Table 1 for glazing product information)

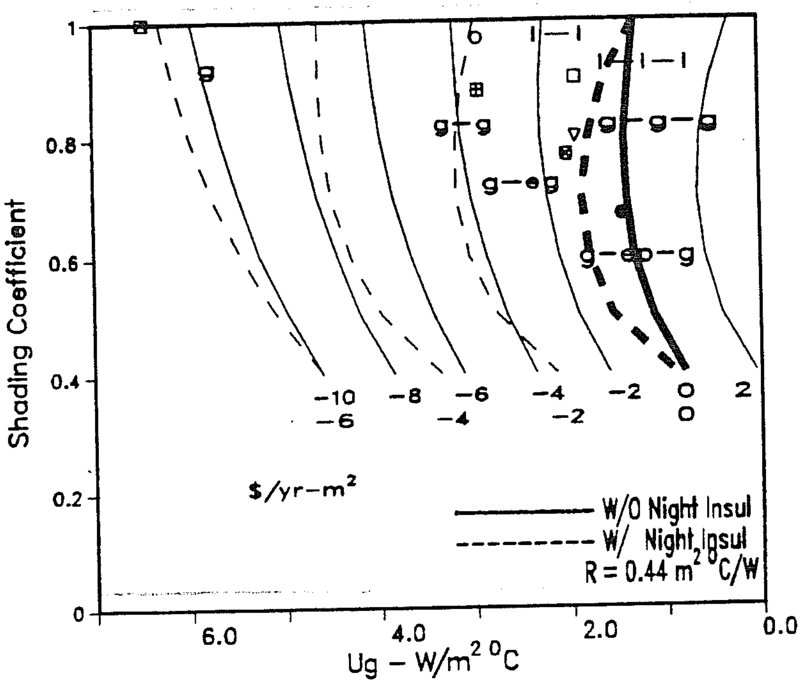

FIGURE 5b - Annual net energy costs in Madison, WI for a south facing primary window of area 24.53 m^2 using heating and cooling requirements.
(See Table 1 for glazing product information)

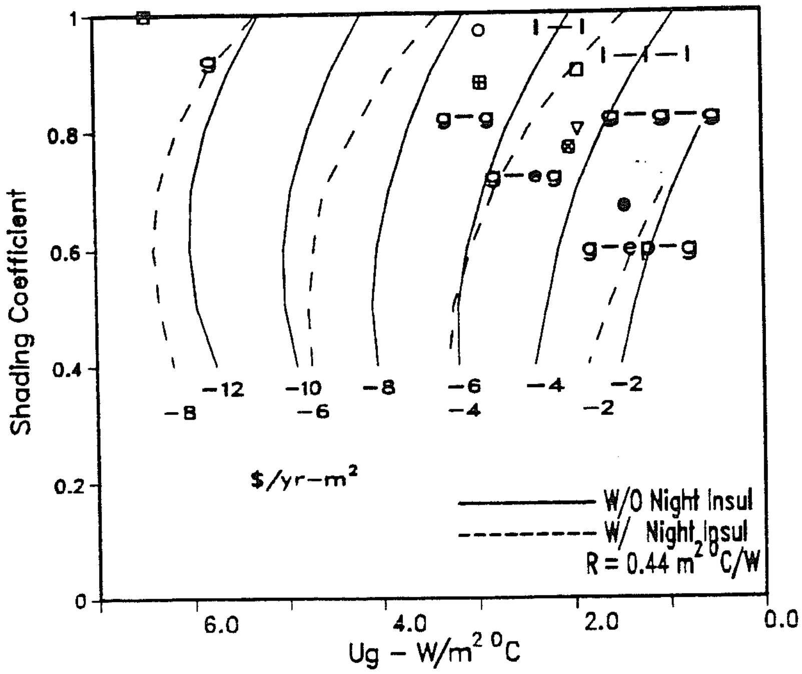

FIGURE 6 - Primary window size as a function of U-value, night insulation, and ratio of the cost of electricity (cooling) to the cost of gas (heating) for two shading coefficients for a south orientation in Madison, WI.

