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ABSTRACT

This paper presents the results of a parametric study of a prototypical single-family ranch-style house. The DOE-2.1B energy analysis simulation program was used to analyze the variation in heating, cooling, and total energy requirements and resultant energy costs due to changes in the following building characteristics: fenestration orientation, size, conductance, and shading coefficient; and levels of internal heat gain, infiltration, and natural ventilation. Climate sensitivity was established by considering results from Madison, Wisconsin, and Lake Charles, Louisiana. To facilitate simplification of the analysis, multiple regression techniques were used to generate a simplified algebraic expression that relates energy use to the parameters varied. This simplified representation of the performance data could form the technical basis for simplified design tools to define optimal fenestration configuration parameters.

INTRODUCTION

Building energy use patterns are a complicated interaction of heat transfer processes characterized by convective/conductive heat transfer, radiant transfer, and mass transfer. All elements of the building contribute to one or more of these items in a manner which has within the past ten years been made more conveniently analyzed through the development of various building energy analysis simulation programs. Generally, studies using such programs concentrate on the analysis of a particular building configuration and the associated trade-offs to better define a final design. Rarely are such practical analyses concerned with parameterizing the configuration properties so that a multitude of differing characteristics can be treated. The study reported in this document, however, represents such an approach. It is part of an on-going study being conducted by the Windows and Daylighting Group of the Applied Science Division at Lawrence Berkeley Laboratory. The purpose of the study is to categorize the different factors which contribute to residential energy use and cost with particular emphasis on the effect due to varying fenestration systems. Whereas, at one time, windows were considered detrimental to the goal of reduced energy use, with the advantageous use of non-renewable sources, improved design strategies, and the advent of new window technologies, this is no longer the case. The development and use of energy analysis computer programs has created an environment in which many different aspects of building energy related phenomena can be confidently investigated with relative ease.

A prototypical single family ranch style house was selected for analysis using the DOE-2.1B energy analysis program (Lawrence Berlekey Laboratory, 1981). The intent in this initial study was to investigate effects arising from variations in the fenestration properties of orientation, size, conductance, and shading coefficient and changes in internal load, infiltration, and natural ventilation levels. An appropriate range was selected for each variable to insure coverage of the expected variations typical in a single-family residence. In addition, the glazing characteristics were defined so that most current and/or new window systems would be bracketed, thus allowing the potential values of conceptual window systems with hypothetical performance characteristics to be examined. Follow-up analyses will be concerned with the use of night insulation, shade management, overhangs, and other areas of residential energy use such as changes in envelope conductance, and size and type of building.

Two WYEC weather profiles (Crow 1980) were used in the analysis. These consisted of Madison WI and Lake Charles LA and their selection was based on the expectedly large thermal loads differences resulting from their geographic loaction and thus, to some extent, insured a satisfactory bound on the problem. It was realized at the start of the project that the intent was not to yield a climatic correlation per se but that the selection of the two would indicate a direction for future studies in which a climate/configuration interface would be examined.

Multiple regression techniques were used to analyze the data resulting from the parametric runs. The work reported in Johnson et.al. (1983) showed the versatility of using such procedures in performing analysis of large amounts of data resulting from studies of this kind. Multiple regression is a statistical analysis procedure in which relationships between different variables are established mathematically using a least squares approach. Generally, sets of independent variables (e.g. U-value) are defined from which a dependent variable (e.g. energy) is predicted. Once an equation for energy performance has been defined, it is possible to manipulate the equation to directly determine optimal performance values. Upon completion of the model description below, a more detailed discussion of the regression procedure and sample results are given.

RESIDENCE DESCRIPTION

The building configuration modeled in the DOE-2.1B program is presented in figure 1. It corresponds, with certain modifications, to the slab-on-grade ranch style house reported in the Lawrence Berkeley Laboratory study (1983) which dealt with the design and construction of energy efficient homes. The configuration is a 54 ft (16.67 m) by 28 ft (8.53 m), one zone structure of wood frame construction. The wall framing corresponds to wood studs 2 in (5.1 cm) by 4 in (10.2 cm) on 16 in (40.6 cm) centers which occupy 25% of the wall area with a U-value of .145 Btu/hr-ft^{2}F (.824 W/m^{2o}C). The roof stud U-value was .04 Btu/hr-ft^{2o}F (.227 W/m^{2o}C) and occupies 10% of the roof area. Insulation levels of the non-stud portions of the wall and roof were set to R=11 (1.8) and R=30 (5.3) respectively giving conductances of .072 (.409) and .026 (.148) . These conductances do not include the outside surface film coefficient. The slab-on-grade floor consisted of a carpet covered 4 in (10.2 cm) concrete slab with insulation resting on a gravel bed. A U-value of .073 Btu/hr-ft^{2o}F (.415 W/m^{2o}C) was used for the floor with an effective area equal to 728 ft^2 (67.6 m^2). The selection of the effective area was derived from a two-dimensional finite element representation of the slab model which yielded equivalent values of conduction gain/loss (Sullivan et. al. 1984).

Window sizes were fixed on three sides at 15% of the wall area. 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). The total residential window area thus varied from 8.65% to 25.79% of the floor area. Four conductance values representative of single pane glazing through a system with a conductance of 0.1 Btu/hr-ft^{2o}F (0.53 W/m^{2}C) as well as three shading coefficient values (.4,.7,1.0) served as the glazing property parametrics. These properties were implemented on all windows simultaneously. Results were obtained for eight orientations covering a complete 360^o rotation in 45^o increments. Shade management was not used in the study; however its influence will be analyzed in future work. Table 1 presents a summary of the basic parametric set. Approximately 3400 DOE-2.1B runs were completed.

Scheduling information for occupants, lights, and appliances were taken from Lawrence Berkeley Laboratory (1983) with some minor revisions. In that study, a composite process heat gain input was defined for all three internal loads. Saturation levels of 3.2 occupants per household and 2.6 W/ft^2 (28 W/m^2) for lighting and appliances were used as the base case in the model. The total internal load level was 3.4 W/ft^2 (36.6 W/m^2). This corresponded to a maximum heat gain input of 10163 Btu/hr (10721 KJ/hr) which equals a heat input to the residence of 53963 Btu/day (56931 KJ/day) sensible and 12156 Btu/day (12875 KJ/day) latent. Multipliers of .75 and 1.5 of the base defined the internal load parametric.

Infiltration was simulated using an algorithm which is based on the work reported in Coblentz and Achenbach (1963). The method accounts for changes to a base level of infiltration due to variations in hourly wind speed and temperature difference between the outside air and room air. Coefficients for the expression were derived from a statistical fit to data during a winter in ten residential buildings in Indiana. These were adjusted for each geographic location in this study to yield an average winter rate of 0.7 air changes per hour for the window size equal to 15% of the wall area. This value was revised for each window size parametric using an assumed .5 cfm/ft-crack (.24 L/sec-crack) based on recommendations contained in ASHRAE Fundamentals (1981). The resultant infiltration levels are presented on Table 1 where it is seen that the window size has only a small effect on total infiltration rates. For the parametric runs, the coefficients corresponding to the base of .7 air-changes/hr were changed to reflect values of .4 and 1.0 air-changes/hr.

Natural ventilation of 10 air-changes/hour in the form of openable windows was implemented when all of the following conditions occurred: a. the windows were opened if the act of opening the windows provided more cooling than would be provided by the mechanical system with the windows closed; b. the enthalpy of the outside air was less than the enthalpy of the inside air (this condition eliminates the possibility of introducing a latent load into the room, thus causing a greater load on the system than would have existed had the windows been left closed); c. the outdoor air temperature was less than 78°F (25.6°C) for October through May and 70°F (21.2°C) for June through September. The base value of 10 air-changes/hr was set to 0 and 5 air-changes/hr for the parametric runs.

A dual setpoint thermostat was used to control the space conditioning system. Heating was set at 70°F (21.1°C) from 7am to 11pm with a night setback to 60°F (15.6°C) from 12pm to 6am. Cooling was set at 78°F (25.6°C) for all hours. In addition, to simulate more realistic operation, the system was off if the outside dry bulb temperature was greater than 65°F (18.3°C) for heating and less than this value for cooling. This logic was intended to deal with those times of the year when one would not expect cooling in winter and heating in summer. A direct expansion air-cooled air conditioning unit was used for cooling and a forced air gas furnace for heating. Cooling system coefficient of performance was 2.174 and furnace steady state efficiency was 0.74. System equipment was sized based on a design cooling temperature of 78°F (25.6°C) and heating temperature of 70°F (21.1°C).

REGRESSION MODEL

Multiple regression techniques were used to generate a simplified algebraic expression relating residential configuration parameters (independent variables) to heating, cooling, and total energy use (dependent variables). Regression analysis uses the method of least squares to characterize the form of the relationship between variables. The method of least squares is a technique used for defining the best fit to data sets by minimizing the distance between the data and the line which describes the fit. Generally, sets of independent variables are defined from which a dependent variable is predicted. The computer program SPSS (Statistical Analysis for the Social Sciences, Nie et. al. 1975) was used in performing the regression. Energy use for the model can be predicted for each orientation by explicitedly defining the conductive and solar radiation effects of the fenestration system and those variations due to changing levels of internal gain, infiltration, and natural ventilation as follows:

$$
\begin{aligned}
E = {} & \beta_1(U_g A_g) + \beta_2(\Sigma U_{go} A_{go}) && \text{window conduction} \\
& + \beta_3(SC_g A_g)^2 + \beta_4(SC_g A_g) + \beta_5(\Sigma SC_{go} A_{go}) && \text{window solar gain} \\
& + \beta_6 L && \text{internal gain} \\
& + \beta_7 I && \text{infiltration} \\
& + \beta_8 N && \text{natural ventilation} \\
& + \beta_9 && \text{wall, roof, floor conduction}
\end{aligned}
\qquad (1)
$$

where

β = regression coefficients
U_g = primary glazing U-value (W/m^2°C)
A_g = primary glazing area (m^2)
SC_g = primary glazing shading coefficient
U_{go} = off-primary glazing U-value (W/m^2°C)
A_{go} = off-primary glazing area (m^2)
SC_{go} = off-primary shading coefficient
L = internal heat gain saturation level (W/m^2)
I = infiltration level (air-changes/hr)
N = natural ventilation rate (air-changes/hr)

The window conductance effect is linear with respect to U and A and is represented by the β_1 and β_2 coefficients. The solar influence is quadratic with respect to SC and A and is defined by the β_3, β_4, and β_5 coefficients. In the development of the original regression equation, quadratic terms were used for both the window conduction and solar gain terms. However, the regression solution indicated the solar gain to be only significant term at the quadratic level. Each of these values is orientation dependent which is to be expected because of the sensitivity of glazing response characteristics to the position of the sun.

