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ABSTRACT

Commercial building energy analyses may be used for new building design, energy end use forecasting and energy audit calculations. Many building simulation programs such as DOE 2.1A or BLAST, are quite complex, and must be run by specialists on main frame computers. A simplified method of commercial building energy analysis has been developed that utilizes a data base of previous DOE 2.1A simulations to predict the outcome of other simulations. We have applied this methodology to an office building in one climate region and have found that it predicts heating, cooling, and total energy use very accurately. The main advantage of this methodology is that less specialized skill is required and only a microcomputer is needed to perform the analyses. Therefore, energy analyses can be done cheaply and quickly.

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INTRODUCTION

Commercial building energy analyses may be used for new building design, energy end use forecasting and energy audit calculations. Most methods of energy analysis are expensive to use and require long training periods for proper use. There are two approaches to reducing the time and expense presently required to perform energy analyses of commercial buildings. One is to write a faster running computer program with simplified algorithms that may have fewer options and be less accurate than complex building simulation programs such as DOE 2.1A[1] or BLAST. Kusuda and Sud used this approach in developing a modified bin method for commercial building energy analysis.[2] A second approach is to create a data base by performing a large number of DOE 2.1A runs for the important building parameters, as regards energy use impact, and then use the data base to predict the outcome of other energy-conservation measures. This paper discusses our version of the latter method.

We have performed a parametric energy analysis using the DOE 2.1A version of the DOE computer program for an office building in one climatic region, that of Denver, Colorado. Based on this analysis, an equation was developed that predicts heating, cooling and total building energy use as a function of eleven building envelope and systems control parameters. These are the key parameters as regards energy use in the Denver climate. This equation takes into account both single-parameter changes and the interactions that occur when two parameters are changed simultaneously.

Because the analysis can be based on previously performed DOE 2.1A runs, the methodology discussed above should enable use of a microcomputer to predict energy use in commercial buildings in various climates cheaply and with high accuracy. Our initial work indicates that, at least for the climate studied, this technique predicts energy use very accurately.

As presently constituted, the methodology is best suited for electric energy end use forecasting or analysis of retrofit measures in commercial buildings. Additional work is necessary to improve its usefulness in the early stages of new building design. Two features not presently available but which are needed are: the ability to model variable aspect ratios and the ability to model variable perimeter to core area ratios.

2. BASE CASE BUILDING CHARACTERISTICS AND OPERATING CONDITIONS

Many assumptions must be made concerning the base case building's operating conditions and characteristics before its interaction with the appropriate climate and its operation can be simulated with DOE 2.1A. The office building we modeled is one of those selected as typical and studied during PHASE II of the Department of Energy (DOE) Building Energy Performance Standards (BEPS) project.[3] It has been altered slightly to make its construction characteristics more uniform throughout the building.

Site Characteristics

Table 1 lists the base case values of the parameters that have been varied in our analysis. The base case building is a 100,000 square foot, (72 ft. x 232 ft.) 6 story office building situated in Denver, Colorado. Denver is located in a climate zone with 6000 heating degree days (base $65^{o}F$) and with 667 hours when the outdoor dry-bulb temperature is greater than or equal to $80^{o}F$. Weather information was obtained from a Test Reference Year (TRY) tape which was for the year 1976.

Building Envelope

The composition of walls, roof, and floors is described under the materials heading in Table 1. The total R-value of the external walls and roof varies with the R-value of the insulation in each assembly. We have not studied the effect of varying the R-value of the underground floors since heat transfer to the ground is presently not well enough understood to be properly modeled. All interior floors have a fixed R-value of 9.

Each of the four exposures has the same window-to-wall ratio (22%), and the windows have the same solar transmission (40%) and glass conductance (.574 $Btu/h.ft^{2o}F$). These values correspond to tinted double pane windows with 3/16 or 1/4 inch thick glass and one-half inch air space. All windows are set back one foot relative to their eight foot height in the base case building. We have studied the effect of fixed shading by varying this setback. Lighting is provided by fluorescent lamps recessed in a suspended ceiling. The average lighting power density is 2.5 $W/ft.^2$ and 50% of the heat of lights is assumed to enter each space according to its installed wattage. The remaining 50% is lost via hallways and stairwells and does not affect heating or cooling loads.

System Variables

Table 2 lists the occupancy schedule and the operating schedules for lights and HVAC systems for each day of the week.[4] The infiltration schedule is seen to be the inverse of the fan schedule. Because the HVAC system keeps the building slightly pressurized, DOE 2.1A assumes that there is no outside air infiltrating into the building when the system is on. Of course, the HVAC system supplies outside air to the occupied spaces. When the HVAC system is off, 0.6 air changes per hour is the assumed infiltration rate thoughout the building.

Three different types of HVAC systems have been studied. The first system is composed of a number of water to air unitary heat pumps for both heating and cooling, with a circulating water loop. A 300 KW electric boiler provides backup heat generation if the water temperature of the loop falls below $60^{o}F$. The other two systems are a double-duct constant volume and a double-duct variable volume system. Both have a gas fired hot water boiler and centrifugal chiller.

3. DESIGN OF SENSITIVITY STUDIES

We designed our sensitivity analyses with the ultimate objective of developing tools for a simplified approach to energy analysis of commercial buildings that would eliminate the need for costly and lengthy computer analysis for preliminary new building design or retrofit prioritization. One of the outputs of the research is a matrix which contains information on the strength of interactions between the most important variables as regards their combined impact on energy use. Two types of parametric energy analyses were performed. In one case, one parameter was varied (five or more values were chosen for each parameter) while all the others were held constant at their base case value. In the second case, two parameters were varied simultaneously while all the others remained constant at their base case values.

The ultimate objective was to combine information obtained from all the single parameter and two-parameter analyses into one large equation to predict heating, cooling and total energy use in a building (see Fig. 1). This final equation was tested against DOE 2.1A runs that had not previously been performed in developing the equations for heating, cooling and total energy use.

4. RESULTS FOR OFFICE BUILDING IN DENVER

Single Parameter Results

We have performed parametric energy analyses for sixteen building parameters with three HVAC system types. We report our results for the heat pump system in this paper. Five of these variables: orientation, ground reflectance, window setback ratio, roof absorptance and wall absorptance, have very small (<2% change) total energy use impacts in Denver's climate region. For the other eleven parameters, curves were fit to the DOE 2.1 simulations.

Of these eleven parameters, only six impact total energy use so as to cause a 10% or greater change in its magnitude. These parameters are wall insulation, glass conductance, window to wall ratio, lighting power, outside ventilation air amount, and nighttime heating setback temperature. A 10% change in total energy use is quite large when we realize that, except for lighting power, the variations in each parameter do not affect lighting, hot water, and elevator energy use, which total 60% of the total base case energy use. A 25% change in space conditioning energy use is required to obtain a 10% change in total energy use.

It is important to note that a change in HVAC system type can have a greater impact on energy use than a change in the value of a building envelope or system control parameter. For example, at a 50% window-to-wall ratio, a heat pump system may use 54% less space conditioning energy than a dual duct constant volume system, whereas, a change in window-to-wall ratio from 75 to 25% reduces heat pump space conditioning energy use by only 25% (see Fig. 2). Figure 3 illustrates the results of fitting an analytic function to a series of DOE 2.1A runs for window-to-wall ratio. Energy use has been expressed in units of kBtu/ft^2/yr for our 100,000 square foot base case building. Changes in window-to-wall ratio affect both solar gain and conductive heat transfer. Heating, cooling and total energy use all decrease linearly with decreasing window to wall ratio. Curves for the other ten variables can be found in Appendix A. Table 3 shows the functional relationship between total energy use and each of the eleven parameters studied. Table 4 illustrates the same information for the heating and cooling energy data. We attempted asymptotic, linear, exponential, and polynominal fits to the DOE 2.1A runs as seemed appropriate. The asymptotic fits were obtained directly from basic principles of heat transfer. The exponential and higher order polynomial fits were unexpected from physical considerations and are merely the best fit to the DOE 2.1A runs.

We have also presented the results of our energy analysis in a format different from that seen in Table 4. We have calculated the value of the coefficient a_i, in equation (1) for typical values of each parameter, P_i.

$$a_i = \frac{\partial E/E}{\partial P_i/P_i} \tag{1}$$

The coefficients a_i are dimensionless and vary with the value of P_i. They are similar to elasticities in the field of economics. One can look at Table 5 and say that a 1% change in parameter P_i yields an a_i% change in energy use. For example, a 1% change in window-to-wall ratio (at WWR = .25) yields a 0.18% change in heating energy use. Negative numbers in Table 5 signify that energy use decreases as the parameter in question varies from left to right over the range indicated. The major advantage of displaying the coefficients for heating and cooling energy use shown in Table 5 is that the values of the coefficients for an individual parameter can be compared for different climates or building types. For example, the effect of changes in window-to-wall ratio on heating or cooling energy use may be compared for an office building located in Denver and Miami or for an office building and retail store in one particular city. When comparing coefficients for different parameters, a word of caution is needed. A 1% change in a parameter such as WWR is an extremely small absolute change, say from .25 to .2525, whereas a 1% change in heating setpoint temperature is a relatively larger absolute change in that parameter. Therefore, the coefficients for temperature related parameters may be safely compared among themselves with the result that changes in night thermostat setback yields the greatest heating energy use change. Analogously, the two insulation parameters may be compared to each other or the three parameters (WWR, GST, LS) varying from 0 to 1.0 may similarly be compared. In addition, except for the coefficients involving temperature these coefficients can be compared among themselves to assess relative sensitivity to equal percentage changes. Although the coefficients are dimensionless, a change in the zero of the temperature measurement scale, in particular from ^{o}F to ^{o}K, will cause a change in a_i. Therefore, comparisons involving temperature coefficients depend upon the choice of temperature scale. We plan to explore improved formats for presentation of these parametric analyses.

Two important facts should be pointed out concerning the curves plotted in Appendix A. First, a wide range of values was studied for each parameter even when this range might not reflect the current technical possibilities. For example, the range of glass solar transmission studied (0-100%) is broader than would be found in actual buildings where a range of 25-80% would be more plausible. Secondly, large changes in heating and cooling energy use occur for some parameters even when total energy use does not change significantly. Using glass solar transmission as an example again, total energy use changes by only 4% over the full range of solar transmission variation from 0 to 100%, even though cooling energy used increased by 126%, fan energy increased by 26%, and heating energy use decreased by 41%. In a climate such as Denver's, where the heating load is greater than the cooling load, these changes in space conditioning end uses tend to cancel one another, leading to a small change in total energy use. In other climates the results could well be drastically different. This would probably be particularly true of cooling load dominated climates like Houston or

Miami where glass shading might produce large energy savings. Thus, it is very important not to extrapolate conclusions made for Denver to locations with a different climate type.

Interaction Matrix Development

Thus far, we have discussed the impact on building energy use of changes in one parameter while all other parameters were held constant. This procedure was followed for all sixteen parameters studied. Since buildings are composed of interdependent subsystems, when real buildings are designed, or when retrofits to existing buildings are planned it is desirable to know the energy use impact of changing several parameters simultaneously. Our objective was to develop a procedure for predicting the importance of interactions between conservation measures by performing computer simulations involving simultaneous changes from the base-case values for two or more parameters.

To this end, we compared two methods of calculating the total energy use reduction achieved by changing the values of two parameters simultaneously while keeping all other parameters fixed. The actual result of a DOE 2.1A simulation where two parameters were simultaneouly changed was compared to the result of simply adding the two individual energy reductions achieved separately by each measure. This was done for the eleven most important parameters (in Denver's climate) as regards total energy use impact. An example that illustrates how two parameters interact follows: We changed the wall insulation R value (RW) from 8 to 16 and the window to wall ratio (WWR) from 22 to 10% and found that algebraically adding the individual energy changes gave a different result than obtained from a single run which altered both parameters simultaneously. The interaction is moderately strong in this case; algebraic addition underestimates the total energy savings by 10%.

Table 6 lists the parameters for which we have performed an interactions analysis, their base case values in column two and their interactions values in column three. For each of the eleven variables, a computer simulation is performed with the other ten variables. For example, in the first simulation, the roof insulation (RR) R value is R30 and the wall insulation R value is R16. The other nine variables remain at their base case values. For the next nine simulations, RR remains at R30 and the other variables WWR through THS take on the values shown in column 3 one at a time. To simulate all the combinations of the eleven variables in column three taken two at a time requires 55 computer runs.

