WINDOW PERFORMANCE ANALYSIS IN A SINGLE-FAMILY RESIDENCE

R. Sullivan
ASHRAE Member

S. Selkowitz
ASHRAE Associate Member

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. Sensitivity to climate was established by considering results from four distinct climatic zones representative of warm and humid (Lake Charles, LA), hot and dry (Phoenix, AZ), temperate (Washington, DC), and cold (Madison, WI) conditions. Analysis of the effects of hypothetical fenestration systems on building energy use was made possible 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 that minimize residential energy use and/or cost.

INTRODUCTION

Window systems play a major role in determining residential energy requirements. They affect the thermal environment of buildings by influencing convective and conductive heat transfer, radiant transfer, and mass transfer. Such mechanisms must be investigated if we are to better understand and reduce residential energy consumption. Research and development efforts in new window systems are concerned with changing 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·ft^2·°F (0.6 W/m^2·°C), plus high solar and visual transmission (Arasteh and Selkowitz 1985; Keller et al. 1984). In this system, double-pane glass is used with low-emittance coatings on two plastic interlayers and different gas mixtures in the air gaps. Low-emittance coatings are used to reduce the radiative component of the thermal losses while maintaining high solar transmittance. Control of optical and thermal characteristics and mass transfer can also be provided by insulating shutters and movable insulation (Selkowitz and Bazjanac 1979).

Selecting the appropriate window system for a building will depend on the particular climatic variable driving the heat transfer. Aesthetics, of course, also play a major role in design decisions and indirectly affect energy use. In cold climates, glass conduction and solar transmittance as well as air-tightness determine a system's contribution to annual 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, we can analytically isolate the window system from the other building components such as envelope insulation levels, infiltration, and internal heat gains, as demonstrated in recent studies at Lawrence Berkeley Laboratory (LBL 1983; Sullivan and Selkowitz 1985). These studies document the independence of the major fenestration components when computing residential thermal loads and energy use. The Sullivan and Selkowitz work (1985) developed a regression expression derived from a large data base of DOE-2 computer simulations of a single-family residential prototype. The expression shows that comparative fenestration performance can be analyzed by considering only those factors directly related to the windows. This study represents a continuation of the past work and is an analysis of specific

Robert Sullivan and Stephen Selkowitz, Lawrence Berkeley Laboratory, Applied Science Division, University of California, Berkeley CA 94720.

fenestration properties. Through using data on solar gain and conductance loss, residential energy use and cost trends are conveniently established.

RESIDENCE DESCRIPTION

The prototypical single-family ranch-style house selected for analysis was 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 in window size, 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·ft^2·F, 0.534 W/m^2·$^\circ$C) glazings, and shading coefficient values of 0.4, 0.7, and 1.0 were the window property parametrics. Results were obtained for eight orientations covering a complete 360° rotation in 45° increments. More details of the thermal and operational characteristics of the prototype are provided by Sullivan and Selkowitz (1985).

Glazing properties were incrementally changed by adding night insulation, shade management, and overhangs. Insulation levels of R=1.0 hr·ft^2·F/Btu (0.18 m^2·$^\circ$C/W), 2.5 (0.44), and 5.0 (0.88) were implemented at night during the months of October through April. Our shade management strategy reduced solar heat gain by 40% when 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 were used Madison, WI, and Lake Charles, LA. Cities in the extreme north and south U.S. were chosen to allow comparison of the effects of the large differences in their thermal loads. Base 65 F (18.3°C) heating degree-day values for Madison and Lake Charles were 7825 and 1717, respectively. Fewer simulations were run for Washington, DC, and Phoenix, AZ, to verify a very convenient proportional relationship between building thermal loads and varying configurational parameters, reported in Sullivan and Huang et al. (1985), The relationship was shown to be independent of climate and covered a broad spectrum of variables that influence a building's energy use.

DISCUSSION

The change in residential energy use due to varied fenestration characteristics was shown by Sullivan and Selkowitz (1985) to be very accurately predicted by the equation:

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

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 graphic techniques for presenting residential energy comparisons as a function of glass conductance and shading coefficient.