The coefficients β_6, β_7, and β_8 define the influence of the internal heat gains, infiltration, and natural ventilation. β_9 contains those items which have not been specifically parameterized in this study, i.e. the wall, roof, and floor conductance effects. Each of these latter coefficients are linear and essentially orientation independent. The term (E) represents the resultant annual heating and/or cooling energy. Total energy is the sum of the two plus the electricity required to produce the internal heat gain (lighting and appliances).

It should be mentioned that the methodology, and specifically the regression coefficients, are valid for use only with configurations with parameters within the range used in the study. Also, different type residences, such as split level, townhouse, and apartments would yield different regression coefficients. However, the general trends observed in this work are adequate for other residential models, provided there is sufficient understanding of the study's limitations. Although one may be tempted to attach specific physical significance to the regression coefficients (i.e. β_1 and β_2 could be interpreted as temperatures), a note of caution is warranted since a climatic correlation was not carried out. Further studies in this area will enable a more precise definition of the physical significance of the results.

The regression fits for the heating and cooling for both climates were extremely good. The squared multiple correlation coefficient, r^2, the proportion of variation explained by the independent variables, was .998 for heating in Madison and .991 for cooling. Lake Charles yielded values of .993 and .995 respectively. A value of 1.0 would mean perfect correlation, i.e. that all variation in the dependent variable could be explained by variations in the independent variables. The standard error of the estimate, which can be interpreted as the standard deviation of the residuals (the difference between the actual and predicted values) varied from 3.7% for cooling in Madison to 1.1% for heating. The Lake Charles value was 2.1% for both heating and cooling. The higher value for cooling in Madison results from the low values of cooling energy required, implying that a small standard deviation is more significant.

Tables 2 and 3 present the coefficient values for both climates and figures 2 and 3 provide a pictorial representation of the glazing coefficients as a function of orientation. Immediately apparent when viewing figures 2 and 3 is the amount of symmetry present. With the exception of the β_3 coefficeint, which represents the quadratic solar term, all the other coefficients are relatively symmetric. Also obvious is the sign difference between the conductance and solar terms in the heating energy coefficients, which in Madison and other heating dominated climates indicates the ability to tradeoff the two window properties. Lake Charles does not exhibit such behavior since it is dominated by the cooling energy coefficients.

In the case of Madison, it is a very easy task to define the optimum window size based on energy use or cost. Taking the derivative of equation 1 with respect to primary window area and setting the equation to zero yields the optimum area with respect to energy use:

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

where the prime on the coefficients indicates the summed heating and cooling energy values, i.e. $\beta_1'=\beta_{1c}+\beta_{1h}$. Areas are definable for:

$$U_g/SC < |\beta_4'/\beta_1'| \qquad (3)$$

Optimization with respect to energy cost can easily be accomplished by assuming a unit cost for gas and electricity. Using $.60/therm ($6.00/Mbtu, $5.69/GJ) for gas and $.07/kwh ($20.50/Mbtu, $19.43/GJ) for electricity, the regression coefficients become:

$$\beta_1' = 19.43\ \beta_{1c} + 5.69\ \beta_{1h} \qquad (4)$$

when using SI units. It will be seen in the next section of this paper that there is a difference in the optimum glazing size based on energy use per se and energy costs. The optimum size also varies with orientation through the regression coefficients, but is also a function of the ratio of window conductance to shading coefficient. This simple example indicates the versatility of the regression analysis approach.

The β_6 through β_9 coefficeints, which are treated in more detail in a later section, give some indication of the significance of the those factors responsible for the derivation of the coefficients; namely, internal gains, infiltration, ventilation, and envelope conductance. For example, Table 2 for Madison, illustrates that both infiltration (β_7) and the envelope (β_9) are large contributors to the heating energy; whereas, the internal gain (β_6) decreases the energy requirement substantially. Likewise, the natural ventilation term (β_8) has essentially no effect on heating. Cooling energy is influenced approximately equally by all four coefficients, but at a much lower level than heating.

RESIDENTIAL ENERGY USE AND COST ANALYSIS

Figures 4 through 11 present heating, cooling, and total energy use and cost data for Madison and Lake Charles as a function of the components used in the regression expression, equation 1. The convenient separation of variables and simplified component contribution definition of equation 1 permits the presentation shown in these figures. Such a breakdown has previously only been available using results from the LOADS portion of the DOE-2.1B program in which constant space temperature thermal loads are defined on a component basis. Implementation of the secondary and primary heating and ventilation systems and associated thermostatic settings affects this component distribution. Thus, it is apparent that the procedures outlined in this report represent a viable methodology, previously unavailable, for studying building energy use.

All terms in equation 1 are linear with the exception of the β_3 solar quadratic term and the β_9 coefficient which was held constant and represents the envelope conductance (less glazing). Heating in both Madison (figure 4) and Lake Charles (figure 8) is dominated by infiltration and envelope conductance losses. The change in heating energy per air-change/hr of infiltration is about 61 Mbtu/ac (64 GJ/ac) in Madison and 13 Mbtu/ac (13.7 GJ/ac) in Lake Charles; whereas, the change per unit area of single pane primary glazing is about .31 Mbtu/ft^2 (3.5 GJ/m^2) in Madison and .065 Mbtu/ft^2 (.74 GJ/m^2) in Lake Charles.

Heating due to the envelope conductance of the wall, roof, and floor is at a level very nearly equal to the largest value expected from the window conductance and infiltration, 49.3 Mbtu (52 GJ) for Madison and 13.3 Mbtu (14 GJ) for Lake Charles. Heating costs variations can easily be obtained for the above figures by multiplication of the values by the appropriate rate. Assuming as before \$.60/therm, the cost per unit air-change/hr of infiltration cost in Madison is \$364/ac and in Lake Charles \$20/ac. The change per unit area of single pane glazing in Madison is \$2/ft^2 (\$20/m^2) and in Lake Charles \$.40/ft^2 (\$4/m^2).

The fact that there are such large contributors to the heating requirements implies actions which can be accomplished to achieve a significant heating reduction. For example, changing from single pane glazing to double pane or triple pane has a dramatic effect, as would increasing the resistance (insulation level) of the other elements of the envelope. Double and triple pane glazing in Madison reduces the heating per area of glazing to .13 Mbtu/ft^2 (1.5 GJ/m^2) and .09 Mbtu/ft^2 (1.0 GJ/m^2) respectively. For Lake Charles, the already low value of .065 Mbtu/ft^2 (.74 GJ/m^2) is reduced to 0.03 (.33) for double and 0.02 (.23) for triple.

The cost benefits associated with such changes are also quite large. In Madison with a primary window area of 200 ft^2 (18.6 m^2), using triple pane glazing instead of single pane, saves approximately $220/yr. Likewise, making the residence tighter to reduce infiltration yields a substantial benefit. For example, reducing the infiltration from a value of 1 ac to 0.4 ac yields a savings of about the same magnitude, $220/yr. These actions, of course, are common knowledge; however, the data resulting from this study quantifies the expected results.

Those items which influence heating also exert some effect on the cooling, although to a much less extent, as can be seen on figures 5 and 9. Both lower infiltration rates and increased envelope resistances reduce cooling as well as heating. The exception to this is the window conductance which has a minimal effect on cooling and essentially can be neglected. Heating reductions are also obtained from the solar gain through windows and the heat-to-space generated by the lights, appliances, and occupants. However, these two items which tend to reduce heating also increase the cooling required, particularly the solar gain term. In Madison, the heating energy benefit due to internal gains is about nine times as great as the cooling energy penalty. Values in Lake Charles tend to offset each other.

When analyzing costs, the differential related to gas (heating) and electric (cooling) indicates that the heating benefit in Madison is about three times the cooling penalty. In Lake Charles, the cooling penalty related to internal gains is 3.5 times greater than the heating cost benefit. A similar analysis can be undertaken for the solar gain term. In Madison, for a south primary window orientation with an area of 200 ft^2 (18.6 m^2), changing from a shading coefficient value of 0.4 to 1.0 saves about $125/yr in heating cost, whereas cooling cost increase by about $160/yr. In Lake Charles, the heating cost saved is $30/yr with a $350/yr penalty for cooling for the same change in shading coefficient.

Total energy and costs are presented on figures 6 and 7 for Madison and 10 and 11 for Lake Charles. Total energy and cost require separate plots because of the cost differences related to heating (gas) and cooling (electric). Also presented on these figures is the net electricity usage associated with the internal heat gain resulting from lighting and appliances. The total energy data for Madison closely matches the heating energy results because of the low cooling energy requirement. At a fixed value of internal heat gain and infiltration, one can easily observe the tradeoff between the window conductance and solar gain arising from increasing primary window area.

There is a significant change, however, when energy costs are considered as seen on figure 7. The high cost of electricity for cooling due to solar gain essentially eliminates the cost benefit arising from the heating energy reduction. This is more conveniently seen on figure 12 which is a plot of the optimum primary window area as a function of orientation for different glazing characteristics. Values for total energy and cost and heating energy and cost are shown. For south, southeast, and southwest orientations, total energy related optimums are definable for a double pane glazing for shading coefficient of 1.0; for triple pane glazing for shading coefficients greater than 0.7; and for high resistive glazing for shading coefficients greater than 0.4. Other orientations yield more limiting glazing characteristics.

Optima using total cost can only be defined for high resistive glazing for shading coefficients greater than 0.7. However, in Madison, possibly a more realistic scenario would be to use the heating energy (which is the same as cost if interested in an optimim) to define an optimum. In this instance, a greater variety of glazings and orientations yield an optimum. For a south orientation, double pane glazing with a shading coefficent equal to 0.7 defines the limit. With the exception of a north orientation, an optimum is definable for all other orientations using high resistive glazing and shading coefficients greater than 0.7.

Lake Charles results shown on figures 10 and 11 indicate more clearly the higher costs of cooling and electricity. As one scans figure 10, with the exception of the natural ventilation term, total energy quantities of the largest value of each parameter are about the same at 21 Mbtu/yr (20 GJ/yr). However, the total energy costs on figure 11 show a substantial difference among the various components with the solar gain and internal gain terms dominating because of their association with the electricity requirements. At the largest value of each parameter, the solar gain cost of $500/yr is about five times the window conductance cost and the net electricity cost due to the higher level of internal loads would be about twice the solar gain cost. A significant reduction in solar gain cost can be achieved by using a primary window orientation facing north with a shading coefficient of 0.4. In this case, for the largest window size, the annual cost due to solar gain is $150/yr. Use of overhangs and/or window shade management are options that will be studied during future work to quantify their influence on reduction of the cooling energy requirements.