The matrix in Table 7 illustrates the results of our interactions analysis. Each entry in the matrix is the percentage difference between two methods of obtaining the energy use reduction resulting from simultaneously changing the values of two of the parameters in Table 6 from their base case values to the values in the column 3. Thus, the larger the magnitude of a matrix element, the larger the interaction between the two parameters and the greater the error in energy use prediction when the result of multiple measures is obtained by simply adding the results of measures taken one at a time.

An example will help to clarify the process. Lighting power will be changed from 2.5 to 1.5 w/ft^2 and the cooling setpoint temperature will be changed from 78 to 82^oF. The energy use reductions obtained from the lighting power reduction and the cooling temperature setpoint changes are 890 and 148 MBtu, respectively. If we were simply to add these reductions together the reduction in energy use would be 1038 MBtu (ΔE_1 = 1038 MBtu). However, an actual DOE 2.1A simulation with both parameters changed simultaneously resulted in an energy use reduction of only 993 MBtu (ΔE_2 = 993 MBtu). Thus, the entry in the matrix (Table 7) where lighting power and cooling setpoint intersect is +5% ((1038-993)/993). Therefore, neglecting interaction results in an overprediction of almost 5% relative to the DOE 2.1A calculated energy use reduction of 993 MBtu. This overprediction is due to the fact that not as much cooling energy is saved with a reduction in lighting power if the cooling setpoint is at 82 rather than 78^{o}F.

In some cases, the interaction term will be quite large (expressed as a percentage) because of moderate differences in small numbers. Therefore, the percentage difference alone may not be an adequate measure of the importance of the interaction term. Some measure of the energy use reduction itself may also be needed.

An example where a large underestimation (165%) of total energy savings occurs is where the glass solar transmission (GST) is 25% and the percentage heat of lights (LS) that goes to the occupied space is 75%. In this case, the impact of individual changes in these two parameters is very slight as can be seen from the figures in the appendix. Algebraic addition of energy reductions yields an energy use increase, ΔE_1, of 13 MBtu whereas simultaneous simulation of the two measures yields on energy savings ΔE_2, of 20 MBtu. The difference between the two methods is 33 MBtu and when this difference is divided by the actual result (20 MBtu) a 165% difference between the methods results. A possible modification of Table 7 would be the addition of another number to each matrix element, the actual total energy use reduction achieved by simultaneously carrying out both measures. Therefore, the matrix element for LS (.75) GST (.25) might be 20/-165%, 20 being equal to ΔE_2 in MBtu and -165% being the underestimation in energy savings. There are many cases in which a large interaction term is not due to division by a small number. For example, the interaction strength for WWR (.1) GC (.3) is 27% and ΔE_2 is 254 MBtu.

When the interaction matrix element is small , multiple measures may be treated by adding the results of single measures taken one at a time. The parametric equations developed for changes in a single parameter can be used for these cases. For large interactions, a different methodology must be used to estimate energy use accurately. When heating and cooling energy use are separately estimated, the errors resulting from not considering interactions between multiple simultaneous conservation measures are generally, larger than for the total energy use estimation.

5. ENERGY USE PREDICTION METHODOLOGY

Our single parameter energy analysis indicated that total energy use (in Denver's climate) can be accurately expressed as an analytic function of each of eleven building parameters, while all others were held constant. When the interaction between two parameters is small, (see Table 6) simple addition of energy savings from multiple measures will provide reliable estimates of combined total energy savings. In order to determine heating, cooling or total energy use as a function of two simultaneously varying parameters, where the interaction between parameters is large, we performed a Taylor series expansion of energy use as a function of two variables P_i and P_j. P_i and P_j represent any two building parameters. Equation (2) is the second order expression used.

$$E\,(P_{i1},P_{j1}) = E_o + \frac{\partial E}{\partial P_i}\Delta P_i + \frac{\partial E}{\partial P_j}\Delta P_j + \partial^2\frac{E}{\partial P_i^2}\frac{\Delta P_i^2}{2} + \partial^2\frac{E}{\partial P_j^2}\frac{\Delta P_j^2}{2} + \frac{\partial^2 E}{\partial P_i \partial P_j}\Delta P_i \cdot \Delta P_j \quad (2)$$

In eq. (2), E_o $(E(P_{io},P_{jo}))$ is the base case energy use and $E(P_{i1},P_{j1})$ is the energy use when the parameters P_i and P_j have values P_{i1} and P_{j1} respectively. All derivatives are evaluated at (P_{io},P_{jo}), the base case values of parameters P_i and P_j. ΔP_i equals $(P_{i1} - P_{io})$, and ΔP_j is defined similarly. The parametric equations developed earlier have not been used in evaluating the derivatives shown in equation (2).

All five partial derivatives were evaluated by using actual DOE 2.1A runs. Appendix B shows the equations used to calculate these derivatives and how they were derived. The approximation used becomes exact if $E(P_i,P_j)$ is a linear function of P_i when P_i is between P_{io} and P_{i1}.

Most of the curves in Appendix A are linear or almost linear over a typical range of variation from the base case value for the parameter in question. Energy use as a function of roof or wall insulation are exceptions to this observation. However, even for these parameters, for most deviations from the base case values the functions are almost linear. If energy use were expressed as a function of wall or roof u-value rather than R value of the insulation, a linear functional dependence would result. However, for convenience sake, we chose to express energy use as a function of R value.

Once the five coefficients (the five partial derivatives)in equation (1) are calculated for all 55 combinations of eleven parameters taken two at a time, heating, cooling, and total energy use can be estimated for any of those combinations. A different set of coefficients is required for heating, cooling and total energy use estimations. Appendix C contains tables and matrices which summarize the values of these three sets of coefficients.

6. MODEL TESTING

After all coefficients needed for the Taylor series expansion were determined for all combinations of parameters taken two at a time, a Fortran program was written to facilitate energy analysis with a microcomputer. We tested our simplified energy analysis methodology by using the computer program to predict energy use for combinations of parameters (taken two at a time) not previously studied. Table 8 shows the results of this comparison between the actual DOE 2.1A simulations and the model predictions. Both first and second order Taylor series approximations are compared to the DOE 2.1A results.

The nineteen test runs that were performed are taken in several regions relative to the six runs used to determine the taylor series coefficients. The first eight comparisons are within the inner rectangle shown in Figure 4. The next three runs are within the larger rectangle and the last eight comparisons are outside the larger rectangle. For the eight comparisons within the inner rectangle, total energy use is always within one percent of the actual DOE 2.1A value. Heating and cooling energy use are each predicted to within 5% of the DOE 2.1A values with both the first or second order approximation. The first order approximation produces slightly better results in the inner rectangle.

The three test runs in the larger rectangle (see Fig.4) produce some cases with large errors in the prediction of heating and cooling energy use. Total energy use is still predicted with an accuracy of 1%. Using the first order approximation only, the error for heating and cooling energy use reaches a maximum of 7.7% in one of the three cases. If second order approximations are used, the maximum error is as large as 9.6%.

For the last eight runs shown in Table 8, we are attempting to predict energy use for parameters with values outside the larger rectangle. As expected, the accuracy of the model is not as good as it was for the earlier comparisons. Total energy use is predictable with an accuracy of 5%, but heating and cooling energy use are occasionally in error by 20% or more. The second order Taylor series approximation produces better results for this set of comparisons.

The predictive capability of the simplified model is very good for both heating and cooling energy use except for cases where the parametric deviation from the base case values is both large and in a direction opposite from that originally taken when the derivatives used in the Taylor series expansion were calculated. For example, the base case values of window to wall ratio (WWR) and glass solar transmission(GST) are 0.22 and 0.40 respectively, and a relatively large error(20% for heating and 4.5% for cooling energy use) results when both of these parameters are changed to 0.75. This is one of the worst cases as the deviations from the base case values are extremely large and the direction of movement from the base case values is opposite to that taken when the expansion coefficients were calculated (see Table 6). Additionally, for both parameters, 75% is near the maximum real - world value, and is obviously on the high energy use side. As can be seen from Table 8, as we move closer to the base case values for GST and WWR, there is a dramatic improvement in the accuracy with which heating and cooling energy use is predicted. For most of the test runs, the model prediction and the actual DOE 2.1A model simulations differ by less than ±5% for both heating and cooling energy use.

Aside from the model testing results shown in Table 8, we also compared actual DOE 2.1A runs to model predictions for the 55 two at a time simulations described in Table 6. The DOE 2.1A simulations and the model predictions differed by less than 15% in all cases for both heating and cooling energy use. In 51 out of 55 cases, the heating energy use differed from the actual DOE 2.1A runs by less than 10% and in only one case did the cooling energy use differ from the actual DOE 2.1A runs by more than 10%. The accuracy of our model can be improved by reducing the region of application of each pair of conservation measures. This requires application of the Taylor series expansion methodology to several regions rather than only one and, thus, entails additional DOE 2.1A runs. Other approaches to developing a predictive model are possible. For example, predictive equations can be derived by solving a large number of simultaneous linear equations.

Two hundred DOE 2.1A runs were required to perform our analyses. This includes both the single parameter and two parameter simulations that were necessary to complete the interaction matrix and calculate the Taylor series expansion coefficients.

7. CONCLUSIONS

The simplified methodology described in this paper appears to work well in the case tested; that is, for a mid sized office building in Denver. A Fortran program that is easy to use and fast running can be used to accurately predict (assuming one takes DOE 2.1A results as a measure of accuracy) heating, cooling, and total energy use as a function of eleven major building parameters. We plan to test the sensitivity of our results to changes in building base-case assumptions and in HVAC system type. In addition, we expect to determine the validity of this approach for other climate regions and building types. Finally, we need to compare the results obtained from our model which uses a prototypical base case building to the results of a DOE 2.1A simulation for a specific building.

There are several disadvantages of the simplified energy use model we have described. A separate model is required for each building type, each HVAC system type and each climate type to be studied. Furthermore, a different prototypical building may be needed for retrofit and new design considerations. Nevertheless, this approach should prove very useful where repetitive energy analyses are required for generic building types, as they are in electric energy end use forecasting or in retrofit program evaluations. The ability of this model to predict peak power use remains to be tested. In the commercial sector, approximately 75% of energy use is concentrated in about four building types* and energy use in these buildings is not as dependent on weather as in residential buildings.[5] Therefore, analysis of four building types in four or five climates may be sufficient to analyze the majority of commercial buildings.[6]

This methodology is not suited to energy analyses for specific buildings, but is accurate for buildings with characteristics similar to the base-case building. Its main advantages are simplicity, low cost, and fast running time. Rapid answers to questions involving energy impacts of gross changes in building design can be obtained at the early design or retrofit stage for new or existing commercial buildings respectively.

*office, retail, educational and health.

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Table 1

BASE CASE VALUES FOR LARGE OFFICE BUILDINGS

LOCATION AND ORIENTATION

City: Denver
Size: 72′ x 232′ (6 stories)
Orientation: Long Axis points 60° east of north
Ground Reflectance: .20

MATERIALS

Average Mass Density: 62 lb/sq.ft.
Walls:

External: 4" heavy weight concrete, R9 polystyrene insulation 5/8" gypsum board. Total R=9.5

Internal: 5/8" gypsum board, 4" air layer, 5/8" gypsum board. Total R=2.7

Roof: 0.5 "roof gravel, 3/8" built up roofing, R15 polystyrene insulation, 6" heavy weight concrete, 4" air layer, 0.5" acoustic tile. Total R=19

Ground Floor: R24 fiberglass batt insulation, 6" heavy weight concrete, 3-1/4" light weight concrete, carpet with fibrous pad. Total R=30

Solar Absorptivity:

Walls: .65
Roof: .30

WINDOWS AND LIGHTING

Glass Solar Transmission: .40
Glass Conductance: .574 Btu/hr.sq.ft. °F (double glazing)
Window-to-wall Ratio: 22%
Window Shading Setback/Window Height: .125 (1 foot setback)
Heat of Lights to Space: .50
Lighting Power: 2.5 W/sq.ft.
Infiltration: .6 air changes/hour

SYSTEMS

Outside Air/Person: 7 cfm/person
Thermostat Setpoints:
Heating: 72°F
Cooling: 78°F
Night Setback:
Heating: 60°F
Cooling: 99°F
Economizer: None

Table 2.
LARGE OFFICE BUILDINGS: SCHEDULES

MONDAY - FRIDAY

Hour	Inf.	Occ.	Light	Heat	Cool	Fans
1.5	1	0	.05	60	99	0
6	1	0	.10	60	99	0
7	0	.10	.10	72	78	1
8		.20	.30			
9-12		.95	.90			
13		.50	.80			
14-17		.95	.90			
18	0	.30	.50	72	78	1
19	1	.10	.30	60	99	0
20			.30			
21			.20			
22		.10	.20			
23		.05	.10			
24	1	.05	.05	60	99	0