Figures 2, 3, and 4 use this equation to define the net useful flux during the heating season in Madison. 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 characteristics. These figures show the differences between the primary orientations of south, east, and north for two window sizes both with and without 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·ft^2 (-2 GJ/yr·m^2) for a northern orientation using low-resistance (single-pane) glass, to a high of 70 Kbtu/yr·ft^2 (0.8 GJ/yr·m^2) for a south-facing orientation and high-resistive (triple-pane) glass.

Changing window area causes a large variation in the curves shown on the figures. With the exception of a northern 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 of 1.0, a conductance as high as 0.79 Btu/hr·ft^2·°F (4.5 W/m^2·°C) provides a net positive energy flow; for the larger window, a conductance of 0.53 Bt/hr·ft^2·°F (3.1 W/m^2·°C) is required. As the shading coefficient decreases, the effect of window area also decreases and at SCs less than 0.4, the U-values at crossover would be the same regardless of window size.

Changing the orientation to an off-south direction reduces the conductance at crossover, with a limit being approached at 0.09 Btu/hr·ft^2·°F (0.5 W/m^2·°C) for a large primary northern window with a shading coefficient of 0.4. Table 2 shows the crossover values for all orientations as well as the effects of using night insulation. Night insulation has a dramatic effect on all aspects of the net flux variations shown on the figures, especially for the southern and eastern orientations. Night insulation gives a window system a net positive energy flow at a much higher glass conductance, and 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 southern orientation and a shading coefficient of 1.0 is 1.23 Btu/hr·ft^2·°F (7.0 W/m^2·°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 of consistent operation of the night insulation.

The relative positions of the conductance and shading coefficient values of the various glazing products in Figures 2 through 4 is quite informative. For a southern 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.

Approaching an eastern orientation, only highly resistive products such as triple-pane glass yield positive values 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 northern orientation reduces the amount of solar gain so appreciably that the glazing product values shown yield negative fluxes. However, new window systems incorporating low-emissivity coatings and low-conductance gas fills between multiple glazing layers can show net positive benefits.

Another interesting fact is that with night insulation the change in net flux due to a change in glass conductance is approximately half that 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 especially significant for the northern orientation shown 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 the summed heating and cooling energy net cost curves for a southern orientation.

Heating cost was based on \$.60/therm (\$6.00/Mbtu, \$5.69/GJ) and cooling on \$.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 results 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 configurational parameters and different electricity-to-gas cost ratios. The curves were generated by calculating the window size that 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 is found by modifying the energy equation to account for the unit costs of gas and electricity. Using the cost figures 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 is reduced mostly by solar-gain control. Through proper window orientation and use of both inside and outside shading devices, cooling loads can be significantly reduced. Figures 7, 8, and 9 present. incremental cooling energy values as a function of window area and shading coefficient for the prototypical residence for south, east, and north orientations. The effects from using shade management and overhangs are also shown.

The general shape of the curves is the same for all orientations, with or without sun-control devices For a particular shading coefficient, the incremental cooling energy is approximately proportional to primary window area. As 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 configurational 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 in 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 explain results shown in Figure 9, which indicates that the use of shade management for a northern 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 southern and eastern orientations. Also, the energy levels are about half those 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 by comparing values of a base configuration to those for varying window properties. The proportional relationship was verified by Sullivan and Huang et al. (1985) 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 configurational variation at one geographic location would yield the same percentage change at a different location.

CONCLUSION

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:

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

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

3. With the exception of a north-facing 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.

4. 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.

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

6. Simulations of cooling-dominated climates suggest that overhangs result in larger reductions in cooling energy than 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.

7. For Lake Charles, annual incremental cooling energy due to changes of window size and shading coefficient were essentially the same for the southern, eastern, and western orientations. A northern orientation required about half the cooling energy required for the southern and eastern of the same area and shading coefficient.

8. Portions of the study verified a proportional relationship among the energy quantities of different configurational parameters for varying geographic locations. This relationship will significantly simplify future studies, since fewer computer simulations will be required.