Figure 13 through 16 are presented to give an indication of the base case summed total energy and cost curves as a function of varying glazing properties for a south orientaion in Madison and a north orientation in Lake Charles. Four distinct data groupings for both energy and cost are apparent in the Madison data as a function of window conductance. Within each grouping are the data for varying shading coefficient. For the total energy data, lower energy values are produced by larger shading coefficients (indicating the beneficial effect of the solar gain); whereas, for the total cost, lower values are produced by smaller shading coefficients (indicating the higher cost associated with cooling).

Optimum window sizes are represented by the lowest energy and cost values on each curve. For those configurations which do yield an optimum other than the smallest size window, the actual change in energy/cost with size is quite small. This insensitivity implies that substantial glazing property variations can exist without noticeable penalty which of course permits flexibility in defining a residential design. The data presented for Lake Charles on figures 15 and 16 indicate that the solar effects dominate and the changes caused by the shading coefficient are more relevant than the window conductance variation. For the cost data, it is particularly obvious, that the primary data grouping is by shading coefficient and the secondary grouping by conductance. No optimum primary area is definable other than the smallest area. Of course a variety of practical and occupant preference factors such as view will dictate the use of some windows in most rooms in residences, The results of this study suggest how to bring the energy and cost consequences of these building features down to acceptable levels.

CONCLUSIONS

This paper has discussed results of an on-going study whose objective is the analysis of configuration parameters on residential energy use and cost. The work has been structured in the form of a parametric study covering a range of residential characteristics; namely, window orientation, size, conductance, and shading coefficient, and levels of internal gain, infiltration, and natural ventilation. The intent has been to bracket each of those variables within a reasonable range so that the various properties can be conveniently analyzed. Several conclusions can be ascertained from the work accomplished thus far:

a. Results indicate very clearly the viability of using regression derived equations to perform such analysis. In this study, a simple algebraic expression was defined which predicted the energy use and cost and optimal window size as a function of configuration parameters.

b. The regression coefficients (in addition to the configuration properties) also give insights into the residence performance associated with specific component effects and geographic locations. For example, in Madison, the energy reduction associated with increased solar gain is apparent in a negative sign attached to the summed heating and cooling solar radiation coefficient; wheareas, in Lake Charles, the resulting regression coefficient signs are positive.

c. The regression solution indicates that the components which contribute to a building´s energy use are independent of each other. Also, thermal loads arising from internal heat gains, infiltration, and natural ventilation are orientation independent.

d. A reduction in energy use in both Madison and Lake Charles for a residence using single pane glazing can be achieved for all orientations with increased window area and reduced conductance. The magnitude of the reduction in Madison can be as high as 50% when using high resistive, high solar transmittance glazing and as much as 16% in Lake Charles.

e. The impact of window orientation on total energy is much less than the effects arising from the other window parameters. Also, these orientation influences are reduced still further by decreased window conductance and shading coefficient. This is partly due to the fact that the configuration had windows on non-primary orientations equal to 15% of the wall area.

f. Futher studies will concentrate on expanding the data base to include effects arising from envelope variations in mass level and insulation level, use of overhangs, night insulation, and shade management. Results from additional climates will also be examined so that a climate/configuration interface can be defined.

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TABLE 1 - BASIC PARAMETRIC SET

Climate
Madison WI, Lake Charles LA

Primary Window Orientation
N, NW, W, SW, S, SE, E, NE

Window Size
(Fixed on Three Sides at 15% Wall Area)

% Wall Area	%Floor Area	Infiltration
0	0 (8.65)	.683
15	4.29 (12.94)	.700
30	8.57 (17.22)	.718
45	12.86 (21.51)	.735
60	17.14 (25.79)	.753

Glass Conductance ($W/m^{2}{}^{o}C$)
5.713, 2.675, 1.715, .534

Shading Coefficient
0.4, 0.7, 1.0

Internal Load (W/m^2)
2.6, 3.4, 5.1

Infiltration (air-changes/hr)
0.4, 0.7, 1.0

Natural Ventilation (air-changes/hr)
0, 5, 10

Other Options
Envelope
Overhangs
Night Insulation
Shade Management

Table 2

Cooling and Heating Regression Coefficients - Madison, WI
(For use with SI units)

Cooling

	β_1	β_2	β_3	β_4	β_5	
S	-.007191	-.002117	.003003	.3680	.2279	
SW	-.006299	.002963	.005754	.3190	.2487	β_6 .0362
W	-.008495	.004300	.004567	.2998	.2688	β_7 1.1652
NW	-.007065	.004546	.003651	.1832	.3054	β_8 -.1873
N	-.002187	.000724	-.000706	.1809	.3229	β_9 2.1469
NE	-.006449	.004102	.000872	.2405	.2903	
E	-.007979	.003641	.002991	.3089	.2616	
SE	-.009234	.005026	.002550	.3977	.2090	

Mean = 7.515
R^2 = .991
σ = .282

Heating

	β_1	β_2	β_3	β_4	β_5	
S	.3726	.4814	.02296	-1.7136	-1.0371	
SW	.3760	.4812	.02049	-1.4229	-1.1435	β_6 -.4134
W	.3846	.4672	.01320	-.7813	-1.3877	
NW	.3936	.4650	.009462	-.4650	-1.6091	β_7 64.6314
N	.4111	.4580	.002142	-.4623	-1.6455	β_8 .0717
NE	.4004	.4646	.009548	-.6869	-1.5217	β_9 52.1882
E	.3850	.4700	.01648	-1.0733	-1.2776	
SE	.3776	.4760	.02632	-1.6398	-1.0658	

Mean = 96.801
R^2 = .998
σ = 1.108

Table 3

Cooling and Heating Regression Coefficients - Lake Charles, LA
(For use with SI units)

Cooling

	β_1	β_2	β_3	β_4	β_5		
S	-.007585	.000667	.002297	.9373	.6564		
SW	-.01427	.008709	.004514	.9621	.7571	β_6	.1532
W	-.008697	.004790	.001508	1.0099	.7990	β_7	6.1157
NW	-.007463	.003964	-.001277	.8484	.8456		
N	-.005084	.002231	-.0007369	.5501	.8466	β_8	-.1857
NE	.002635	-.000909	-.0007217	.7213	.9161	β_9	4.1112
E	-.009982	.007651	.002170	.9813	.7878		
SE	-.003165	.003758	.003021	.9387	.7871		

Mean = 26.70
R^2 = .995
σ = .557

Heating

	β_1	β_2	β_3	β_4	β_5		
S	.07351	.1044	.01031	-.5100	-.2966		
SW	.07981	.1032	.067586	-.3899	-.3310	β_6	-.1564
W	.08818	.0978	.003719	-.2480	-.4104	β_7	15.0465
NW	.09478	.0940	.005651	-.1574	-.4550		
N	.09304	.0921	.002095	-.1695	-.4666	β_8	.4020
NE	.09147	.0972	.002535	-.2009	-.4372	β_9	14.1277
E	.08291	.1014	.006710	-.3493	-.3838		
SE	.07519	.1051	.01070	-.5016	-.3018		