SATURDAY

Hour	Inf.	Occ.	Light	Heat	Cool	Fans
1-5	1	0	.05	60	99	0
6		0	.05			
7		.10	.10			
8		.10	.10			
9-12		.30	.30			
13-17		.10	.15			
18		.05	.05			
19		.05	.05			
20-24	1	0	.05	60	99	0

SUNDAY

Hour	Inf.	Occ.	Light	Heat	Cool	Fans
1-6	1	0	.05	60	99	0
7-18		.05				
19-24	1	0	.05	60	99	0

Table 3. Parametric Equations. Total Energy Use as a Function of Building Parameters

Parameter	Range	Functional Form	Fitted Equation
Roof Insulation RR	R0 to R50	Asymptotic	$E = 1513(3.22+RR)^{-1} + 4868$
Wall Insulation RW	R0 to R50	Asymptotic	$E = 2219(1.52+RW)^{-1} + 4695$
Window to Wall Ratio WWR	0 to 1.0	Linear	$E = 4999 + 1598.9(WWR - .22)$
Glass Solar Transmission GST	0 to 1.0	Quadratic	$E = 4977 + 112.7(GST-.4) + 592.1\ (GST- .4)^2$
Glass Conductance GC	0.5 to 1.5 Btu/h.ft^2°F	Linear	$E = 4952 + 511.6(GC - .574)$
Lighting Power LIT	0 to 3.5 (W/ft^2	Exponential	$E = e^{(8.51 + .20(LIT - 2.5))}$
Heat of Lights to Space LS	0 to 1.0	4th order polynomial	$E = 4965- 79.6(LS-.5) + 785.9(LS-.5)^2 - 1414.6\ (LS-.5)^3 + 738.5\ (LS-.5)^4$
Outside Air OA	3 to 11 cfm/person	Quadratic	$E = 4968 + 61.1(OA-7) + 5.5(OA-7)^2$
Heating Setpoint TH	66 to 74°F	Linear	$E = 4976 + 31.0(TH-72)$
Cooling Setpoint TC	76 to 84°F	Linear	$E = 4974 - 42.6(TC-78)$
Night Thermostat THS	50 to 70°F	Quadratic	$E = 4963 + 56.6\ (THS-60) + 2.4\ (THS-60)^2$

Table 4.

PARAMETRIC EQUATIONS FOR HEATING AND COOLING

Parameter	Notes	Functional Form	Fitted Equation
Roof Insulation Heating		Asymtotic	$E_H=1507.65(3.22+R)^{-1} + 800.63$
Roof Insulation Cooling		Linear	$E_C=6(RR+3.22)/5 + 621.14$
Wall Insulation Heating	R3 to R19 only	Asymtotic	$E_H=2682/(1.52+RW) + 609.3$
Wall Insulation Cooling		Linear	$E_C=618 + 4.26\ RW$
Window to Wall Ratio - Heating		Linear	$E_H=755.16 + 671.65\ WWR$
Window to Wall Ratio - Cooling		Linear	$E_C=536.16 + 611.65\ WWR$
Glass Solar Transmission - Heating		Linear	$E_H=1110.8 - 468.1\ GST$
Glass Solar Transmission - Cooling		Linear	$E_C=448.8 + 607.7\ GST$
Glass Conductance Heating		Quadratic	$EH=487.6+791.2GC-132(GC)^2$
Glass Conductance Cooling		Quadratic	$E_C=789.4-280.3GC+98.9GC^2$
Lighting Heating		Linear	$E_H=1732 - 347.1(LIT)$
Lighting		Linear	$E_{Light}= +979.4(LIT)$
Lighting Cooling		Linear	$E_C=217.35+169.8(LIT)$
Outside Air Heating		Quadratic	$E_H+374.4+58.4(0A)+2.4(0A)^2$
Outside Air Cooling		Quadratic	$E_C=1042.5-76.2(0A)+3.1(0A)^2$
Heat of Lights to Space - Heating		3rd order polynomial	$E_H=1764-2874.2LS+2731.3LS^2-892.5LS^3$
Heat of Lights to Space - Cooling		3rd degree polynomial	$E_C=234.66+816.40LS+313.61S^2-516.9LS^3$
Heating Setpoint Heating		Linear	$E_H=-997.0+26.4TH$
Heating Setpoint Cooling		Linear	$E_C=138.2+7.3TH$
Cooling Setpoint Heating		Linear	$E_H743.6+2.05TC$
Cooling Setpoint Cooling		Quadratic	$E_C10,941-219.55TC+1.12TC^2$
Night Thermostat Setback - Heating		3rd degree polynomial	$E_H-3853.6+275.3THS-5.95THS^2+.0447THS^3$
Night Thermostat Setback - Cooling		2nd degree polynomial	$EC=1440.8-29.1THS+.268THS^2$

Table 5. Coefficients of Elasticity for Heating and Cooling

Parameter	Range	Heating*	Cooling*
Roof Insulation	R0 → R30	0.0 to -0.05 minimum at R4 = -0.11	0.0 to 0.5
Wall Insulation	R3 → R19	-0.33 to -0.16 minimum at R3	0.02 to 0.12
Window-to-Wall Ratio	.25 → .75	0.18 to 0.40	0.22 to 0.46
Glass Solar Transmission	.25 → .75	-0.12 to -0.46	0.25 to 0.50
Glass Conductance	0.30 → 1.5 Btu/h.ft.^{2o}F	0.30 to 0.43	-0.10 to 0.04
Lighting Power	1.5 → 3.5 W/ft^2	-0.43 to -2.35	0.54 to 0.73
Heat of Lights to Space	.25 → 1.0	-1.39 to -0.12	.49 to -0.13
Outside Air	5.0 → 9.0 cfm/person	0.57 to 0.835	-.30
Heating Setpoint	68 → 78°F	2.25 to 2.0	0.78 to 1.25
Cooling Setpoint	74 → 82°F	.175	-4.62 to -5.78
Night Thermostat Setback	70 → 50°F	4.34 to 1.72	0.82 to -0.18

*Except as indicated, elasticities are monotonic over the indicated range.

Table 6.
Parameters Varied and their Values
For Interactions Analysis, Large Office Buildings

Parameter	Base Case Values	Interaction Values
Roof Insulation R Value RR	15	30
Wall Insulation R Value RW	8	16
Window to Wall Ratio WWR	.22	.11
Glass Solar Transmission GST	.40	.25
Glass Conductance $Btu/h.ft^2 {}^oF$ GC	.574	.30
Lighting Power (W/ft^2) LIT	2.5	1.5
Heat of Lights to Space LS	.50	.75
Outside Air cfm/person OA	7	5
Heating Setpoint (^oF) TH	72	68
Cooling Setpoint (^oF) TC	78	82
Night Thermostat Setback (^oF) THS	60	55

Table 7. Interaction* Matrix
Decreasing Energy Use Relative
to Base Case Heat Pump System
Large Office Building Denver

	Wall R Value RW (16)	Window to Wall Ratio (WWR (.10)	Glass Solar Transmission GST (.25)	Glass Conductance GC (.3)	Lighting Power LIT (1.5)	Heat of Lights to Space LS (.75)	Outside Air OA (5)	Heating Setpoint TH (68)	Cooling Setpoint TC (82)	Heating Setpoint Setback THS (55)
Wall R Value RW (16)	—	-10%	-12%	+2%	-3%	+17%	+4%	-16%	-3%	+5%
Window to Wall Ratio (WWR (.10)	-10%	—	-34%	+27%	+3%	-10%	-1%	-13%	+6%	+6%
Glass Solar Transmission GST (.25)	-12%	-34%	—	-17%	+5%	-165%	-17%	-36%	-12%	+4%
Glass Conductance GC (.3)	+2%	+27%	-17%	—	-4%	+9%	+8%	-13%	-4%	+5%
Lighting Power LIT (1.5)	-3%	+3%	+5%	-4%	—	-6	-6%	-5%	+5	-2%
Heat of Lights to Space LS (.75)	+17%	-10%	-165%	+9%	-6%	—	+45%	-35%	-20%	+4%
Outside Air OA (5)	+4%	-1%	-17%	+8%	-6%	+45%	—	-14%	-7%	+9%
Heating Setpoint TH (68)	-16%	-13%	-36%	-13%	-5%	-35%	-14%	—	-10%	-17%
Cooling Setpoint TC (82)	-3%	+6%	-12%	-4%	+5%	-20%	-7%	-10%	—	+3%
Heating Setpoint Setback THS (55)	+5%	+6%	+4%	+5%	-2%	+4%	+9%	-17%	+3%	—

*The interaction term is a measure of the difference between two methods of determining energy use reductions when two parameters are varied simultaneously. The two methods are: (1) addition of the results obtained when one parameter only is varied followed by base case energy subtraction for each run and (2) subtraction of base case energy use from result obtained with simultaneous alterations for both parameters. Negative percentages indicate that method (1) underestimates the energy savings relative to method (2).

Table 8. Summary of Predictive Capability of Simplified Energy Use Model

Parametric		Total Energy Use					Heating Energy Use					Cooling Energy Use				
		DOE 2.1A Results MBtu	Model Prediction		% Difference		DOE 2.1A Results MBtu	Model Prediction		% Difference		DOE 2.1A Results MBtu	Model Prediction		% Difference	
			1st Order	2nd Order	1st Order	2nd Order		1st Order	2nd Order	1st Order	2nd Order		1st Order	2nd Order	1st Order	2nd Order
WWR = .16	GC = .43	4809	4797	4819	<1	<1	787	764	784	2.9	<1	639	651	647	1.9	1
WWR = .16	LIT = 2.0	4417	4432	4460	<1	1	993	1002	1018	1.0	2.5	518	523	531	1.0	2.5
LIT = 2.0	TC = 80	4433	4446	4469	<1	<1	1038	1049	1060	1.0	2.0	478	478	499	0.0	4.4
THS = 57	TH = 70	4752	4795	4784	1.0	<1	724	742	749	2.5	3.5	641	644	645	<1	<1
RR = 22	RW = 12	4853	4881	4892	<1	<1	779	809	815	4.0	4.6	683	673	654	1.5	4.2
RW = 12	WWR = .16	4782	4816	4819	<1	<1	763	790	797	3.5	4.5	640	634	633	1.0	1.0
GST = .33	GC = .40	4851	4869	4866	<1	<1	816	823	813	1.0	<1	646	656	659	1.5	1.0
LIT = 2.0	LS = .62	4485	4524	4527	<1	<1	955	980	1003	2.6	5.0	612	626	605	1.6	1.0
RW = 19	TC = 80	4734	4722	4772	<1	<1	737	719	808	2.4	9.6	608	603	593	<1	2.5
WWR = .10	GST = .25	4804	4792	4833	<1	<1	859	897	863	4.4	<1	557	514	564	7.7	1
GST = .25	GC = .23	4741	4776	4761	<1	<1	734	755	713	3.0	3.0	632	645	655	2.0	5
LIT = .5	GC = .23	3032	2991	3157	1.4	4.1	1265	1250	1307	1.2	3.3	327	309	403	5.5	23
LIT = .25	LS = .75	3124	2970	3172	5.0	1.5	1632	1415	1687	13.3	3.4	275	339	267	23.3	3
RW = 3	WWR = .25	5281	5086	5094	3.7	3.5	1203	1004	1020	16.5	15	639	669	666	4.7	4
GST = .75	RW = 11	5054	4912	5024	2.8	1	684	659	679	3.7	<1	919	844	868	8.2	5.5
RW = 11	OA = 9	5047	5023	5053	<1	<1	1021	1024	1040	<1	2.0	624	593	608	5.0	2.5
WWR = .60	GST = .45	5673	5520	5665	2.7	<1	1110	1135	1135	2.2	2.2	996	911	987	8.5	1
WWR = .50	GST = .50	5552	5373	5469	3.2	1.5	1011	1038	1001	2.7	1.0	993	877	963	11.7	3
WWR = .75	GST = .75	6516	5734	6194	12.0	5	947	1076	761	13.7	20	1754	1152	1676	34.3	4.5