9. This study emphasized 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 not specify single glazing because of the condensation problems and thermal comfort effects. The night insulation and shade management results are based on proper and consistent use of these options. The degree to which this is achieved in practice is not well documented.

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ACKNOWLEDGMENT

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TABLE 1

Performance of Typical Glazing Products for Use with Figures 2 through 5

Type	U ($W/m^{2 \cdot o}C$)	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
1-1	2.87	0.97
1-1-1	1.80	0.90

g: 3.18 mm (1/8") DS float glass
1: 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 $m^{2 \cdot o}C/W$
Active months: October - April
Active hours: 7 pm - 6 am
Outside air temperature: Less than 15.5^{o}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

SC	South $6.13m^2$	South $24.53m^2$	East $6.13m^2$	East $24.53m^2$	North $6.13m^2$	North $24.53m^2$
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 ($R = 0.44\ m^2 \cdot {}^oC/W$)

SC	South $6.13m^2$	South $24.53m^2$	East $6.13m^2$	East $24.53m^2$	North $6.13m^2$	North $24.53m^2$
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

	Shade Management				Overhangs			
SC	South	East	North	SC	South	East	North
Δ Cooling Energy = 4 GJ/yr							
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							
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							
1.0	2.3	2.1	-	1.0	3.8	4.2	-
0.7	2.0	2.2	-	0.7	-	-	-
0.4	-	-	-	0.4	-	-	-