Mean = 21.398
R^2 = .993
σ = .455

Figure 1

Residential Model Description

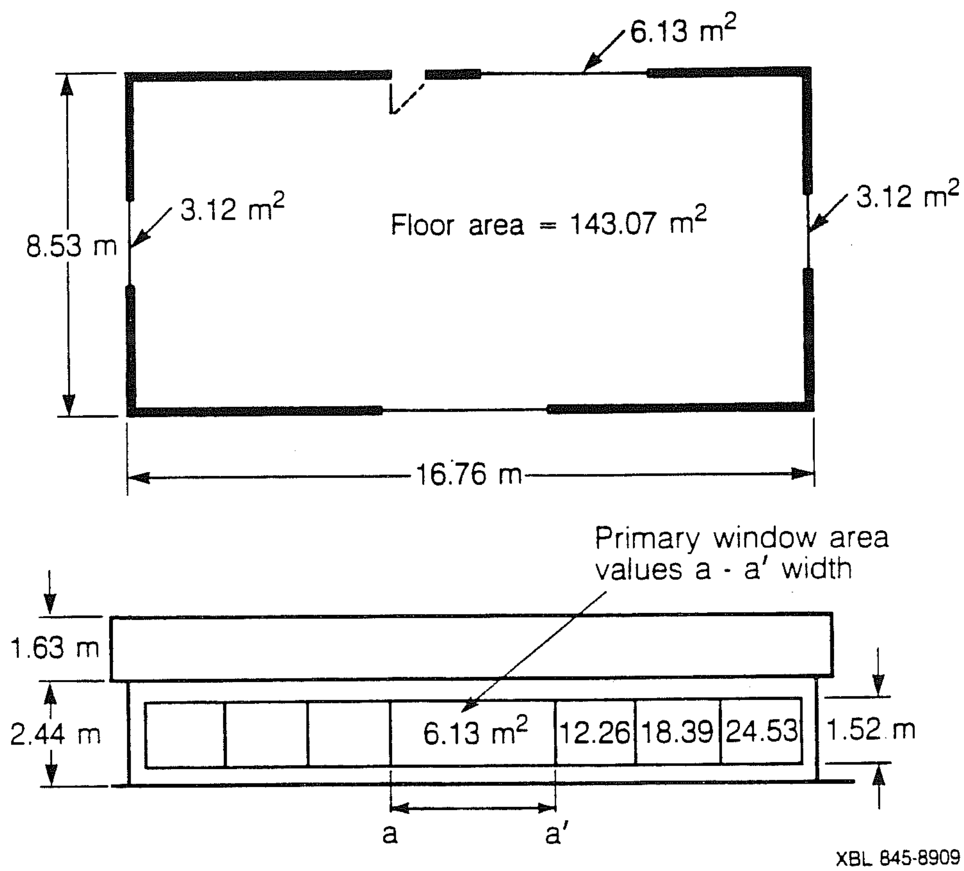
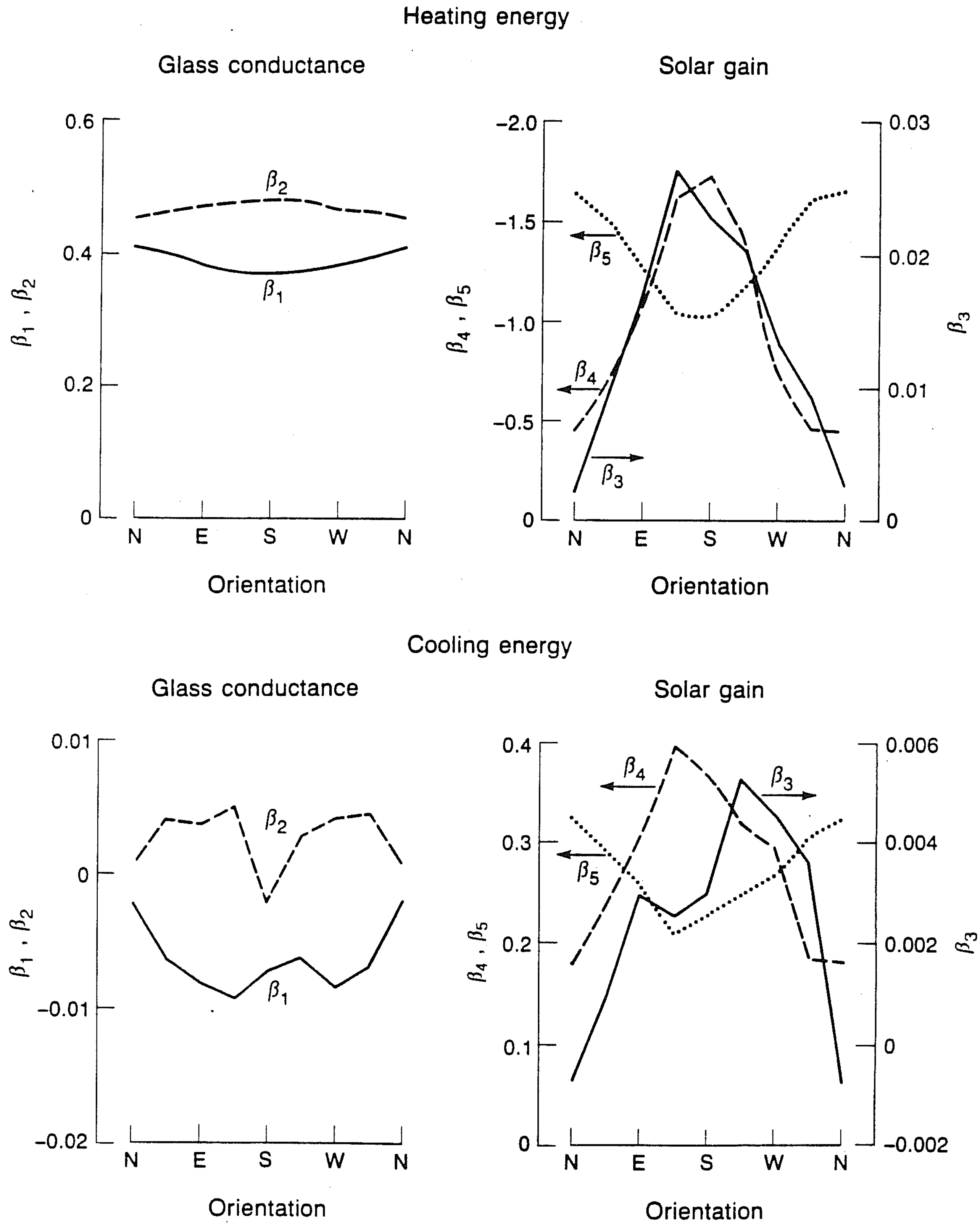


Figure 2

Residential Heating Energy and Cooling Energy Regression Coefficients as a Function of Primary Window Orientation in Madison, WI (For use with SI units)



Note: For use with SI units

XBL 8411-6280

Figure 3

Residential Heating Energy and Cooling Energy Regression Coefficients as a Function of Primary Window Orientation in Lake Charles, LA
(For use with SI units)

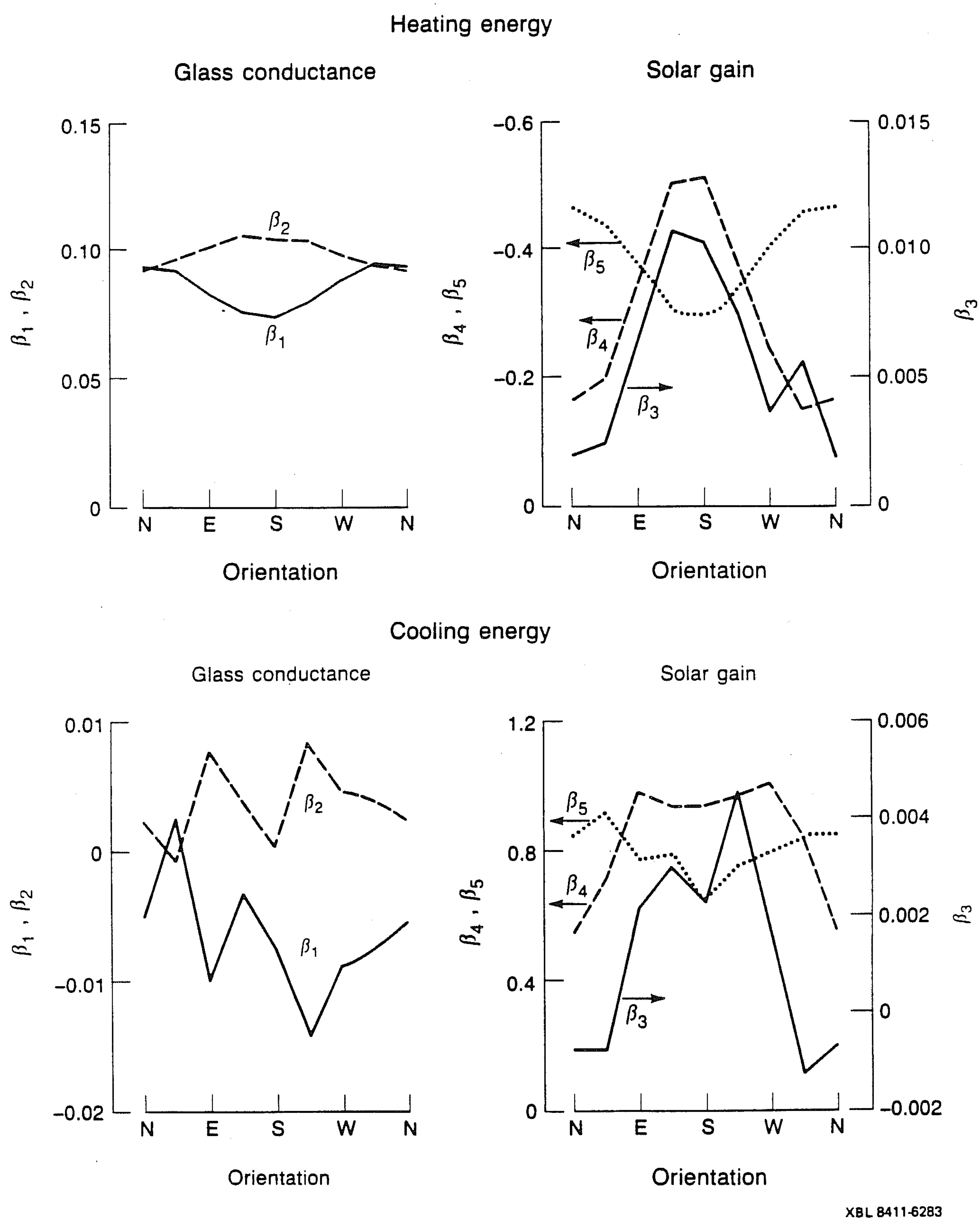


Figure 4

Residential Heating Energy and Cost Components as a Function of Configuration Variables in Madison, WI

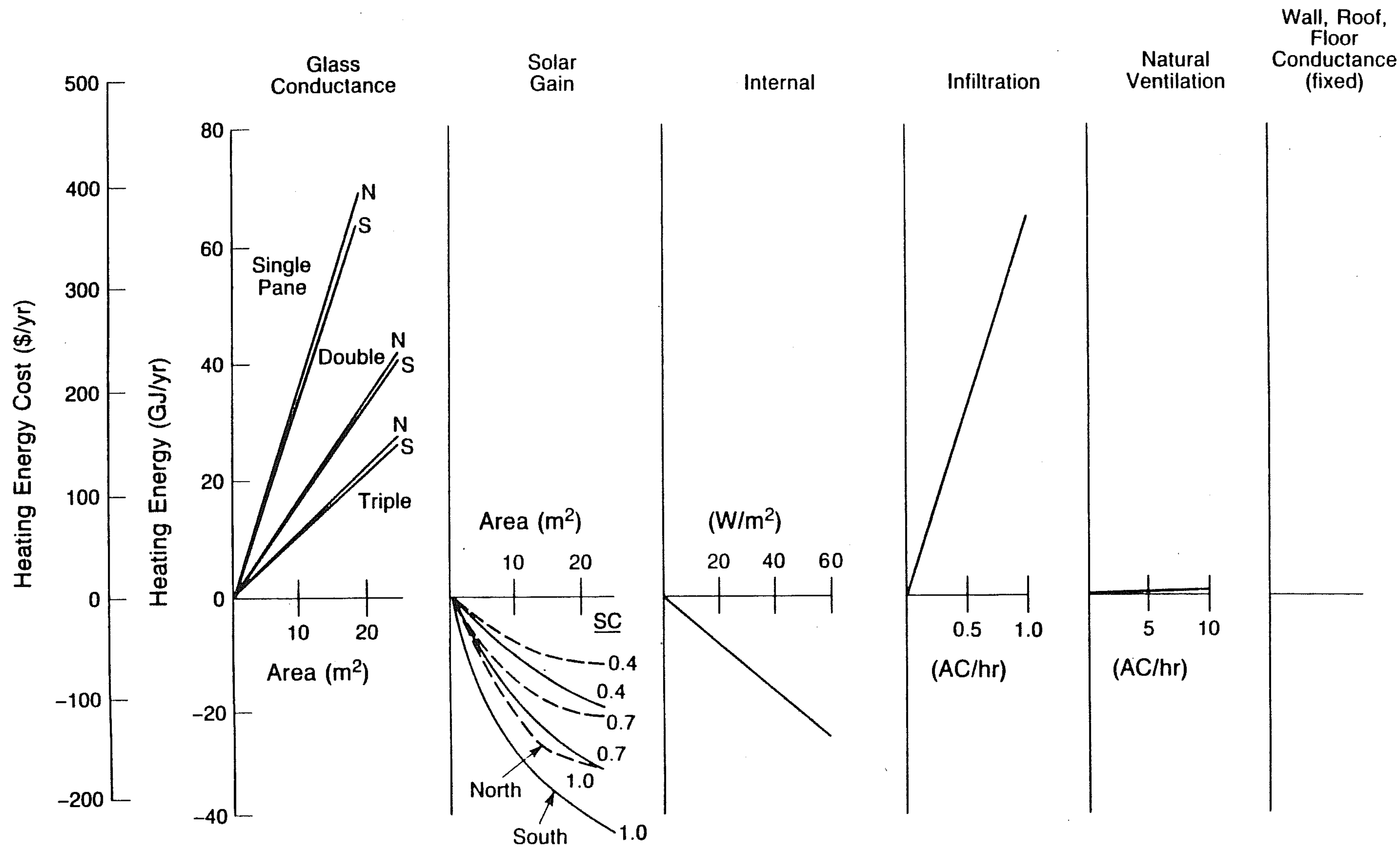


Figure 5

Residential Cooling Energy and Cost Components as a Function of Configuration Variables in Madison, WI