SIMPLIFIED ENERGY USE MODEL FOR COMMERCIAL BUILDINGS

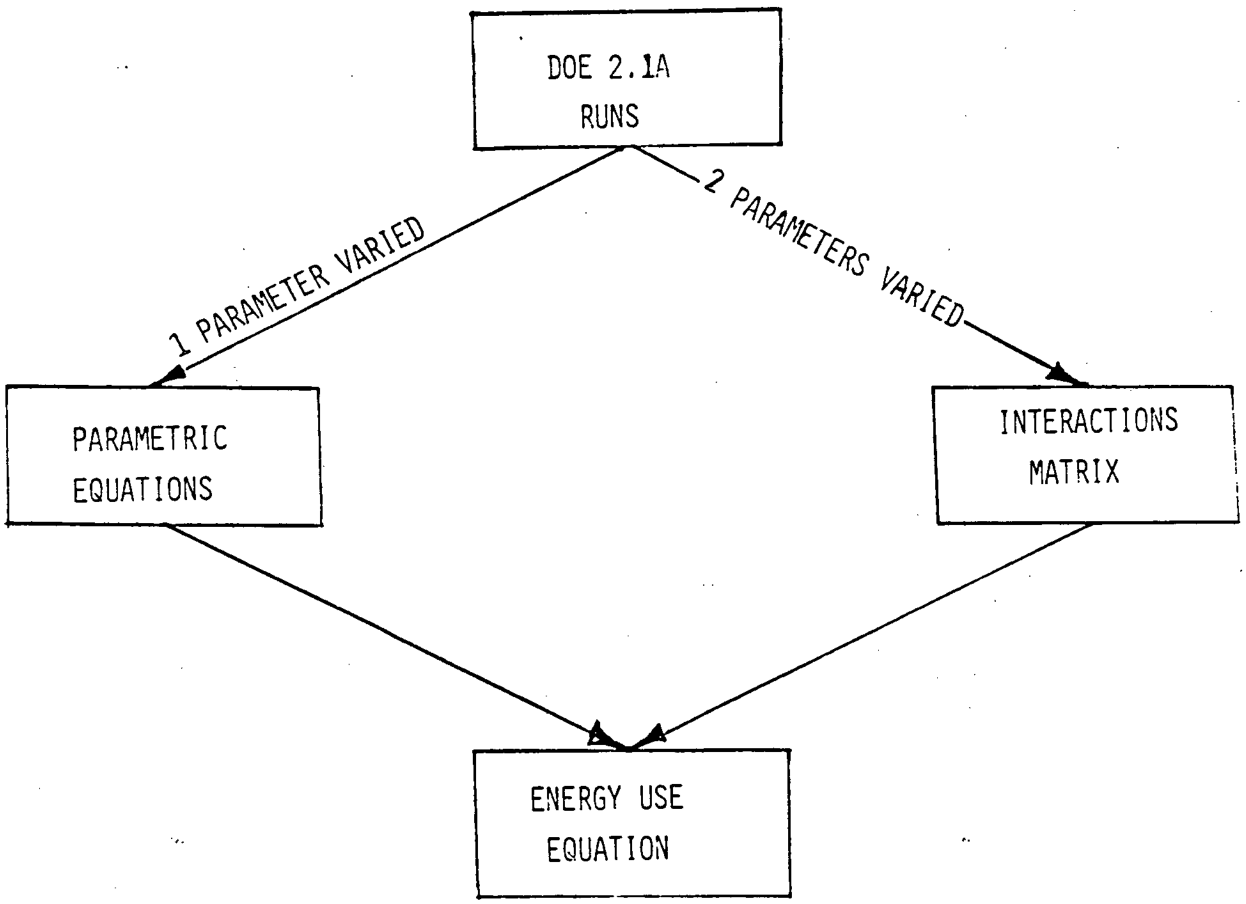

Figure 1: Schematic diagram shows method for arriving at a simplified energy use equation.

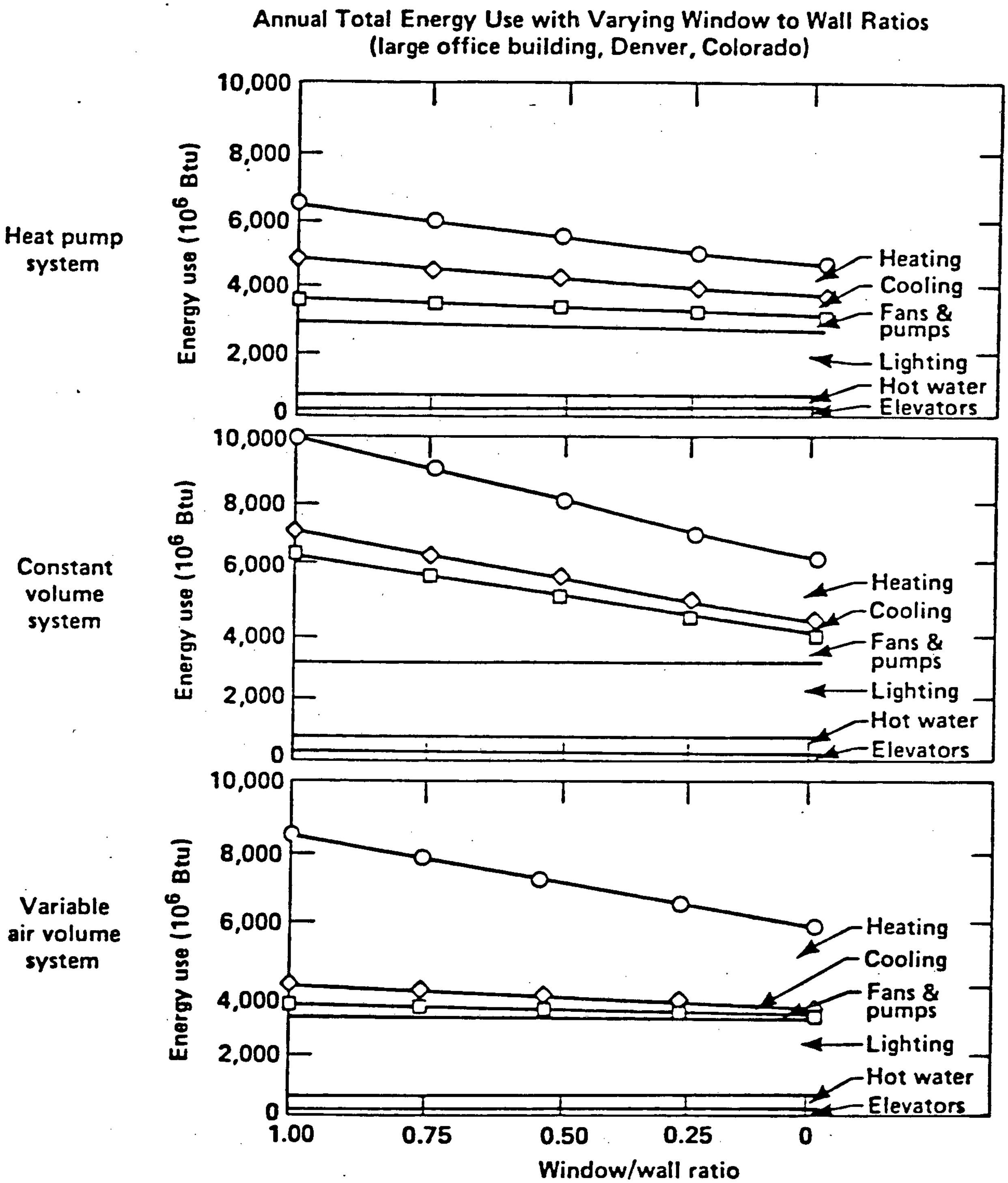

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Fig. 2 Annual energy use is shown for three HVAC system types as a function of window-to-wall ratio.

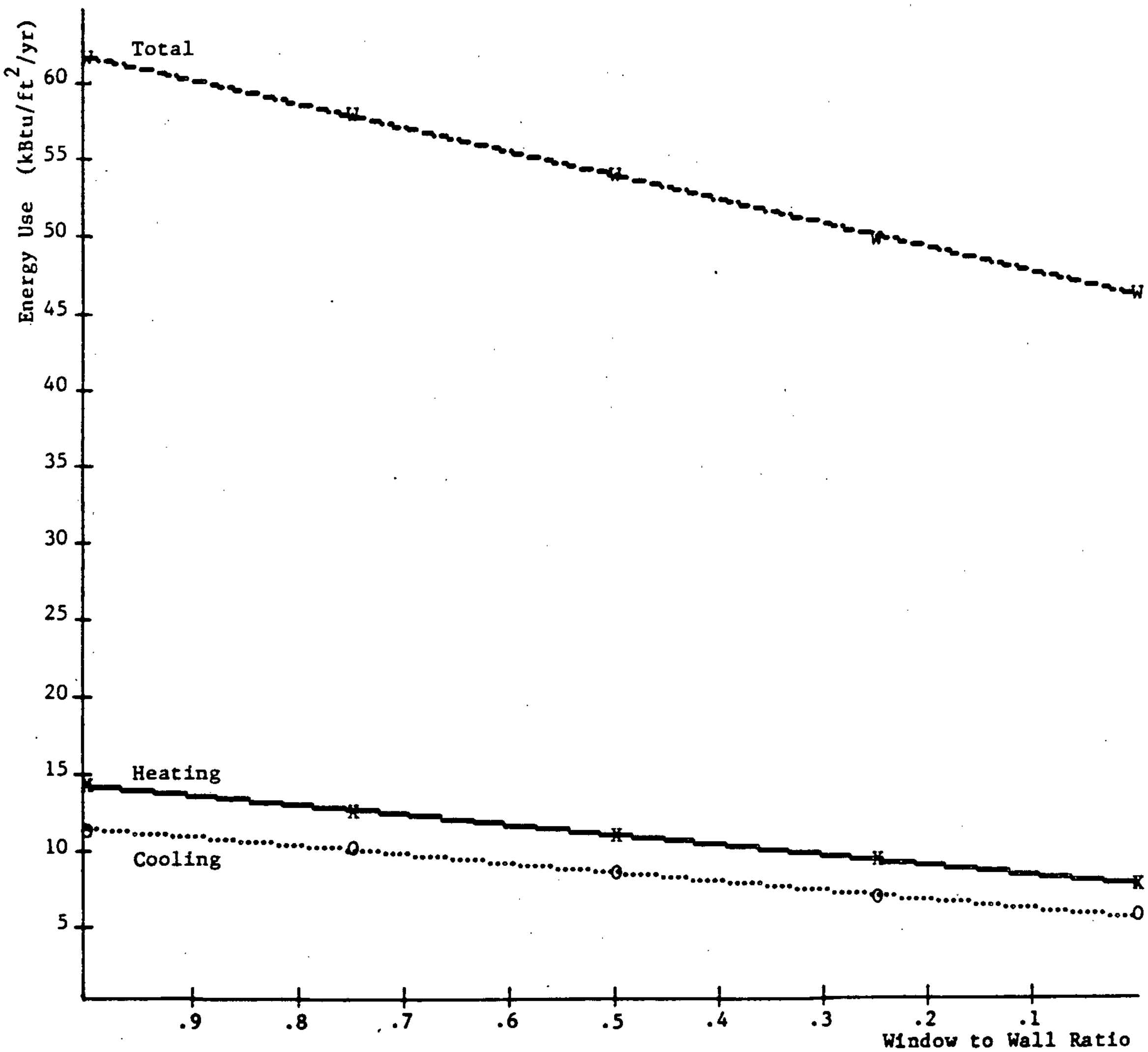


Figure 3: Heating, cooling and total building energy use (KBtu/ft^2/yr) is plotted as a function of window to wall ratio.