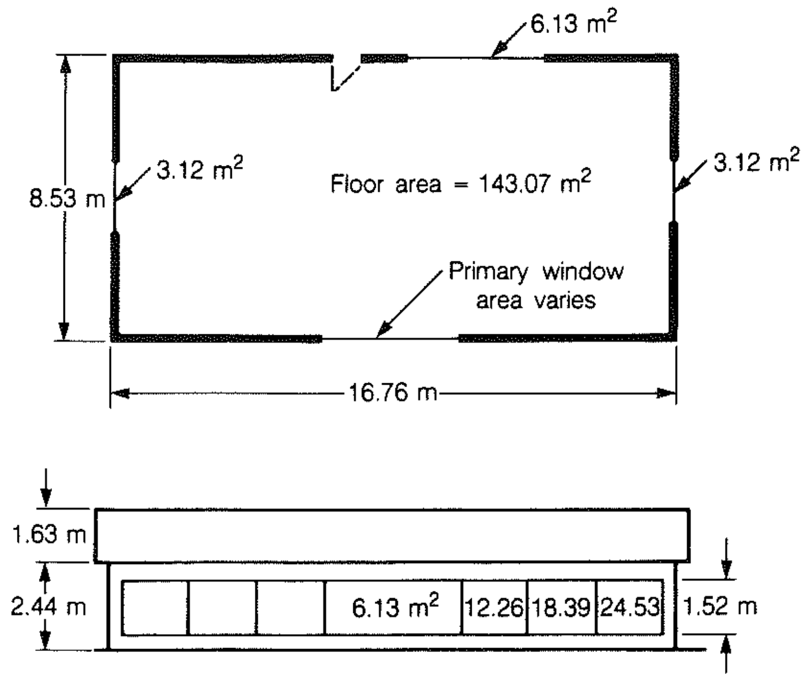


Figure 1. Residential model description

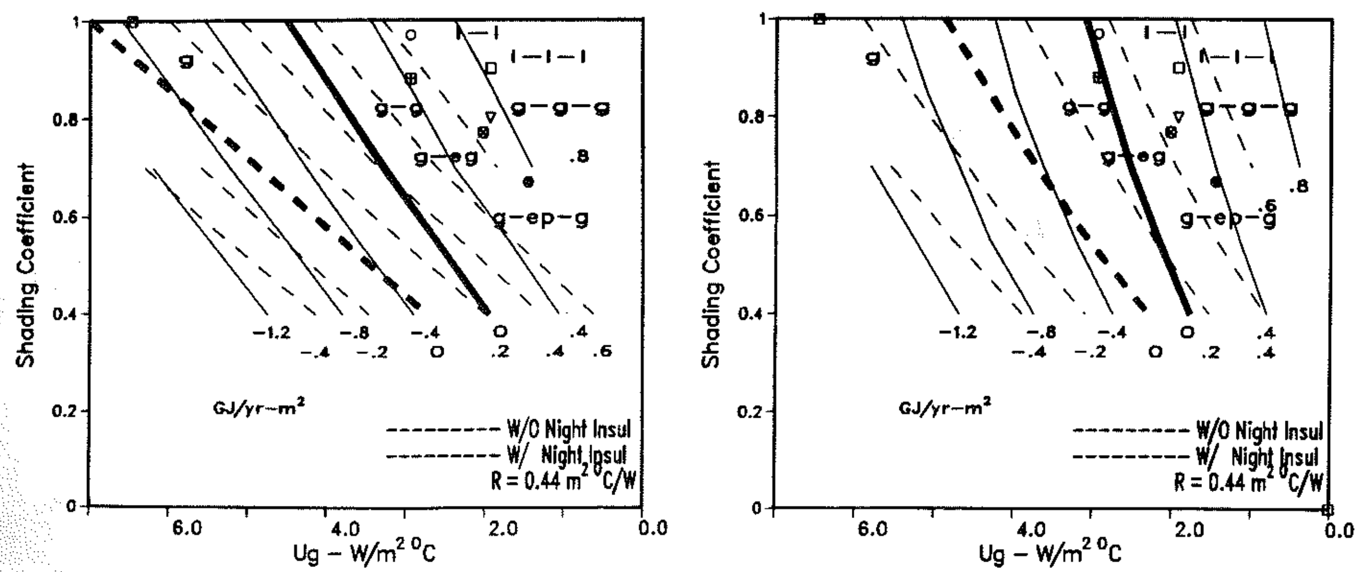
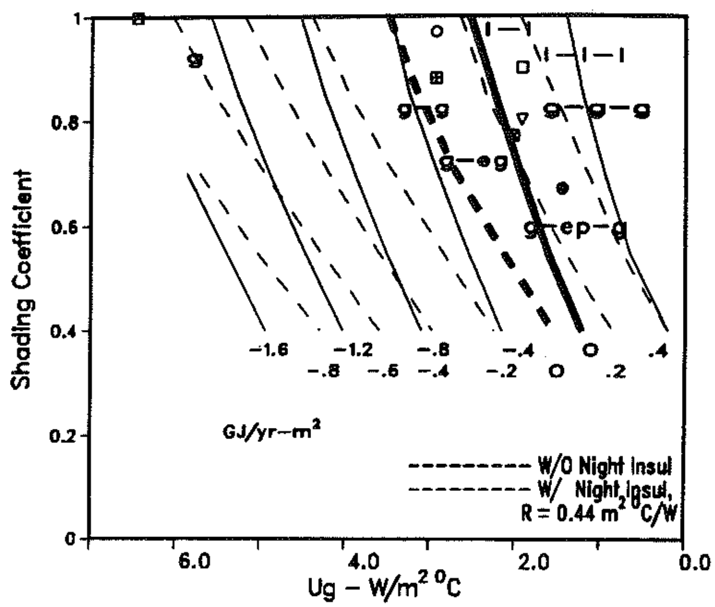


Figure 2. Annual net flux in Madison, WI for a primary window of area 6.13 m^2 (left) and 24.53 m^2 (right), facing south and using heating energy requirements. (See Table 1 for glazing product information)