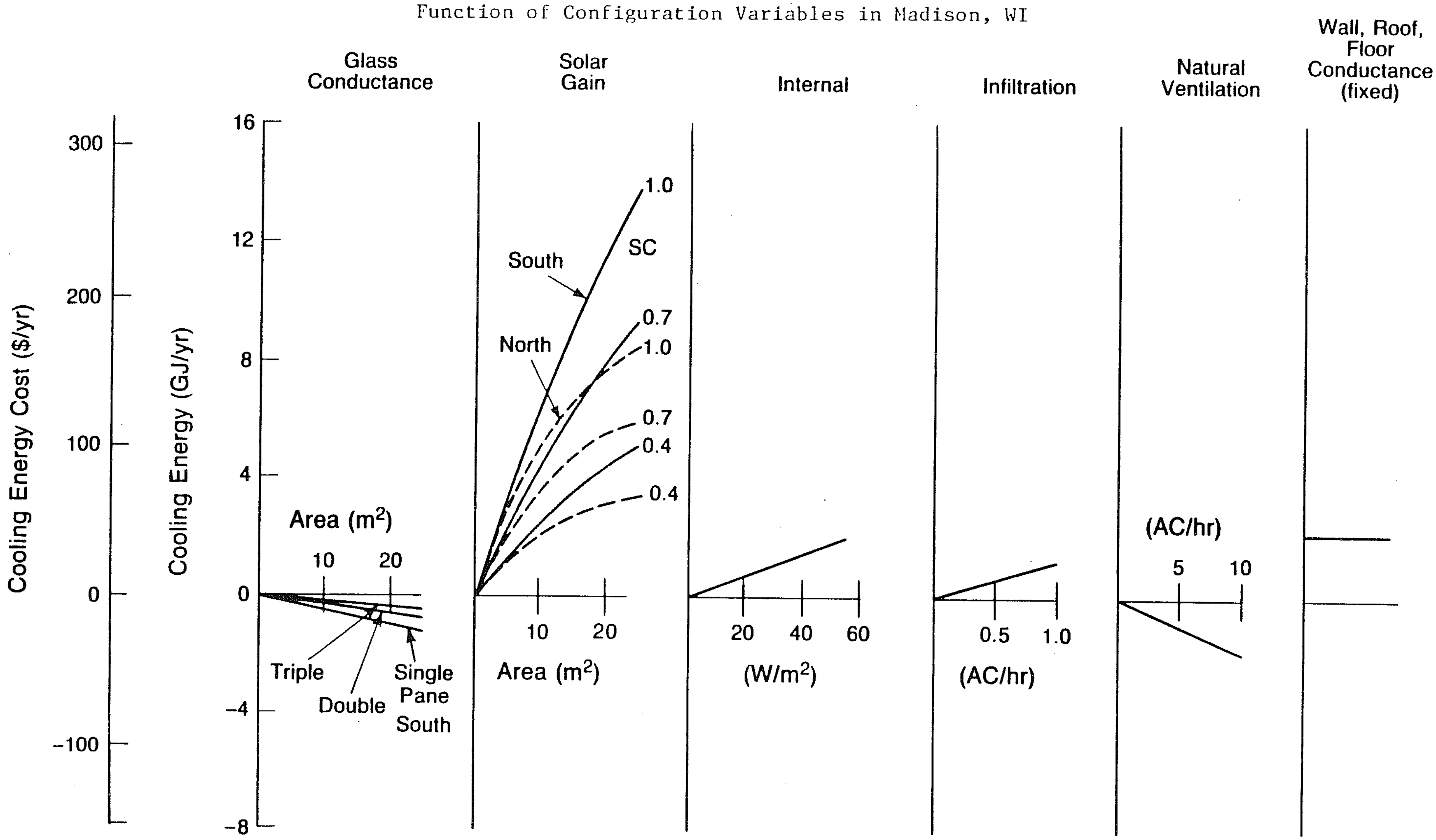


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Figure 6

Residential Total Energy as a Function of Configuration Variables in Madison, WI

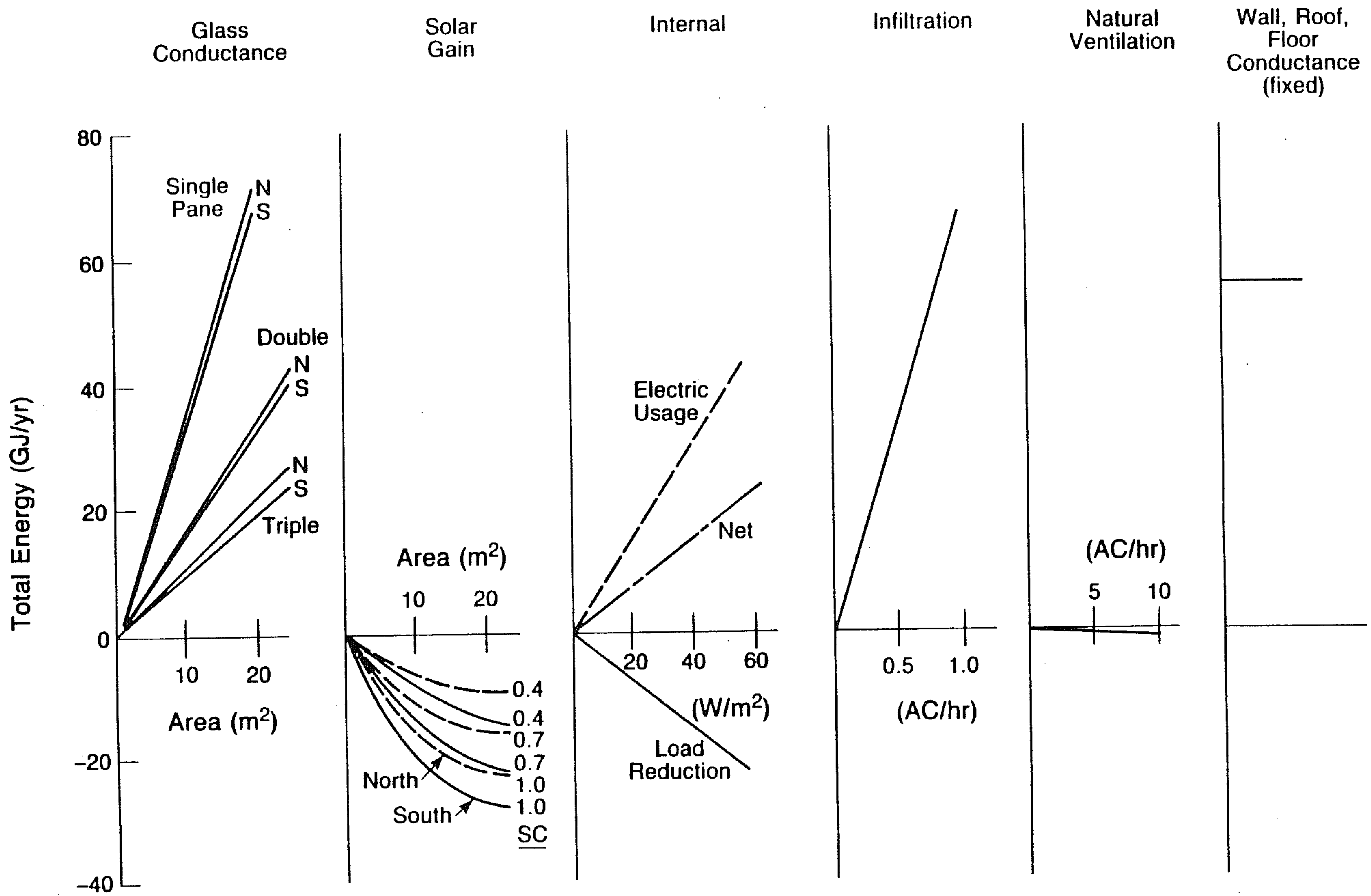

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Figure 7

Residential Total Energy Cost Components as a Function of Configuration Variables in Madison, WI