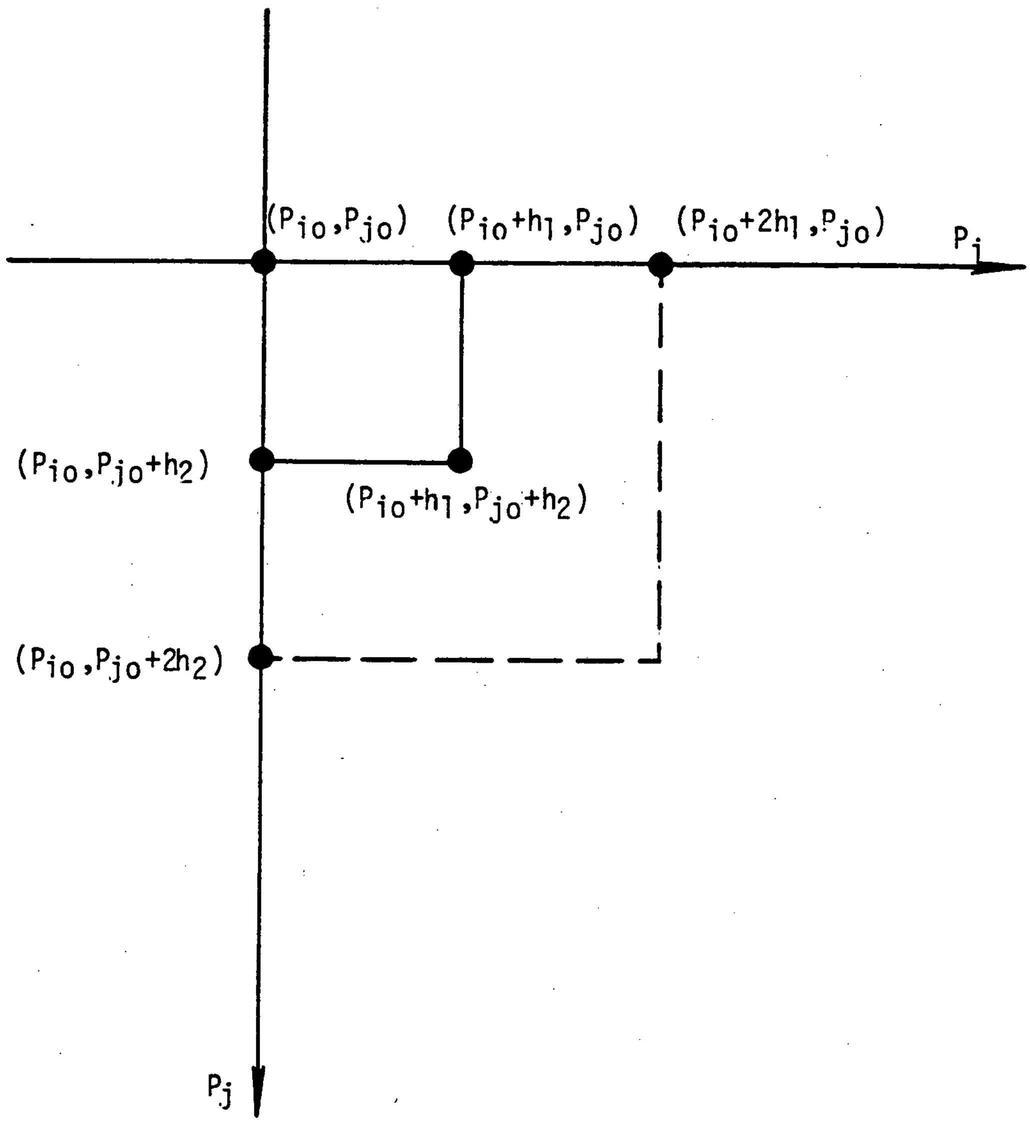
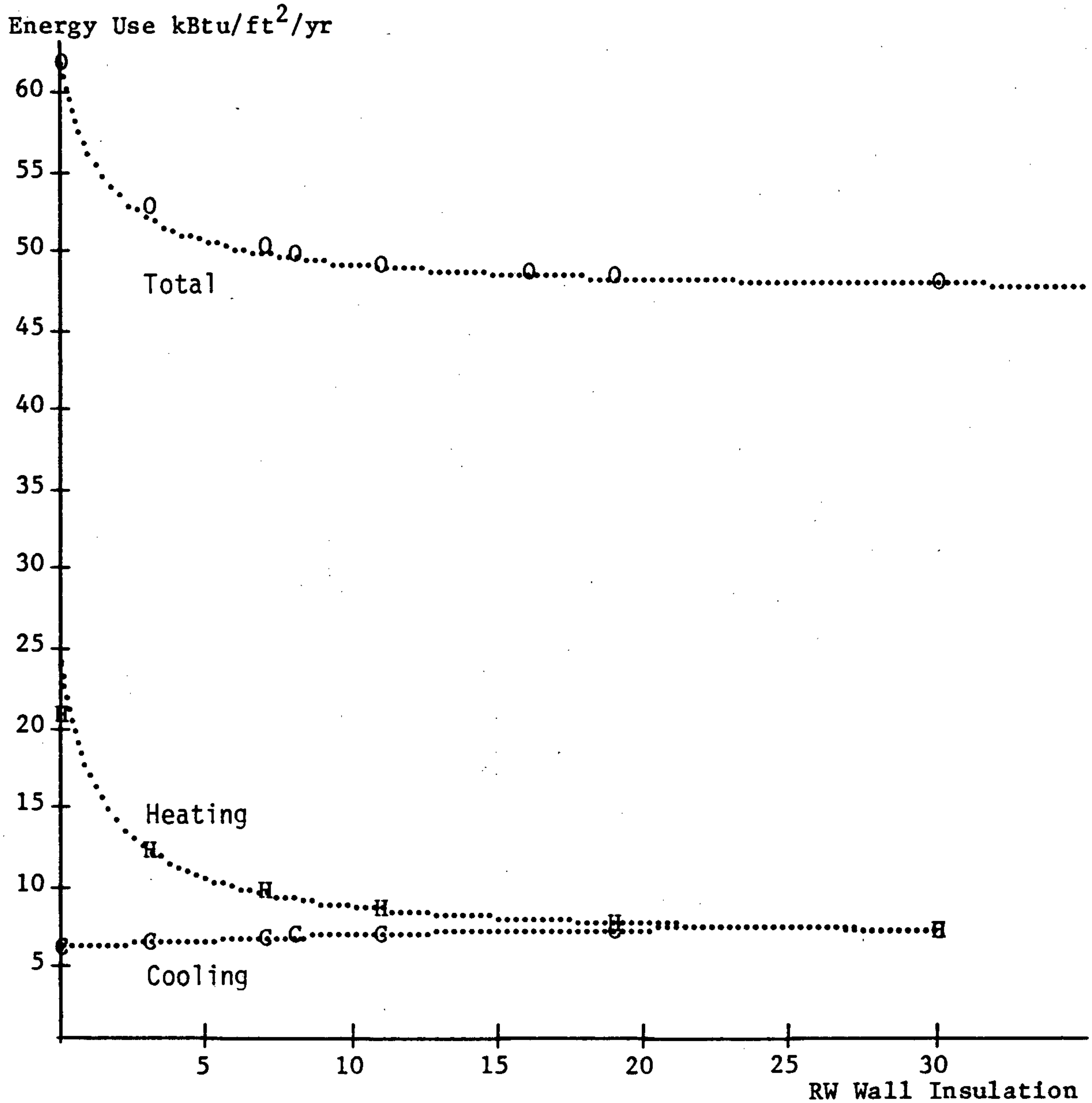
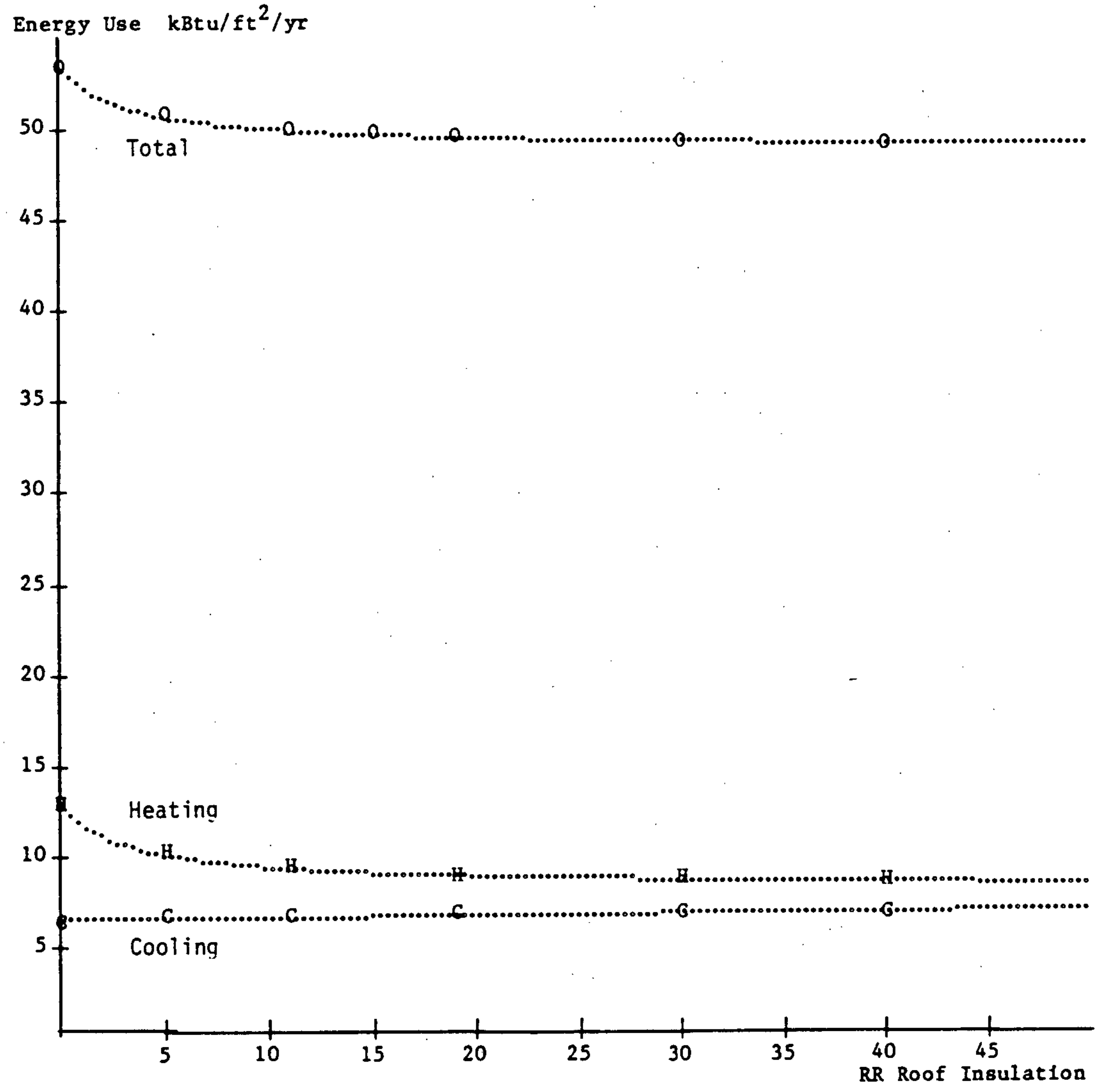
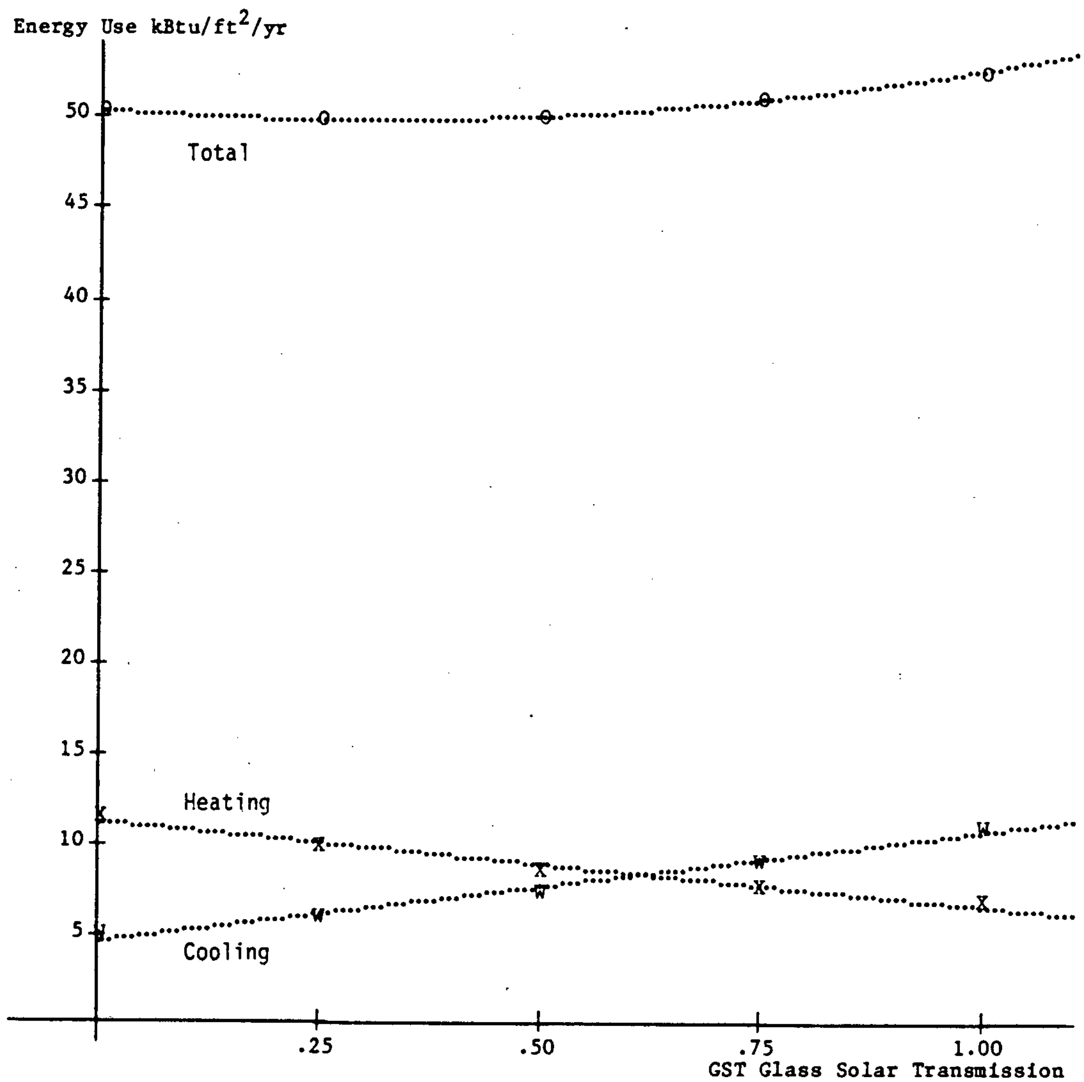


Fig. 4 The inner rectangle (solid lines) and outer rectangle (dashed lines) enclose two of the regions in which the simplified energy analysis model was tested.