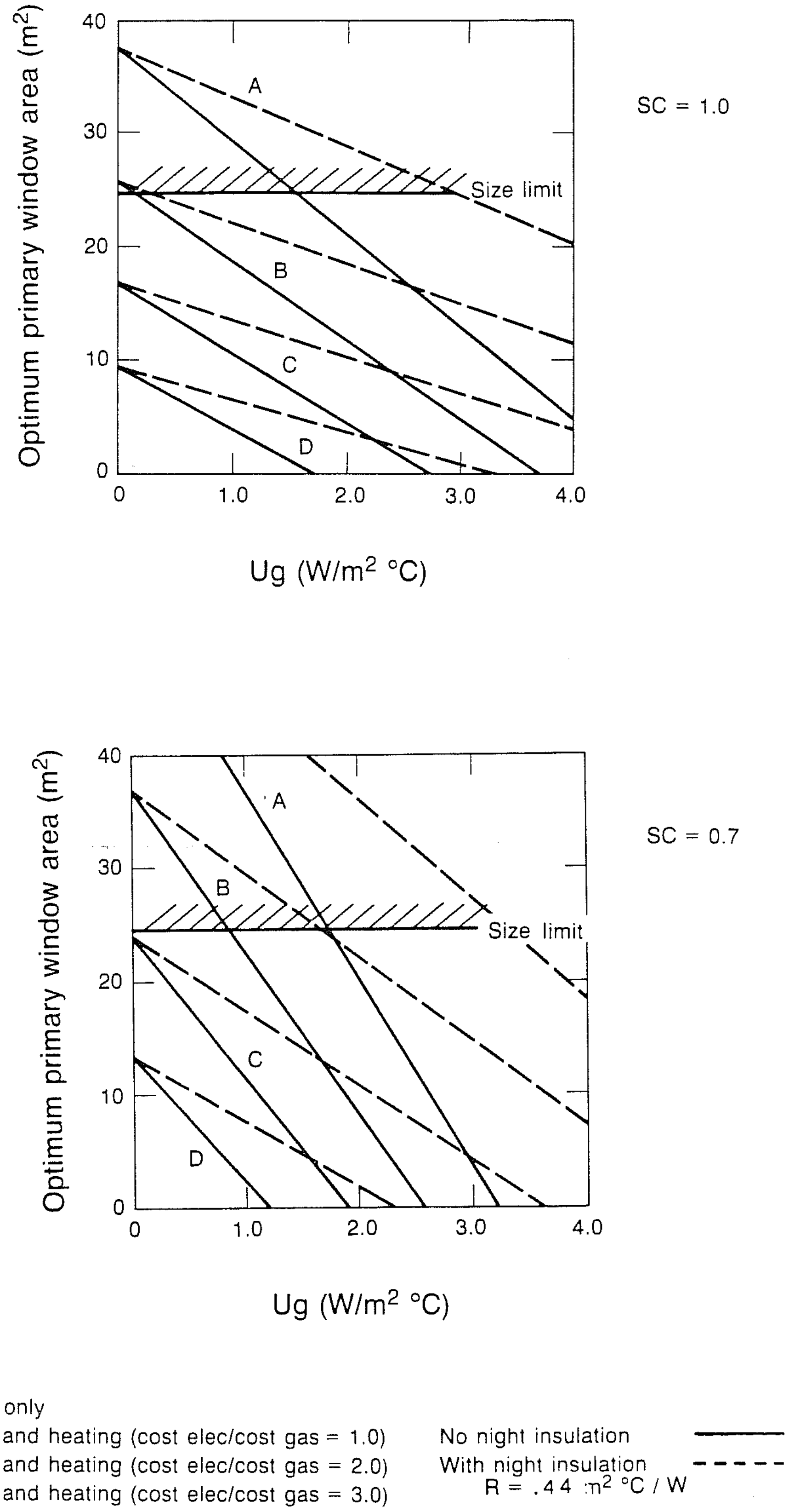

FIGURE 7 - Annual incremental cooling energy in Lake Charles, LA for a south facing primary window as a function of window area and shading coefficient.