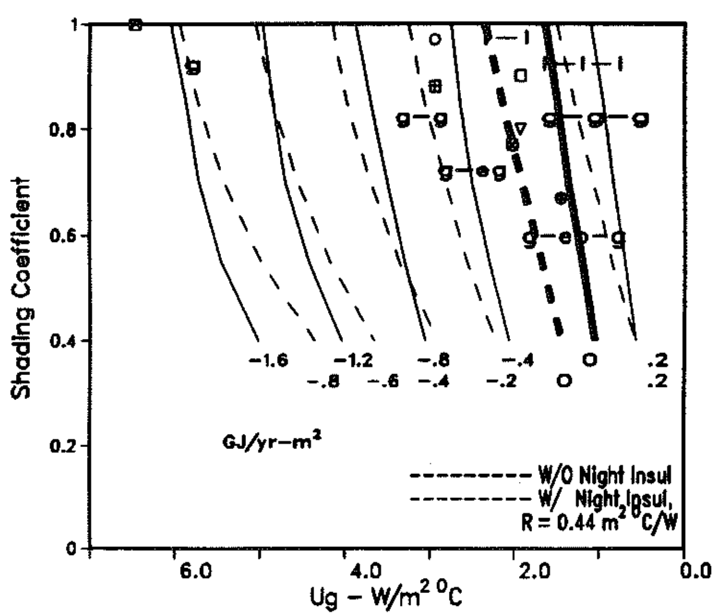
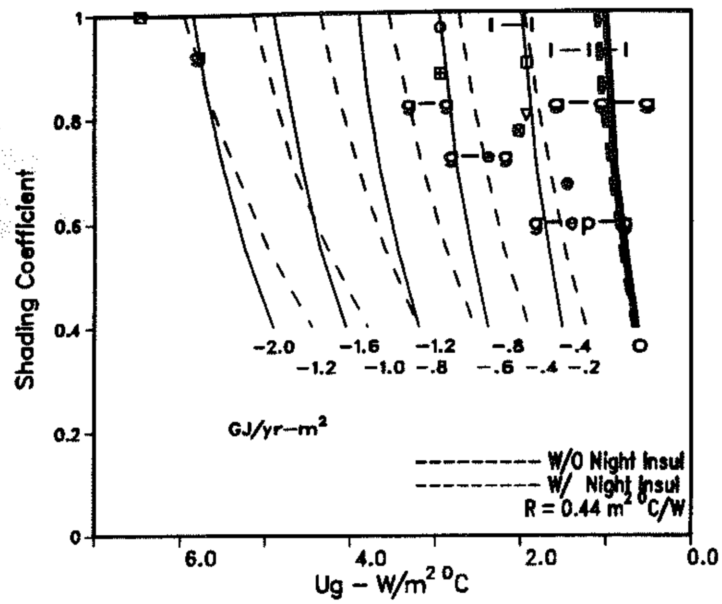


Figure 3. Annual net flux in Madison, WI, for a primary window of area 6.13 m^2 (top) and 24.53 m^2 (bottom), facing east and using heating energy requirements. (See Table 1 for glazing product information.)



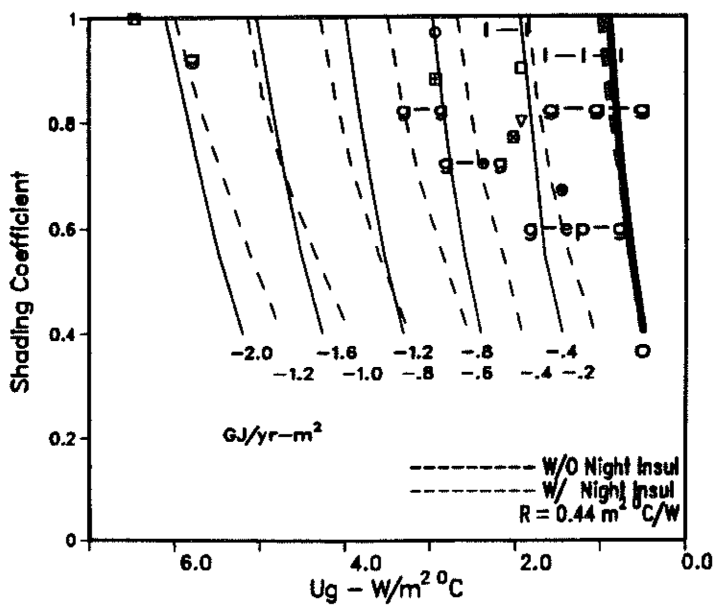
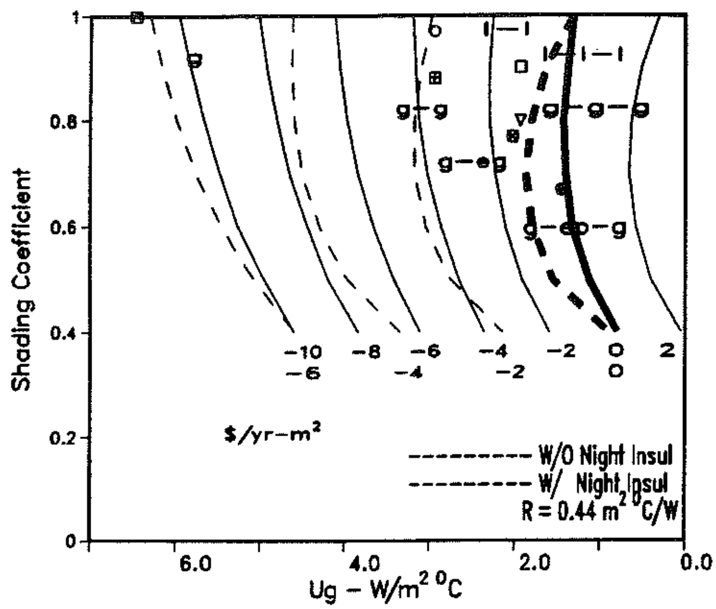