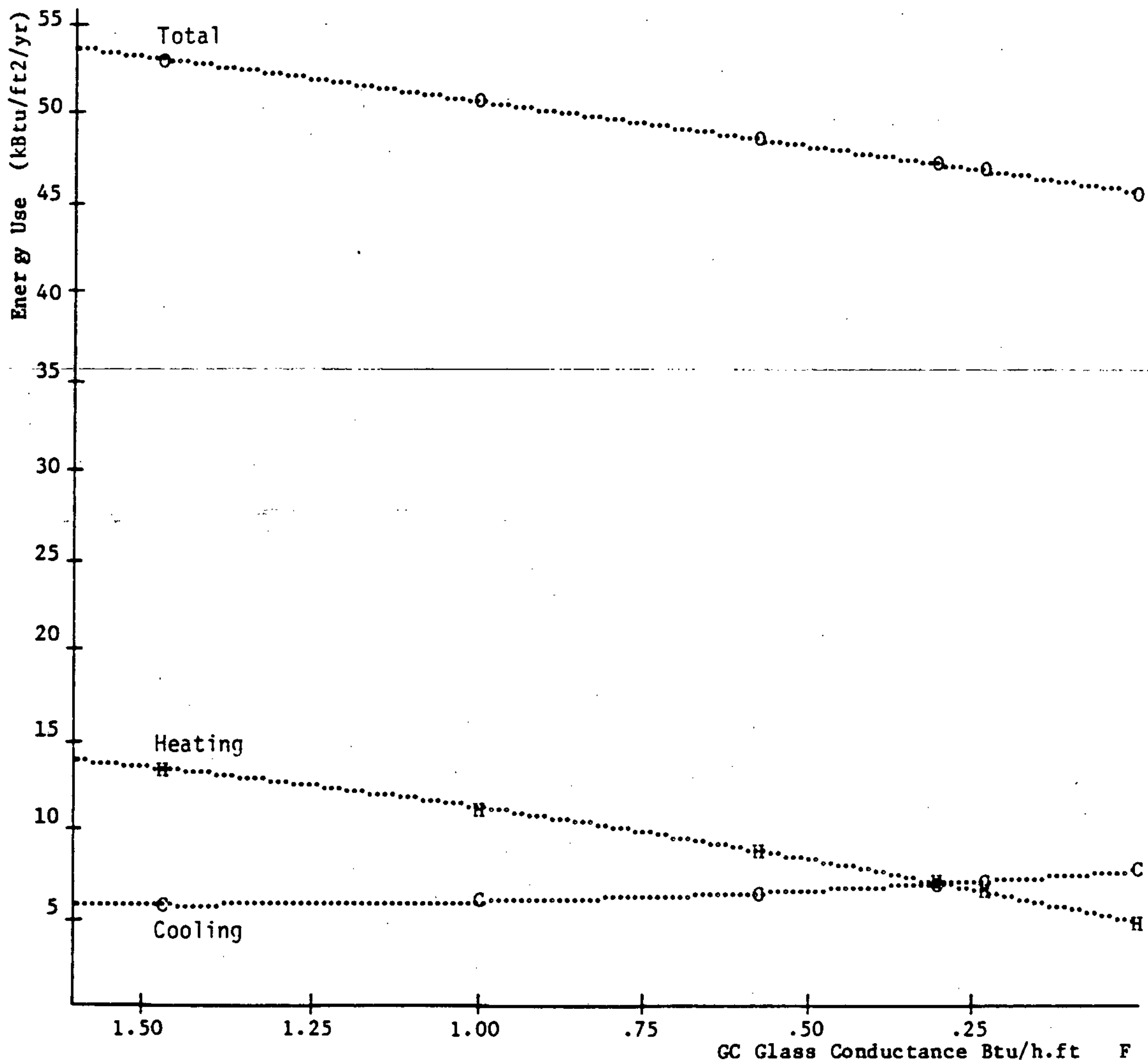

Energy Use kBtu/ft2/yr
60
55
50
45
40
35
30
25
20
15
10
5
Total
Heating
Cooling
5
10
15
20
25
30
RW Wall Insulation

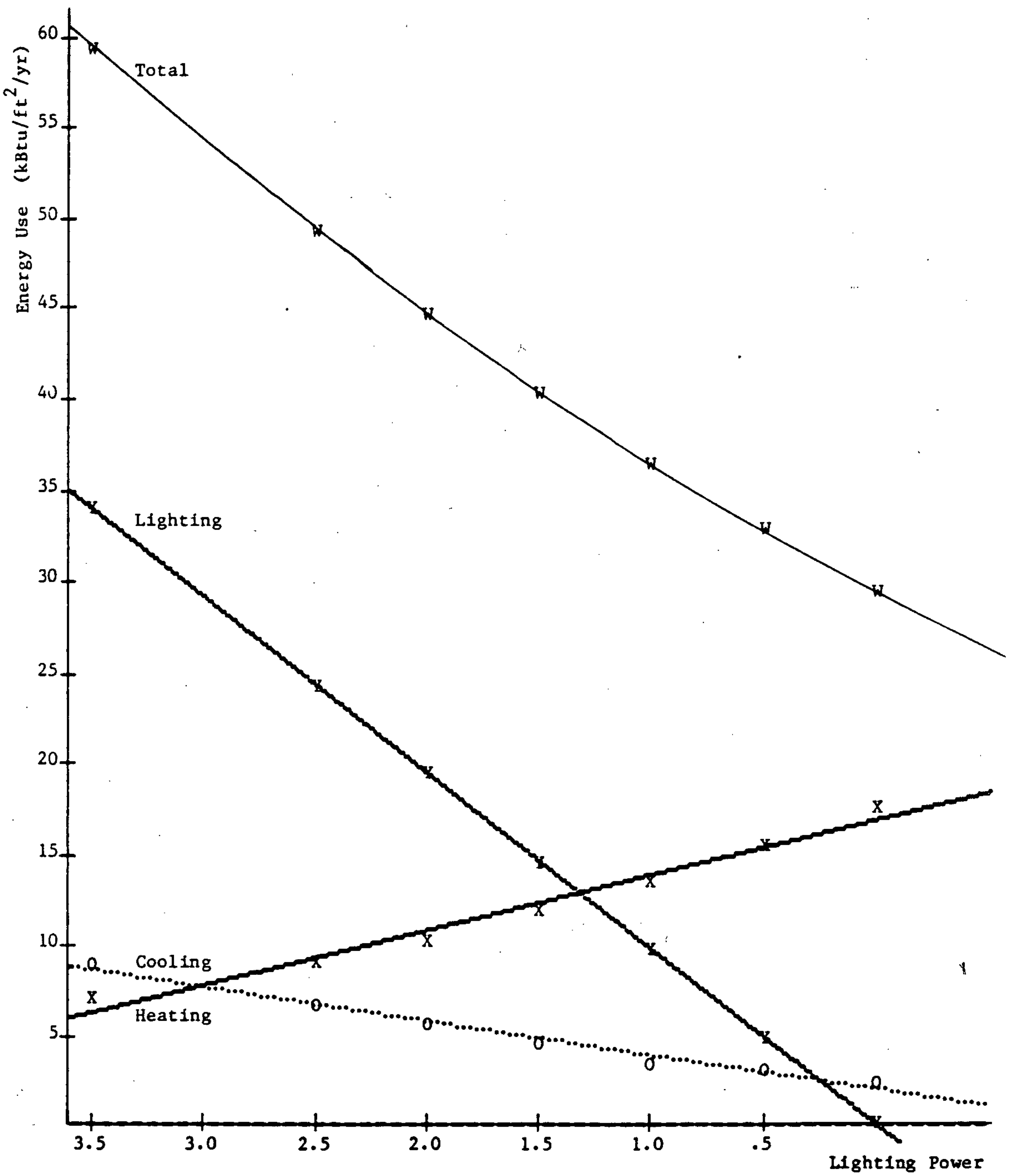


Energy Use kBtu/ft2/yr
50
45
40
35
30
25
20
15
10
5
Total
Heating
Cooling
5
10
15
20
25
30
35
40
45
RR Roof Insulation

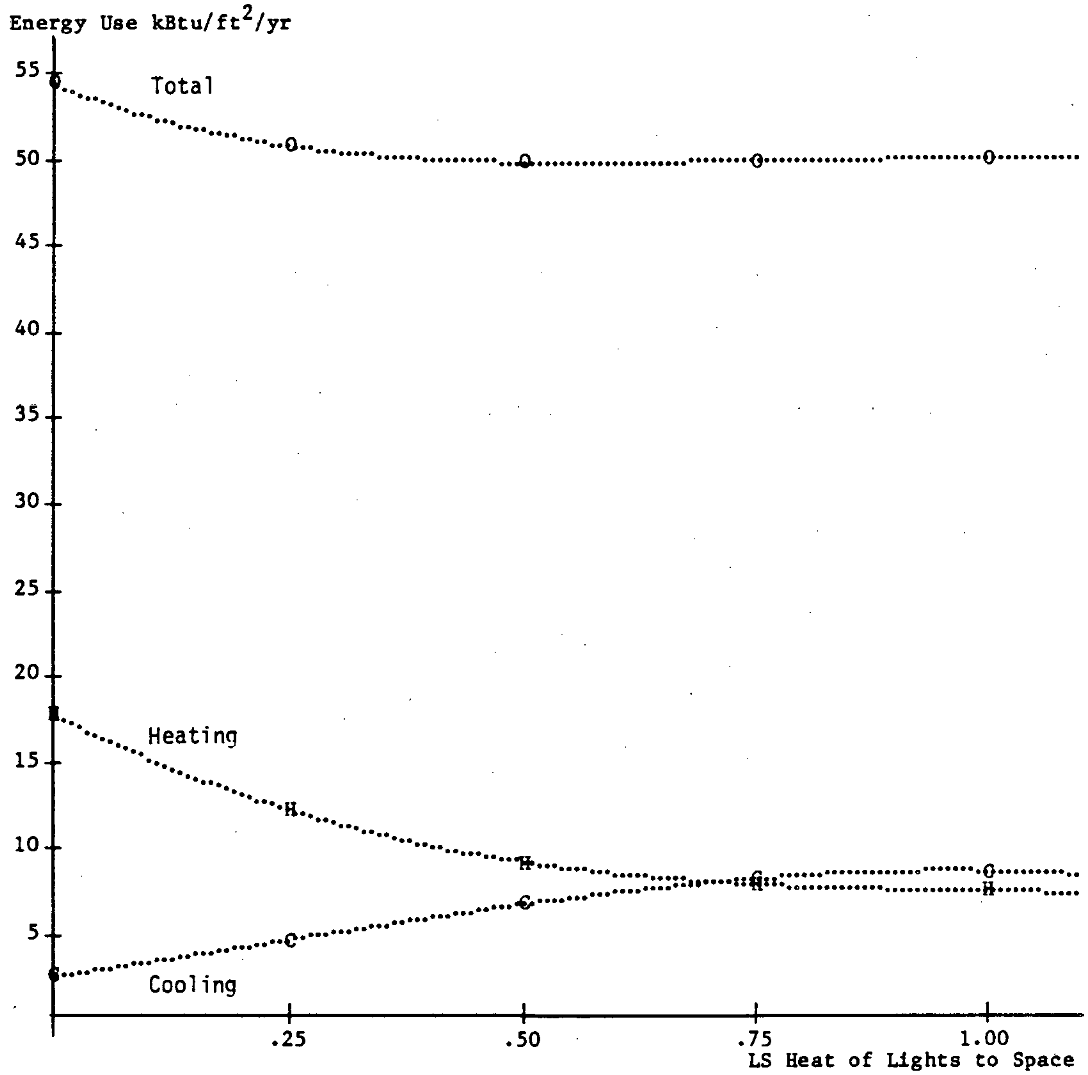


Energy Use kBtu/ft2/yr
50
45
40
35
30
25
20
15
10
5
Total
Heating
Cooling
.25
.50
.75
1.00
GST Glass Solar Transmission