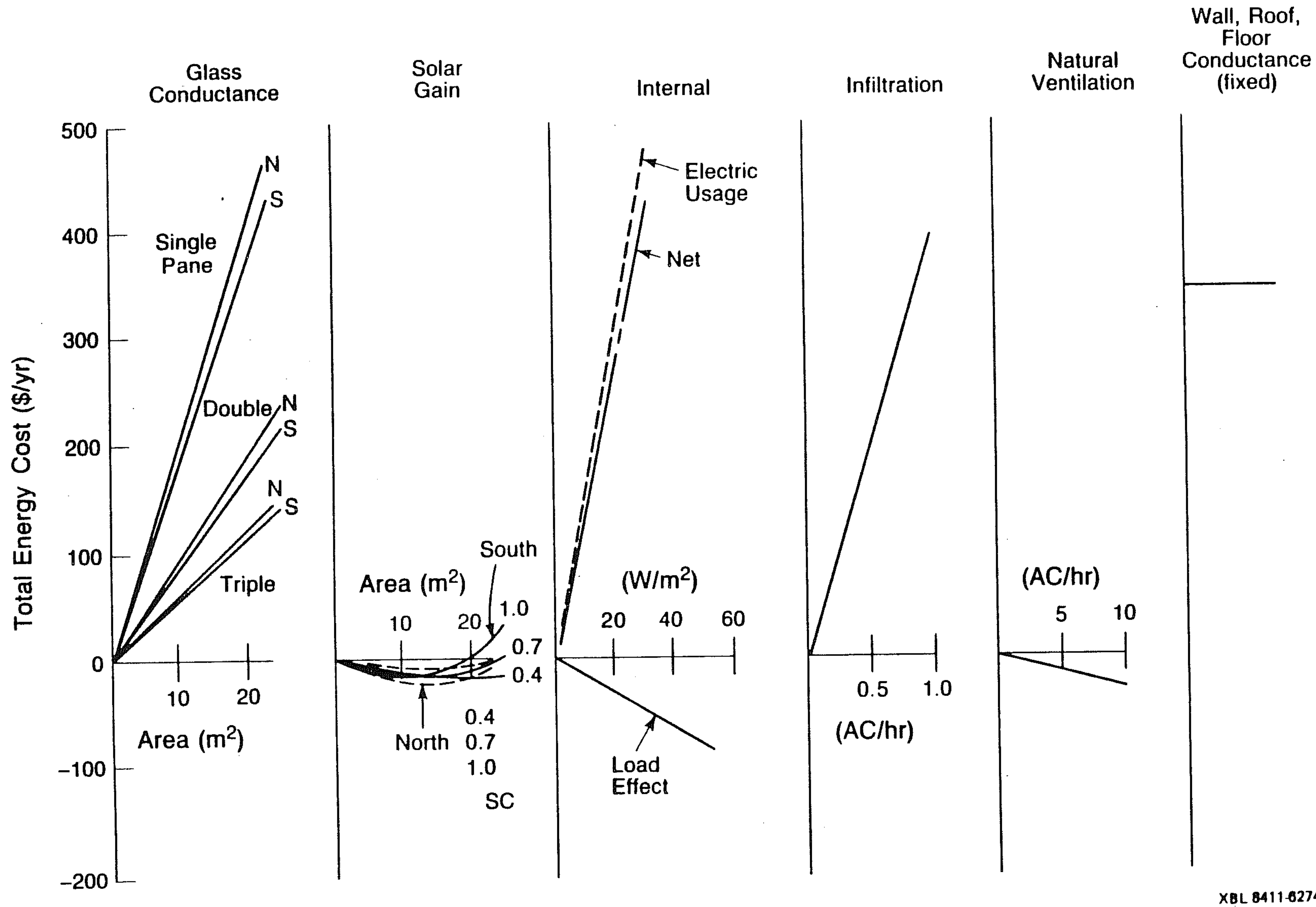

Figure 8

Residential Heating Energy and Cost Components as a Function of Configuration Variables in Lake Charles, LA

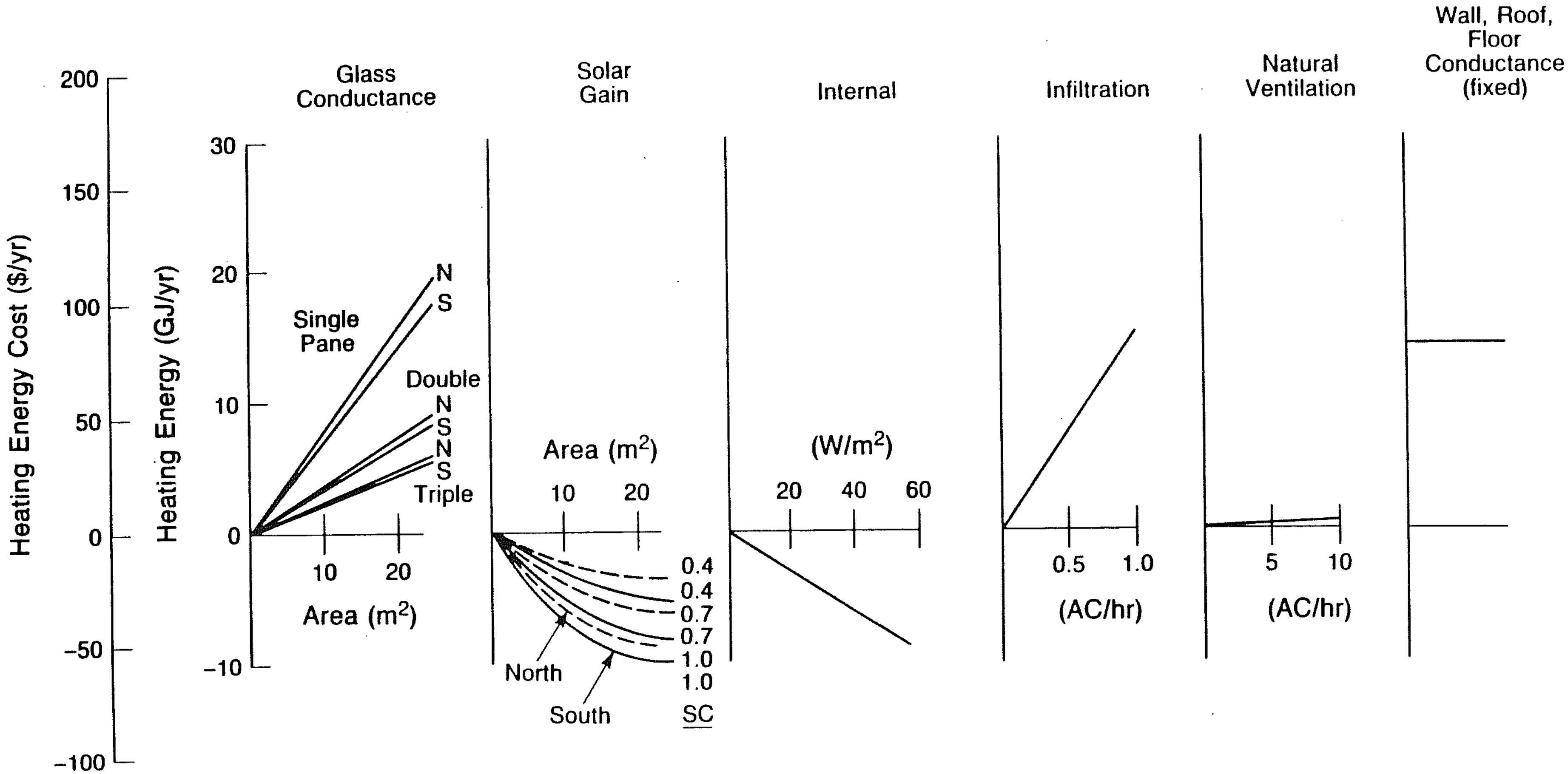

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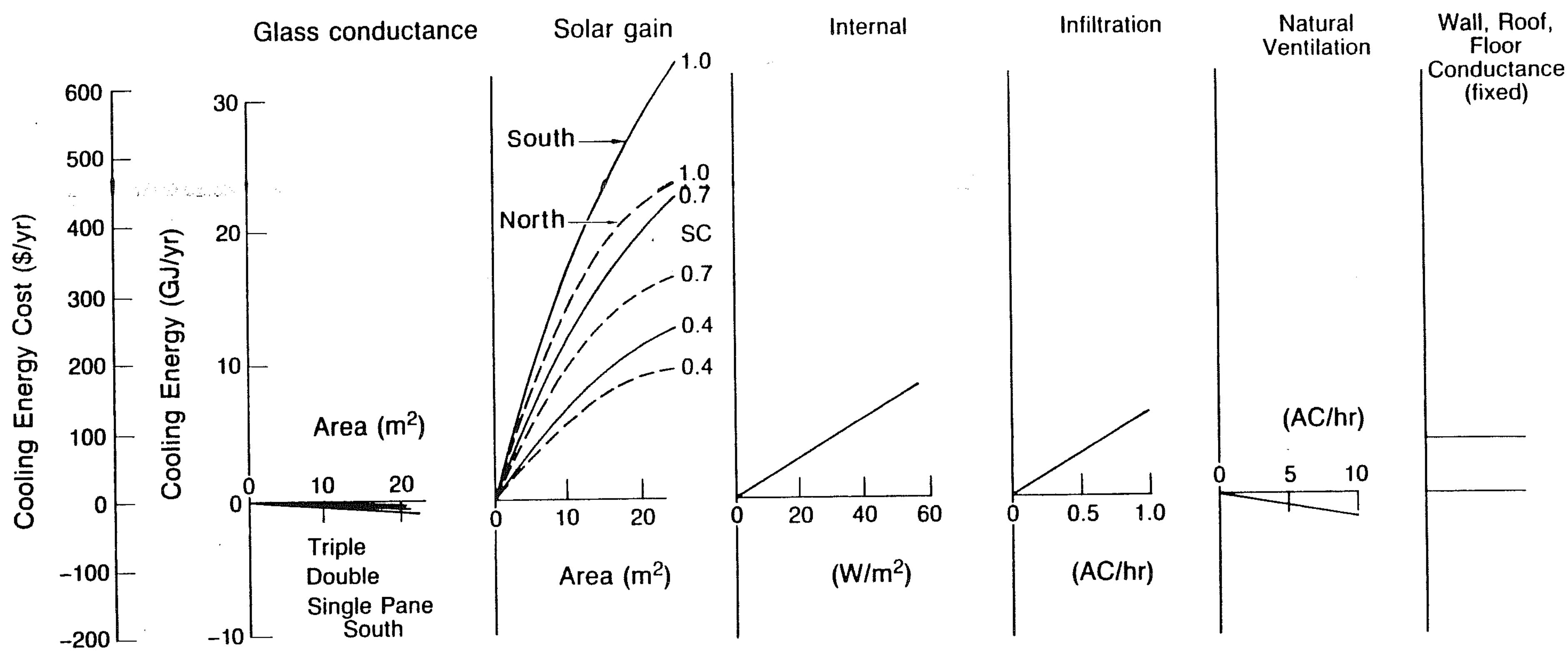
Figure 9

Residential Cooling Energy and Cost Components as a Function of Configuration Variables in Lake Charles, LA



XBL 8411-6284

Figure 10

Residential Total Energy Components as a Function of Configuration Variables in Lake Charles, LA