Figure 4. Annual net flux in Madison, WI, for a primary window of area 6.13 m^2 (top) and 24.53 m^2 (bottom), facing north and using heating energy requirements. (See Table 1 for glazing product information.)



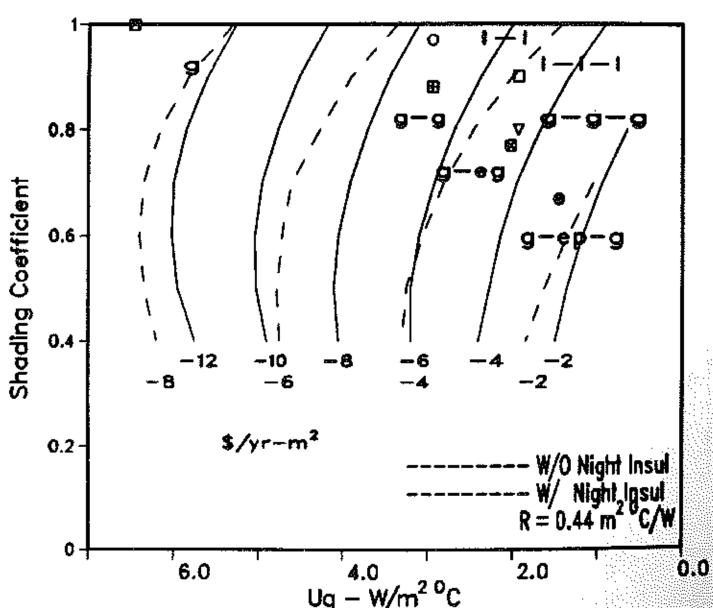


Figure 5. Annual net energy costs in Madison, WI, for a primary window of area 6.13 m^2 (top) and 24.53 m^2 (bottom), facing south and using heating and cooling energy requirements. (See Table 1 for glazing product information.)