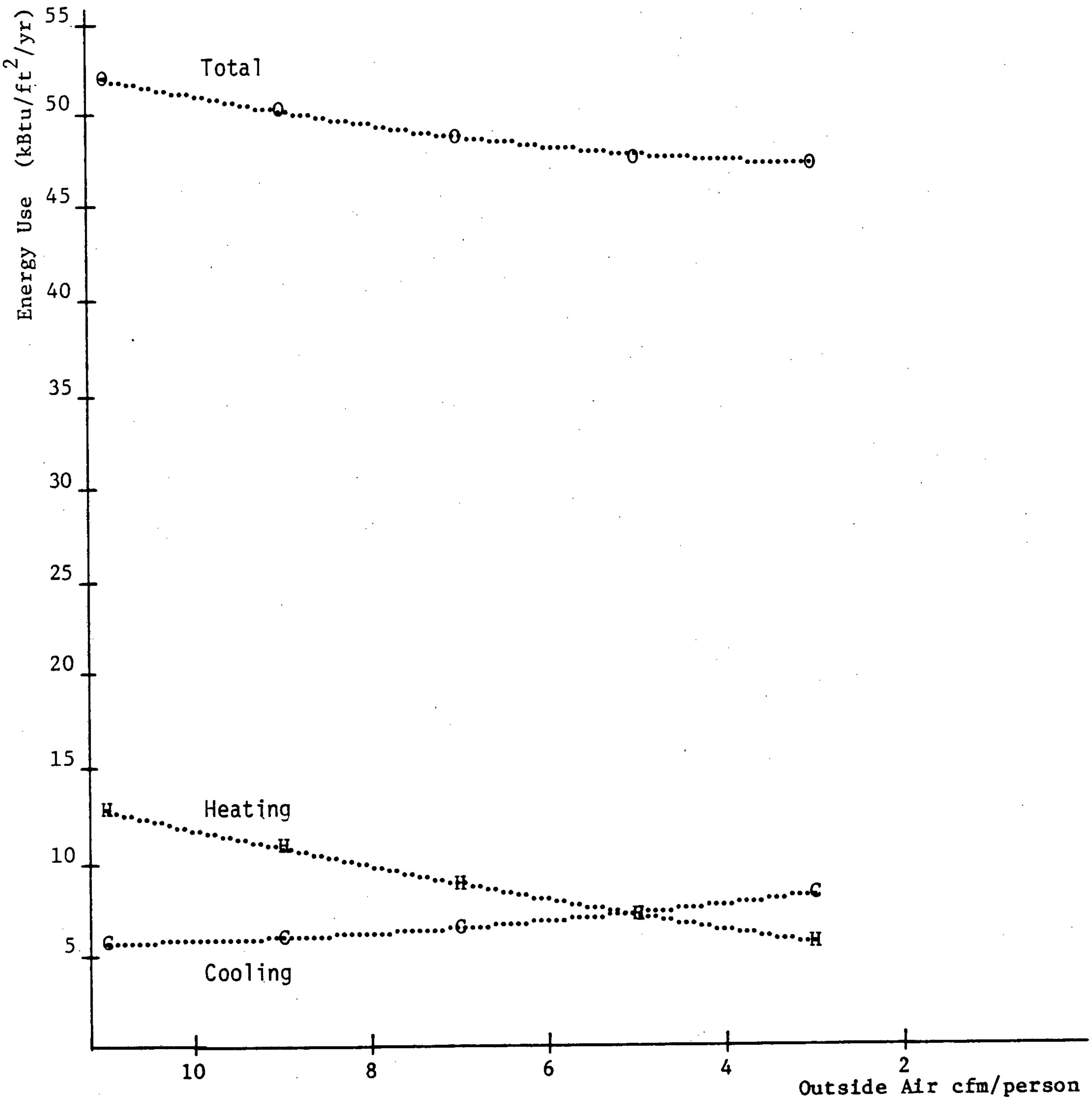

Energy Use (kBtu/ft2/yr)
55
50
45
40
35
30
25
20
15
10
5
Total
Heating
Cooling
1.50
1.25
1.00
.75
.50
.25
GC Glass Conductance Btu/h.ft F



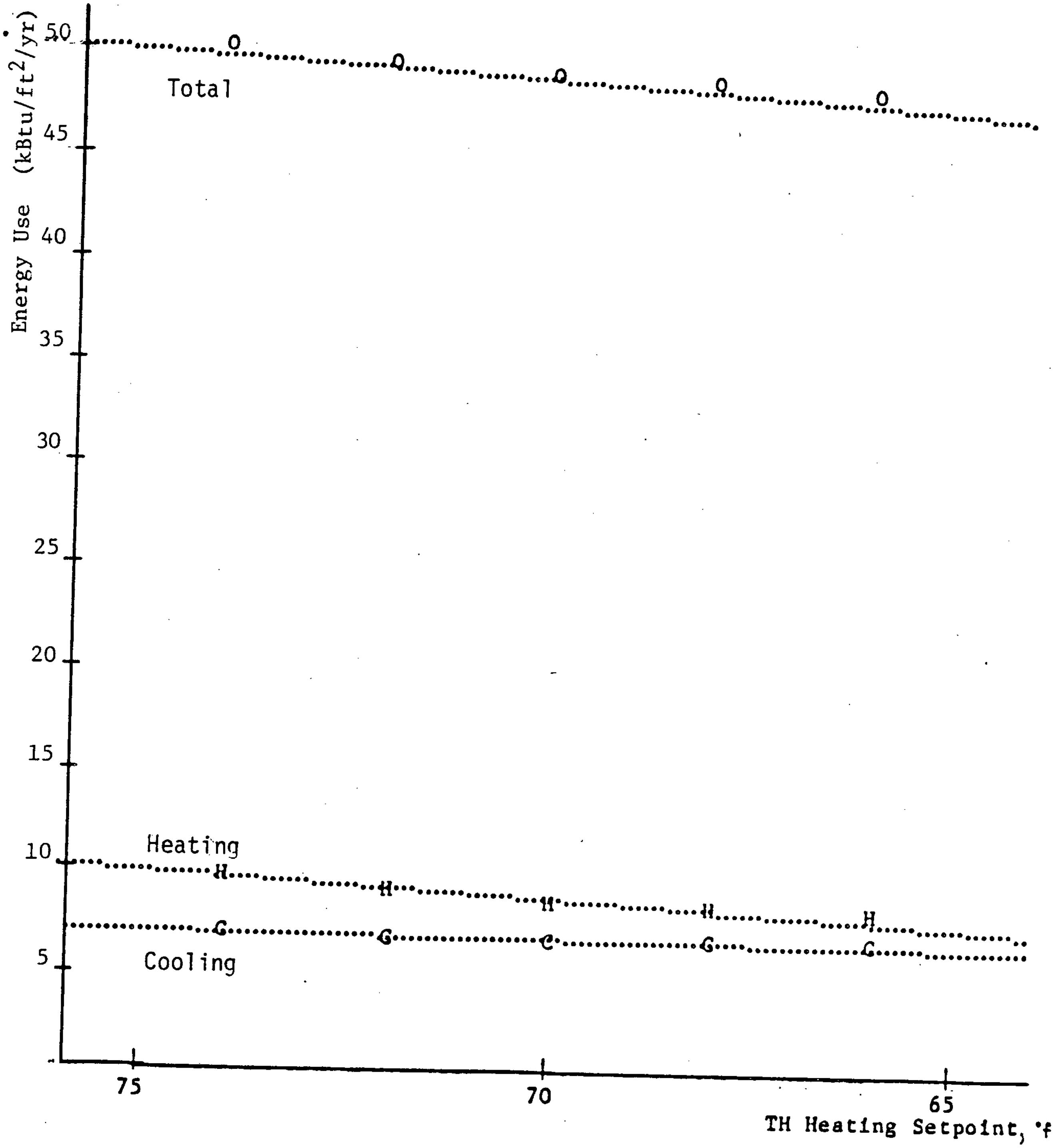
Energy Use (kBtu/ft²/yr)
60
55
50
45
40
35
30
25
20
15
10
5
Total
Lighting
Cooling
Heating
3.5
3.0
2.5
2.0
1.5
1.0
.5
Lighting Power

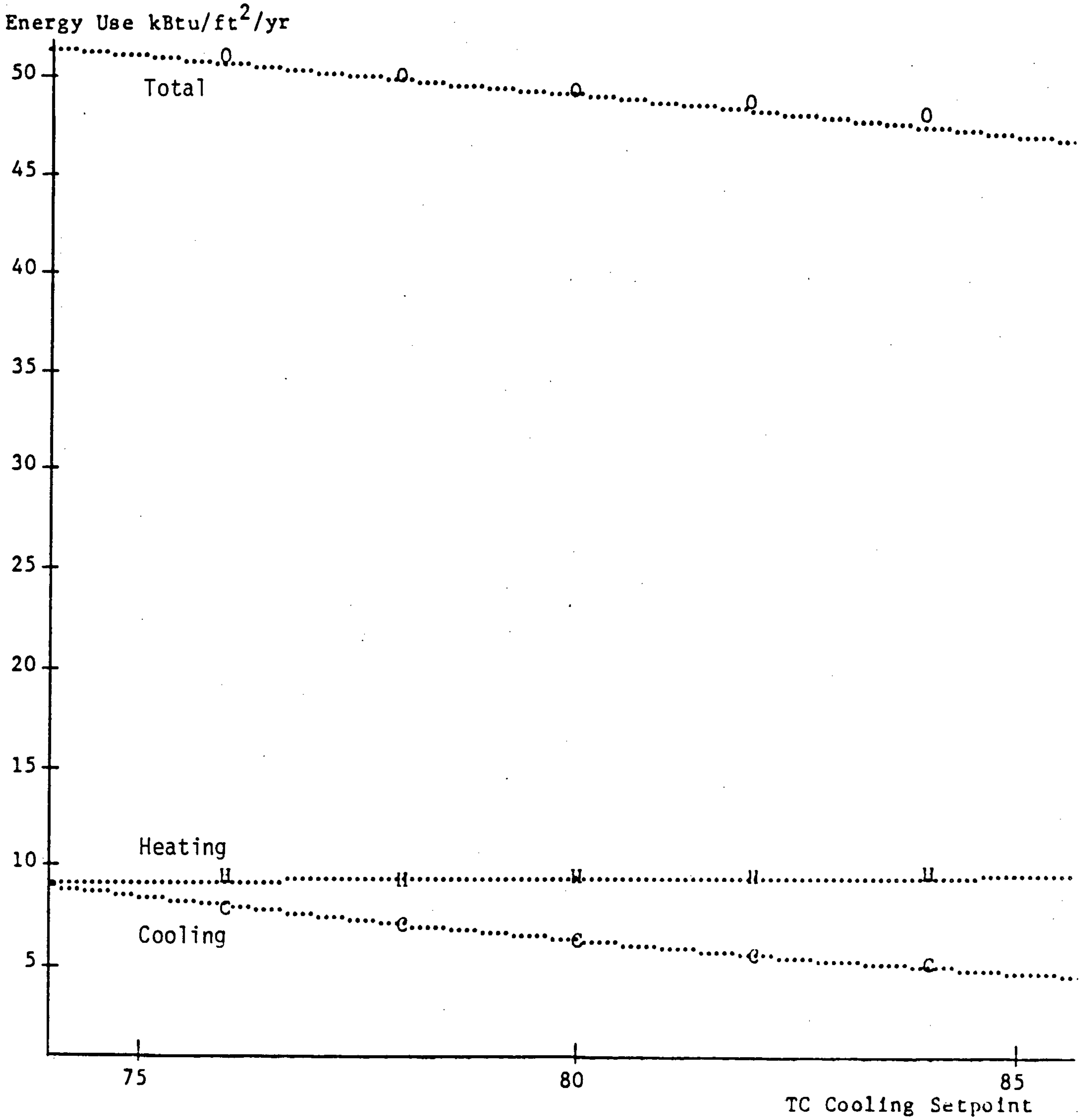


Energy Use kBtu/ft2/yr
55
50
45
40
35
30
25
20
15
10
5
Total
Heating
Cooling
.25
.50
.75
1.00
LS Heat of Lights to Space