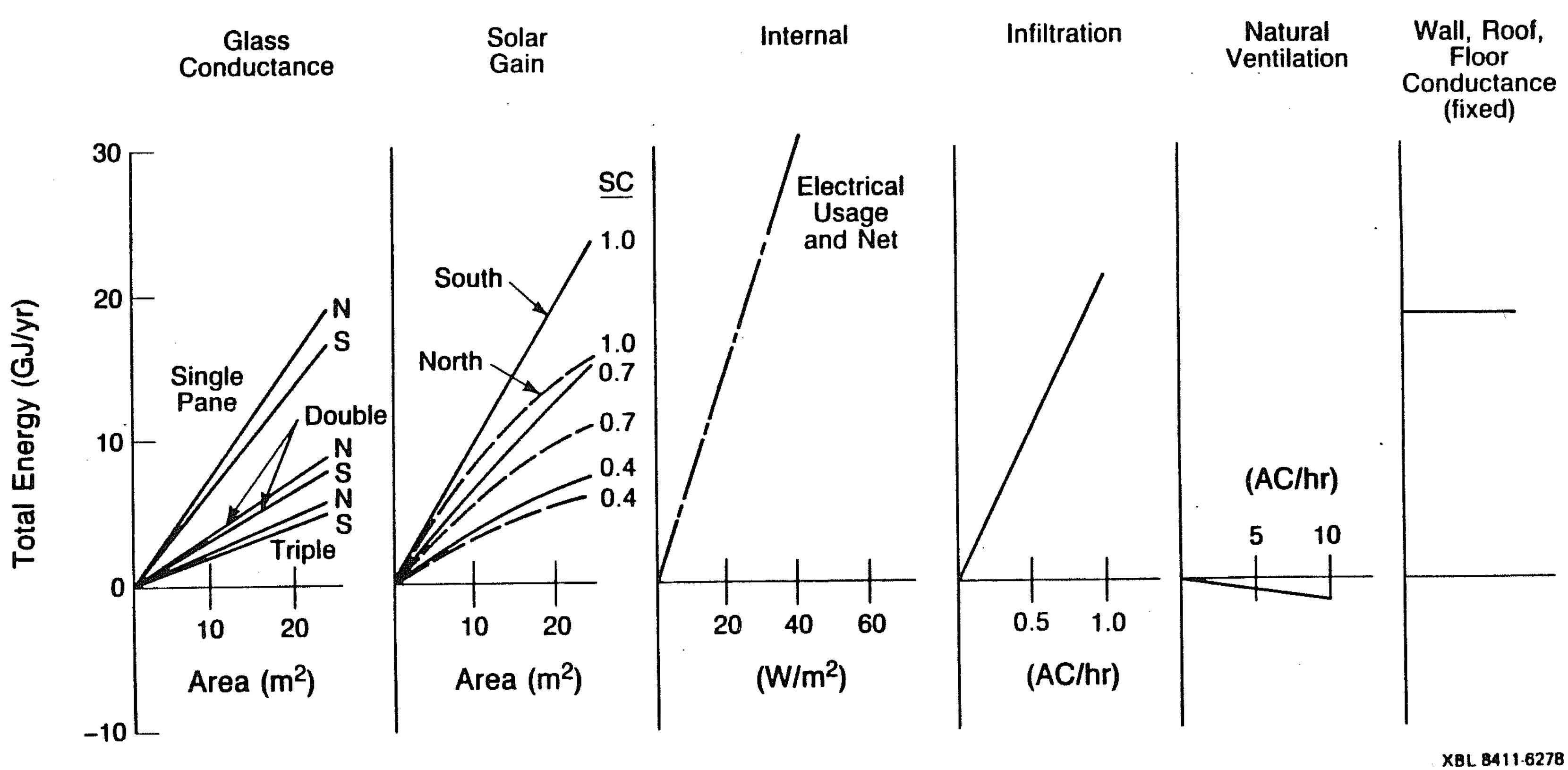
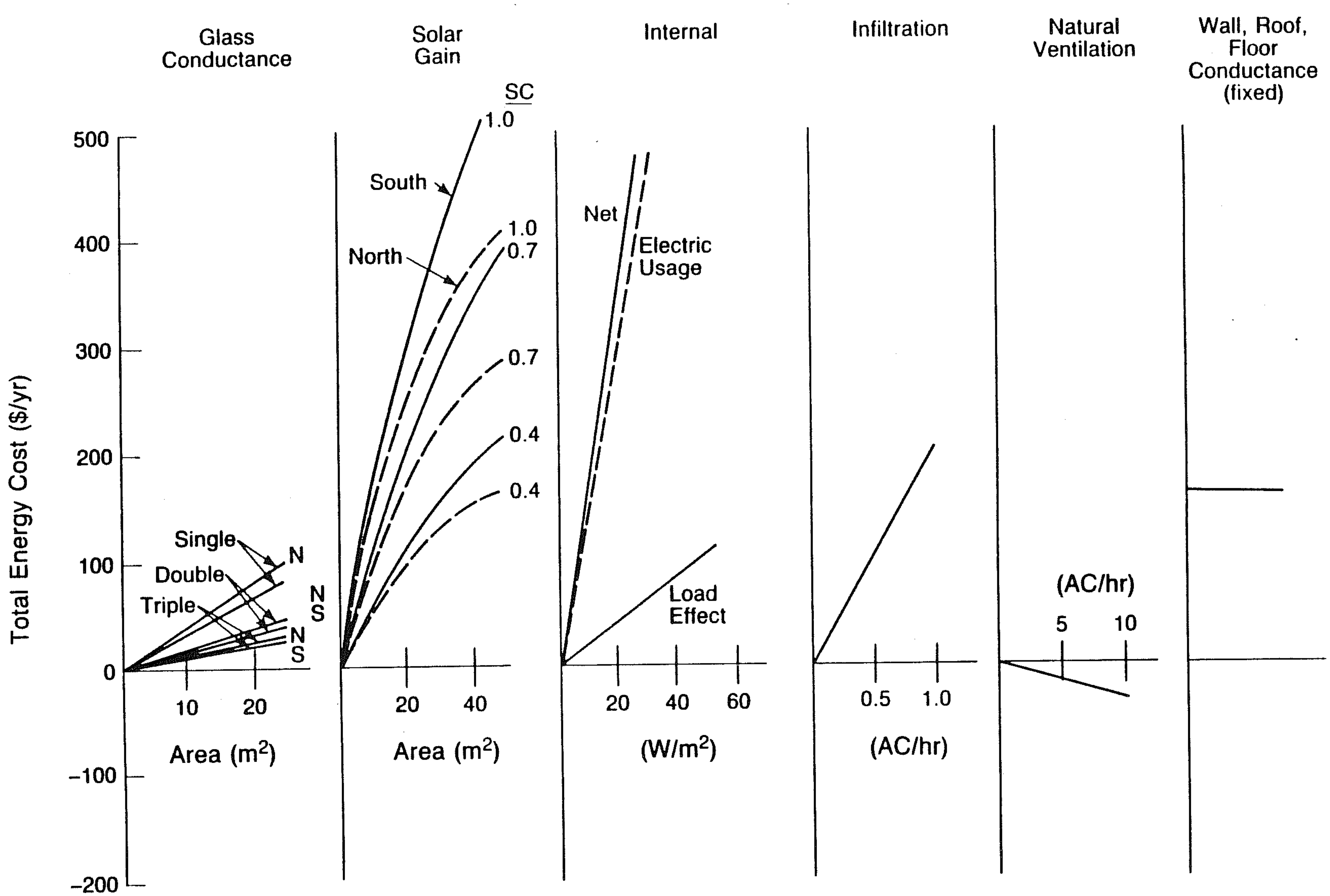


Figure 11

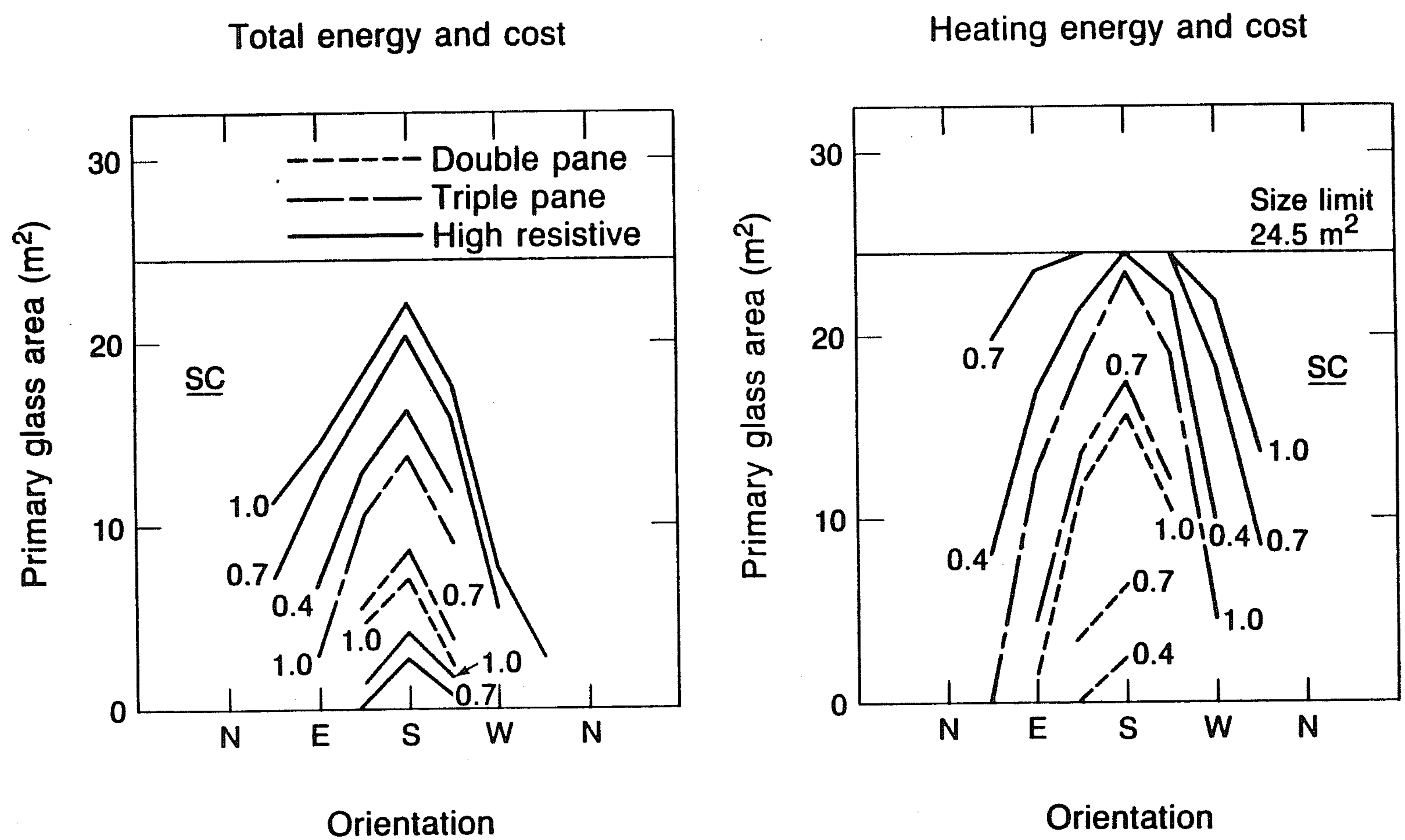
Residential Total Energy Cost Components as a Function of Configuration Variables in Lake Charles, LA