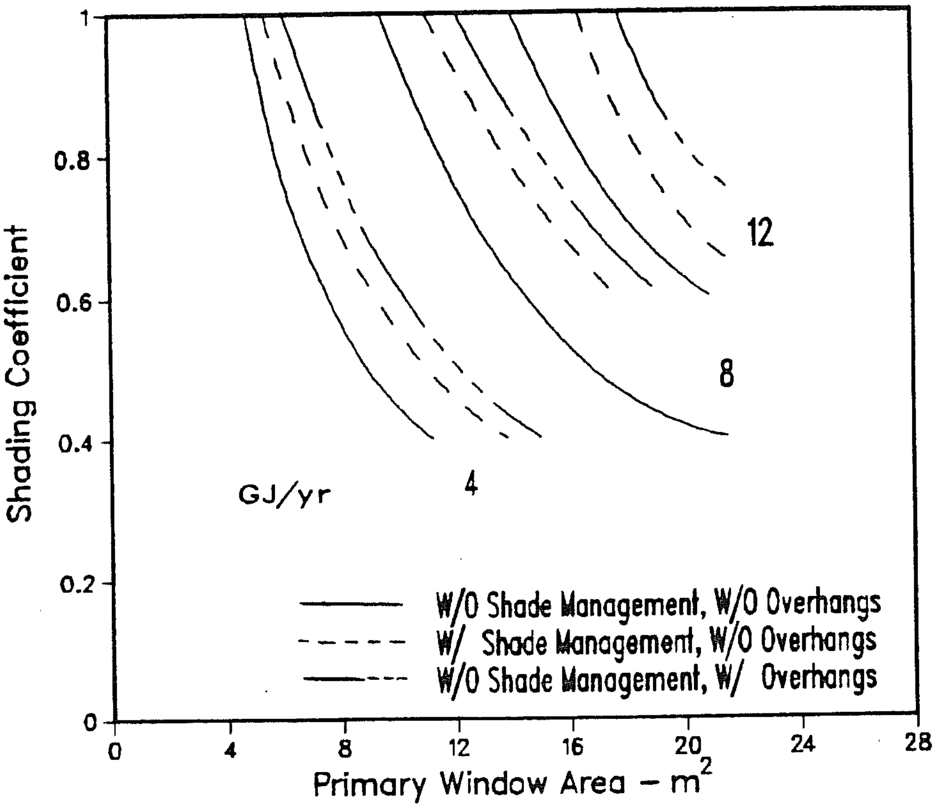

FIGURE 8 - Annual incremental cooling energy in Lake Charles, LA for an east facing primary window as a function of window area and shading coefficient.

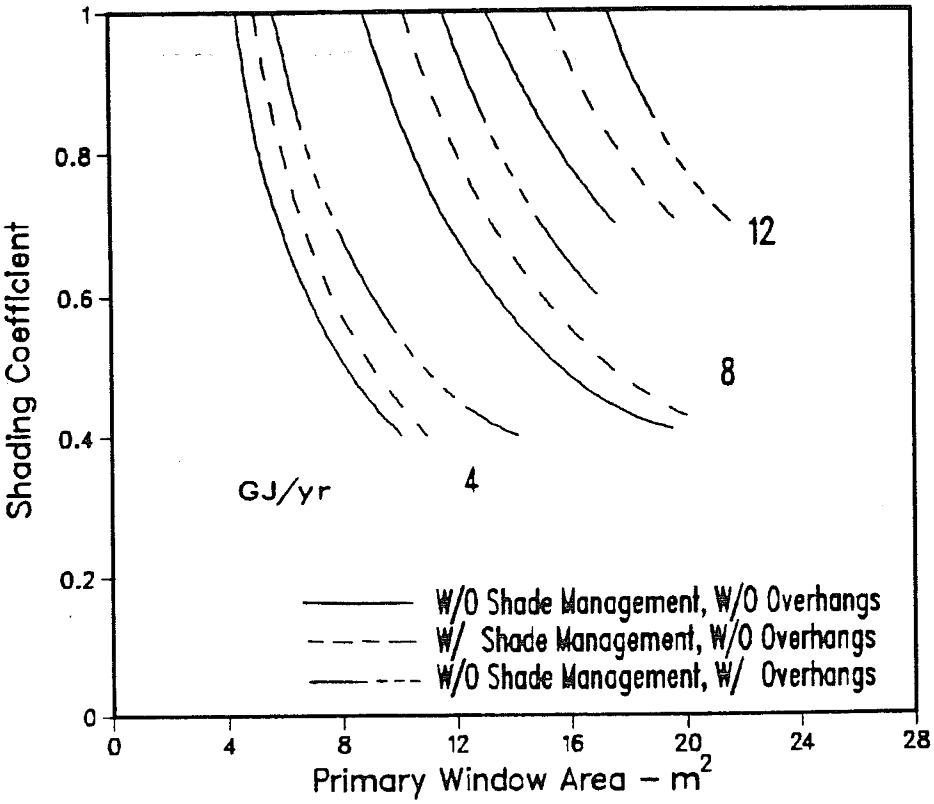

FIGURE 9 - Annual incremental cooling energy in Lake Charles, LA for a north facing primary window as a function of window area and shading coefficient.