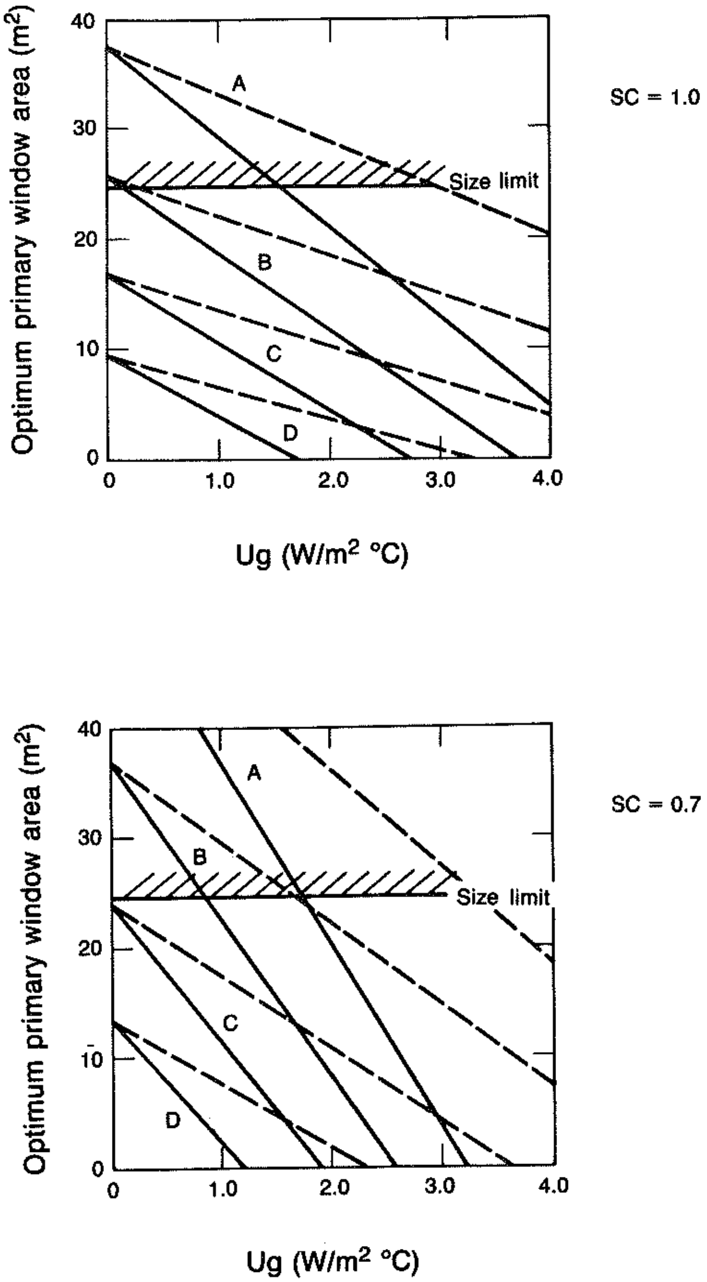


Figure 6. *Optimum primary window size as a function of U-value, night insulation, and ratio of cost of electricity (cooling) to cost of gas (heating) for a shading coefficient of 1.0 (top) and 0.7 (bottom) for a south orientation in Madison, WI*

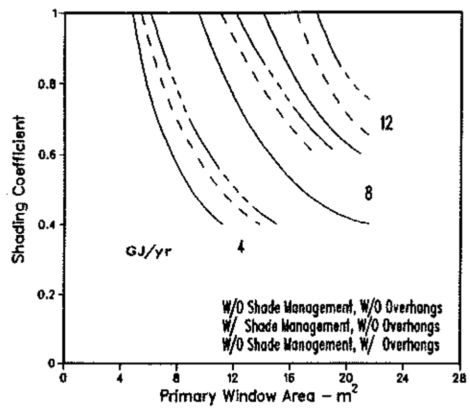


Figure 7. Annual incremental cooling energy in Lake Charles, LA for a primary window facing south as a function of window area and shading coefficient

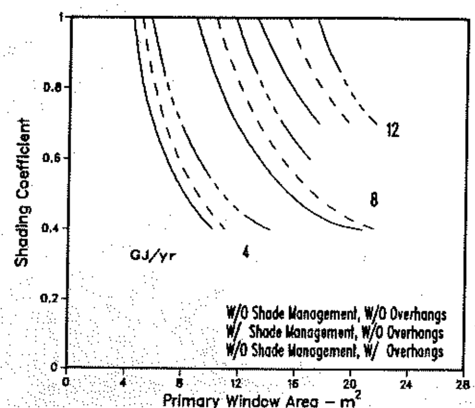


Figure 8. Annual incremental cooling energy in Lake Charles, LA for a primary window facing east as a function of window area and shading coefficient