XBL 8411-6277

Figure 12

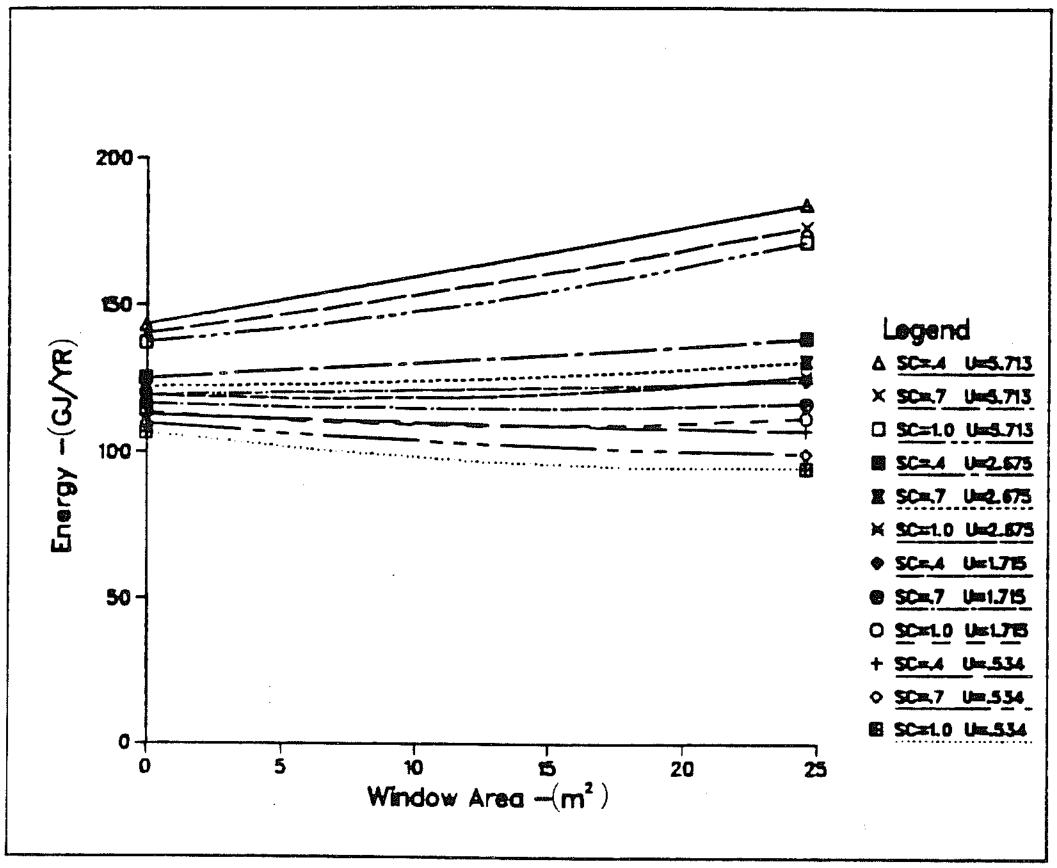
Primary Window Optimum Size as a Function of Orientation Based on Total Energy and Cost and Heating Energy and Cost Requirements in Madison, WI



XBL 8411-6272

Figure 13

Annual Residential Total Energy Use for a
South Primary Window Orientation in Madison, WI
for Varying Window Area, Shading Coefficient, and Conductance



FLOOR AREA

= 143.1 m^2

Figure 14

Annual Residential Total Energy
Cost for a South Primary Window Orientation in Madison, WI
for Varying Window Area, Shading Coefficient, and Conductance

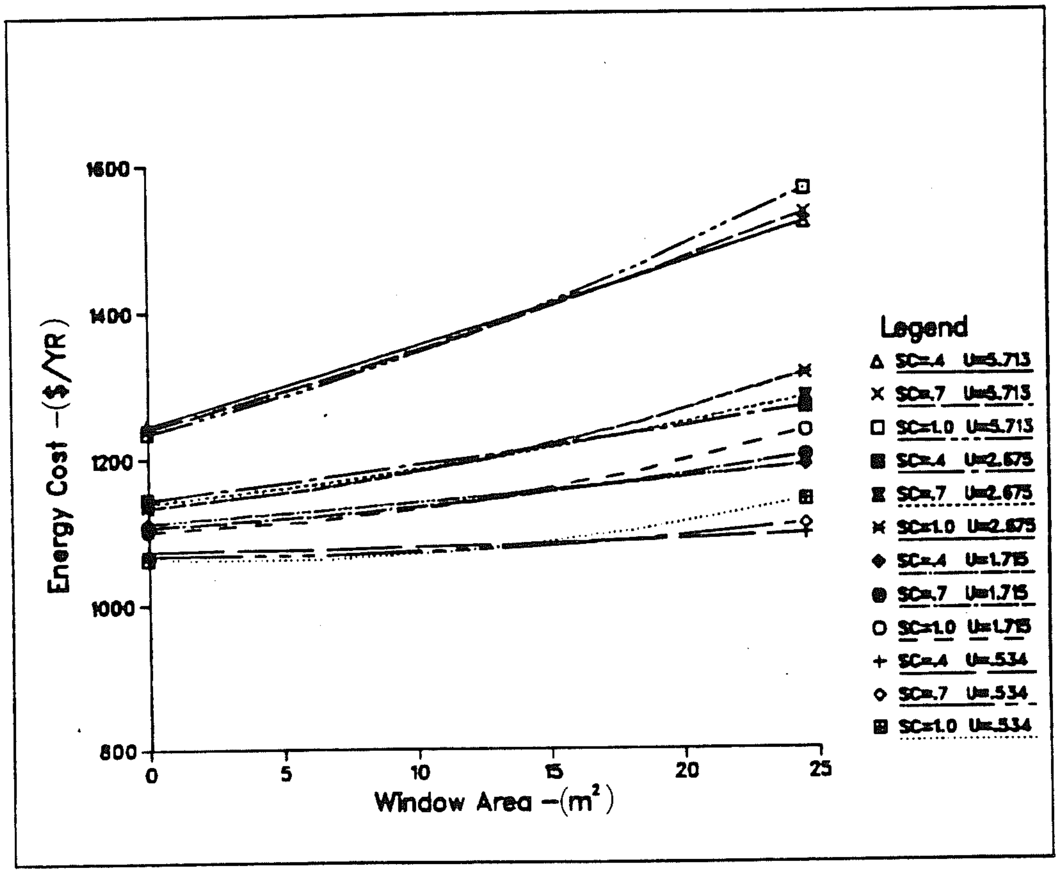


Figure 15

Annual Residential Total Energy Use
for a North Primary Window Orientation in Lake Charles, LA
for Varying Window Area, Shading Coefficient, and Conductance

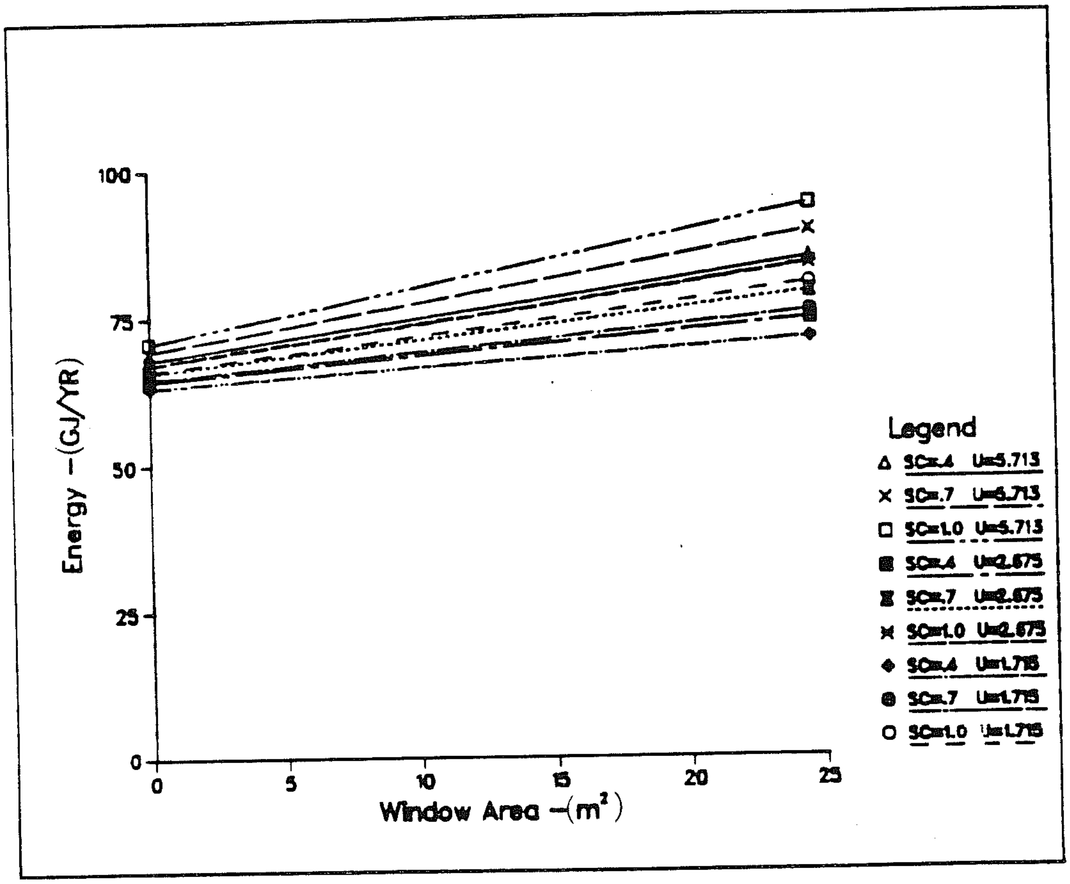


Figure 16

Annual Residential Total Energy Cost for a
North Primary Window Orientation in Lake Charles, LA
for Varying Window Area, Shading Coefficient, and Conductance