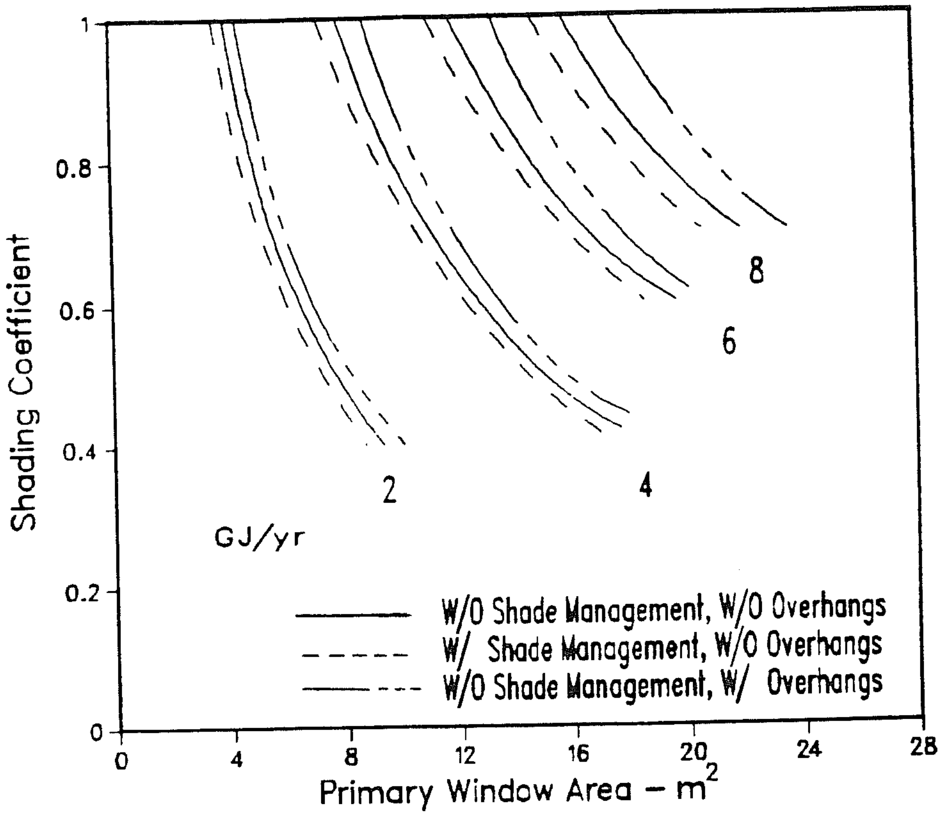

FIGURE 10a - Residential heating energy comparison for various configurations and geographic locations showing the effect of window parameters.

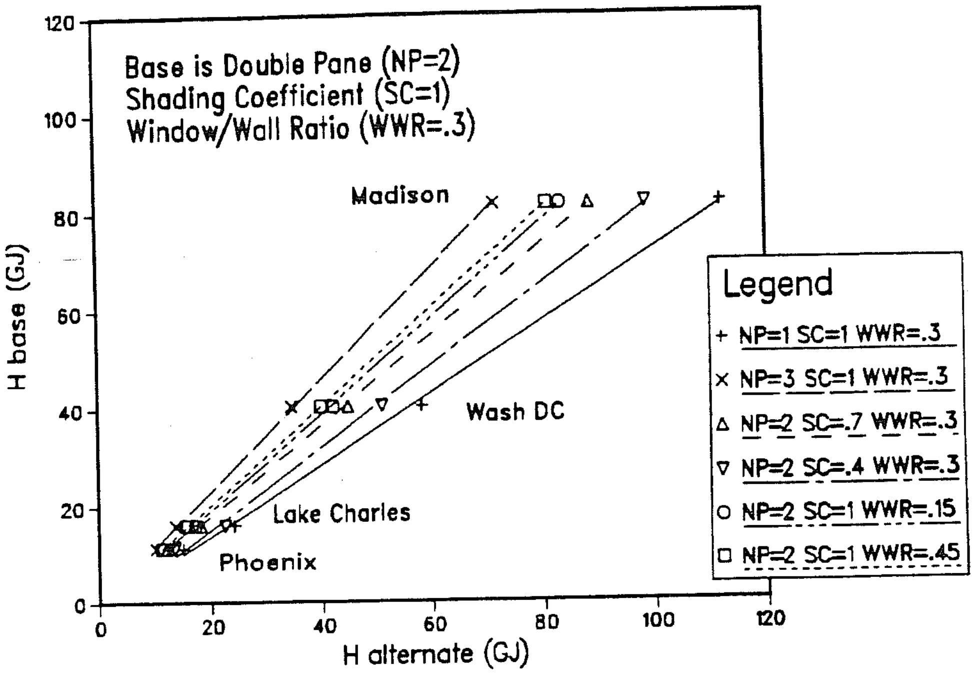

FIGURE 10b - Residential cooling energy comparison for various configurations and geographic locations showing the effect of window parameters.