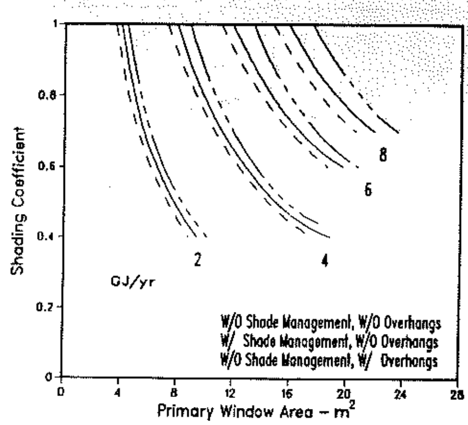
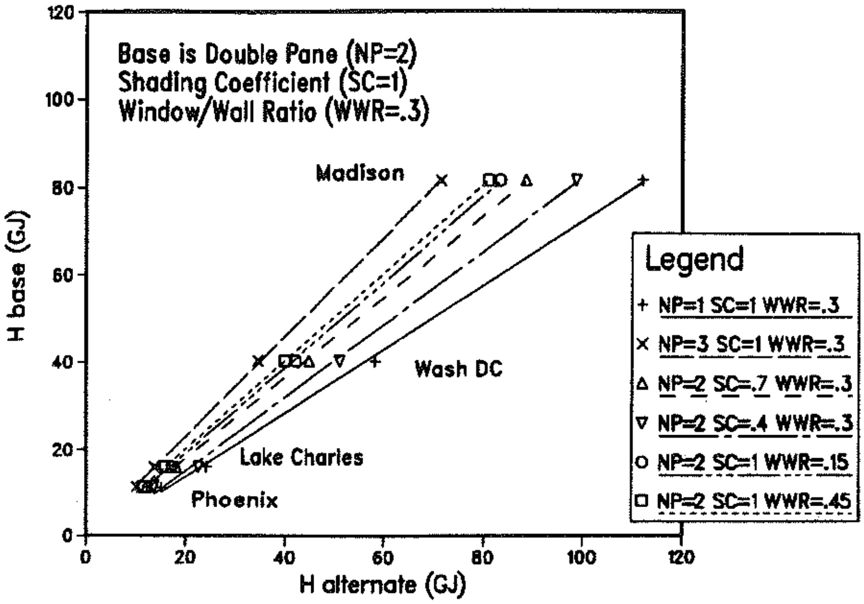


Figure 9. Annual incremental cooling energy in Lake Charles, LA for a primary window facing north as a function of window area and shading coefficient



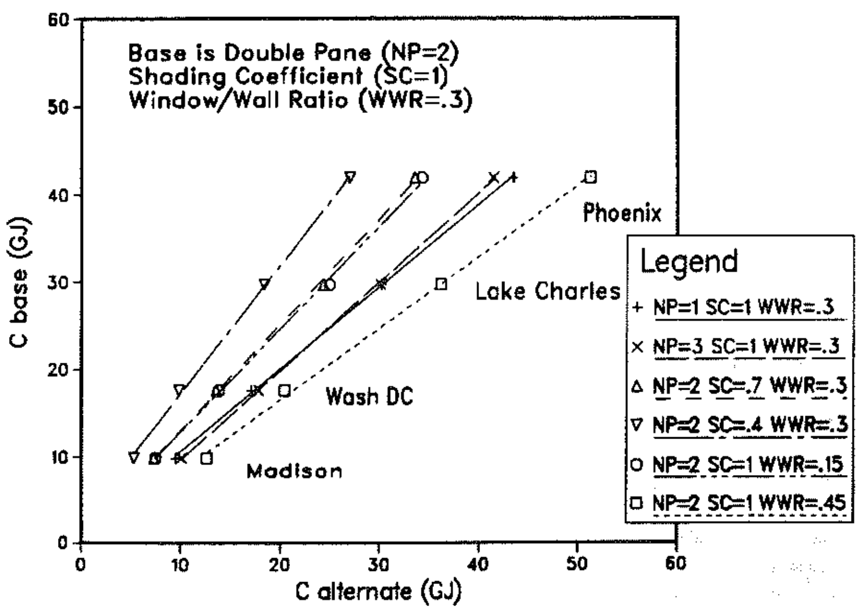


Figure 10. Residential heating energy comparison for various fenestration configurations and geographic locations showing the effect of window parameters