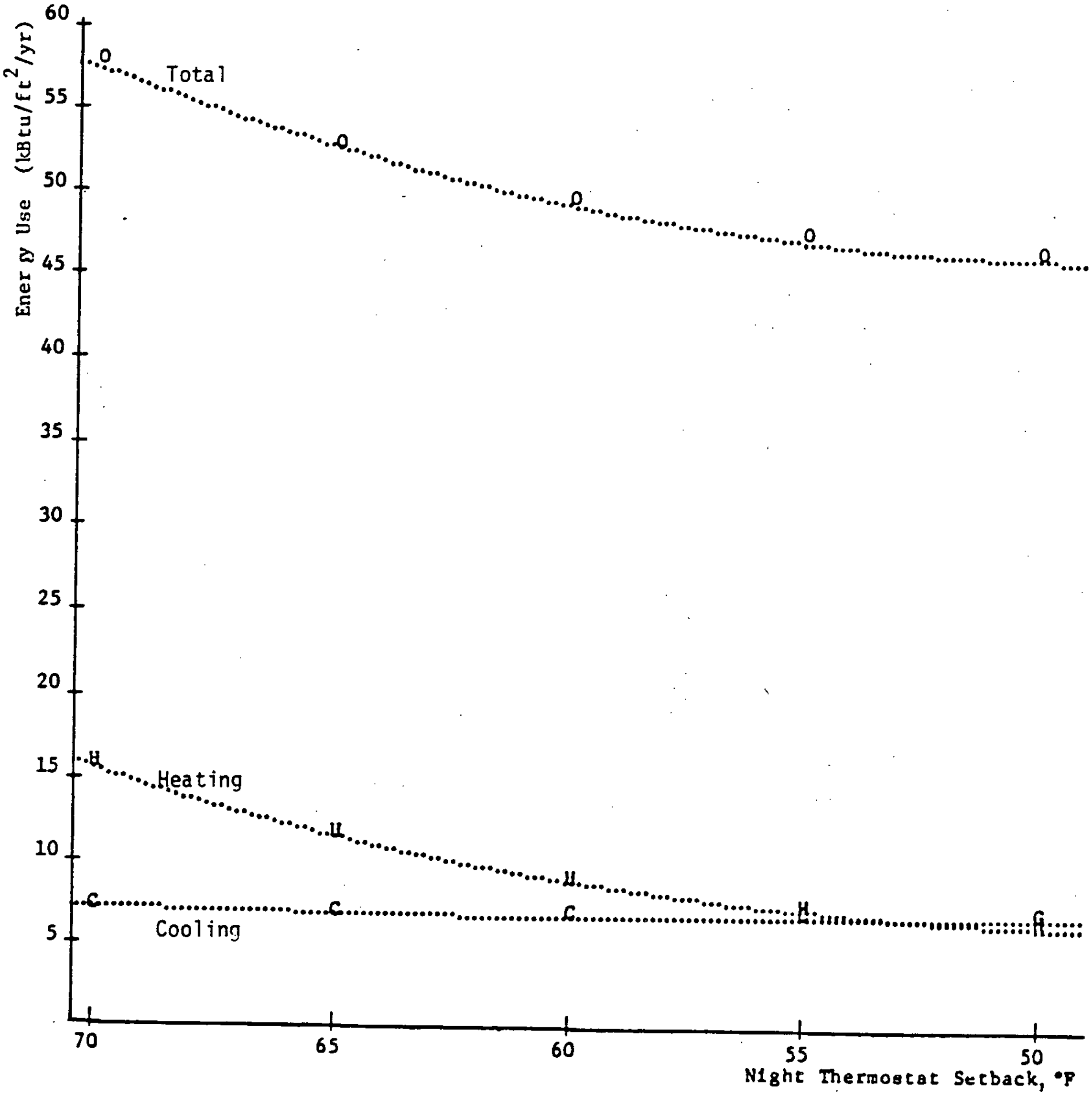


Energy Use (kBtu/ft^2/yr)
55
50
45
40
35
30
25
20
15
10
5
Total
Heating
Cooling
10
8
6
4
2
Outside Air cfm/person


Energy Use (kBtu/ft²/yr)
50
45
40
35
30
25
20
15
10
5
Total
Heating
Cooling
75
70
65
TH Heating Setpoint, °F



Energy Use kBtu/ft2/yr
50
45
40
35
30
25
20
15
10
5
Total
Heating
Cooling
75
80
85
TC Cooling Setpoint


60
55
50
45
40
35
30
25
20
15
10
5
Energy Use (kBtu/ft²/yr)
Total
Heating
Cooling
70
65
60
55
50
Night Thermostat Setback, °F

Appendix B

Derivation of Equations Used to Calculate Taylor Series Expansion Coefficients

Six DOE 2.1A simulations are needed to calculate the Taylor series expansion coefficients. The parametric values for these DOE 2.1A runs are shown in Fig. B.1, where (P_{io}, P_{jo}) is the base case position about which the expansion is performed. The following approximate formula is used for the first partial derivative of E (P_i, P_j) with respect to P_i.

$$\frac{\delta E}{\delta P_i}(P_{io}, P_{jo}) = \frac{E(P_{io} + h_1, P_{jo}) - E(P_{io}, P_{jo})}{h_1},$$

The first partial derivative of E (P_i, P_j) with respect to P_j is obtained in a similar way. E(P_{io}, P_{jo}) is the base case value of energy use (heating, cooling or total).

$$\frac{\delta E}{\delta P_j}(P_{io}, P_{jo}) = E\frac{(P_{io}, P_{jo} + h_2) - E(P_{io}, P_{jo})}{h_2}$$

The second partial derivatives are obtained from the following formula:

$$\frac{\delta^2 E}{\delta P_i^2}(P_{io}, P_{jo}) = E\frac{(P_{io} + 2h_i, P_{jo}) - 2E(P_{io} + h_i, P_{jo}) + E(P_{io}, P_{jo})}{h_i^2}$$

The mixed partial derivative is obtained as follows:

$$\frac{\delta^2 E}{\delta P_i \delta P_j} = \frac{\delta E}{\delta P_i}\frac{P_{io}, P_{jo} + h_2 - \frac{\delta E}{\delta P_i} P_{io}, P_{jo}}{h_2}$$

$$= E\frac{(P_{io} + h_1, P_{jo} + h_2) - E(P_{io}, P_{jo} + h_2)E(P_{io} + h_1, P_{jo}) + E(P_{io}, P_{jo}}{h_1 h_2}$$

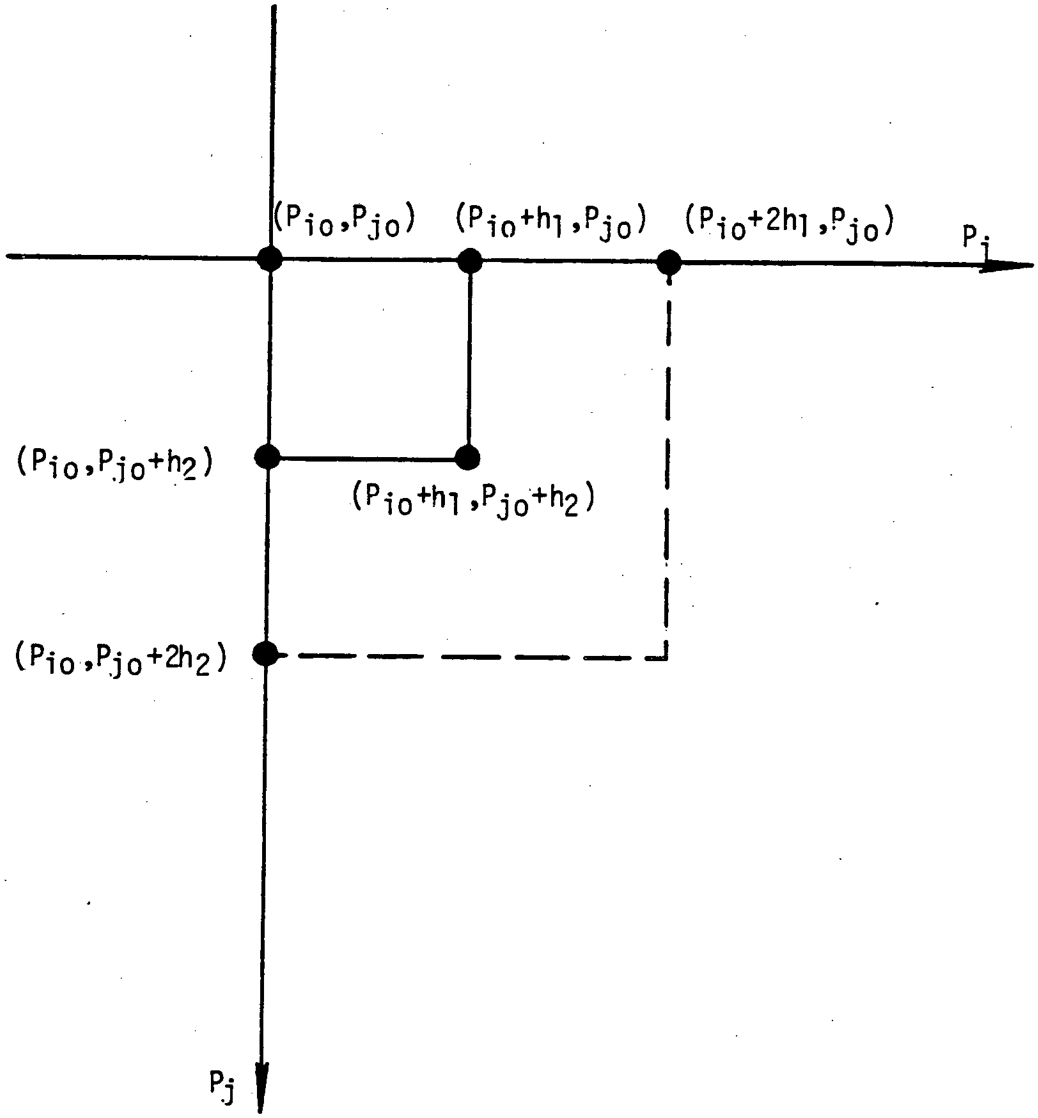


Fig. B1 The parametric values are shown for the six DOE-2.1 runs needed to calculate the Taylor series coefficients.

Appendix C

Table of Taylor Series Coefficients

Total Energy Use

Heating Energy Use

Cooling Energy Use

Table C.1. Taylor Series Coefficients for Total Energy Use Predictions

i	1	2	3	4	5	6	7	8	9	10	11
P_i	RR	RW	WWR	GST	GC	LIT	LS	OA	TH	TC	THS
$\frac{\partial E}{\partial P_i}$	-3.13	-15.4	1463.64	-20.00	558.39	891.00	40.00	52.00	21.75	-37.00	42.20
$\frac{\partial^2 E}{\partial P_i^2}$	0.12	1.0	1818.18	1511.11	173.16	132.00	96.00	14.50	-3.94	-2.25	3.40

Table C.2. Taylor Series Mixed Partial Derivative ($\frac{\partial^2 E}{\partial P_i \partial P_j}$) for Total Energy Use Predictons

	RR	RW	WWR	GST	GC	LIT	LS	OA	TH	TC	THS
RR											
RW	-.02										
WWR	1.82	33.0									
GST	3.56	14.17	606.1								
GC	.97	-2.28	2023.9	-827.25							
LIT	.80	3.38	290.91	293.33	-156.93						
LS	1.60	8.50	618.18	880.00	11.68	240.00					
OA	-.17	-.63	-13.64	-70.00	32.85	-30.5	-58.00				
TH	.67	1.19	-86.36	-78.33	-32.85	-13.25	41.00	-4.00			
TC	-.07	-.25	-36.36	-30.00	10.95	-11.50	-35.00	2.25	1.56		
THS	-.04	-.43	34.55	-12.00	13.14	-4.80	-5.60	2.60	-3.00	-.45	

Table C.3. Taylor Series Coefficients for Heating Energy Use Predictions

	RR	RW	WWR	GST	GC	LIT	LS	OA	TH	TC	THS
$\frac{\partial E}{\partial P_i}$	-3.27	-16.9	+691	-540	+653	-288	-528	88.0	26.0	2.75	35.0
$\frac{\partial^2 E}{\partial P_i^2}$	0.14	1.56	579	133	-405	79.0	1504	6.0	-0.125	-0.06	2.9

Table C.4. Taylor Series Mixed Partial Derivatives $\left[\frac{(\partial^2 E}{\partial P_i P_j}\right]$ for Heating Energy Use

	RR	RW	WWR	GST	GC	LIT	LS	OA	TH	TC	THS
RR											
RW	-.32										
WWR	1.21	28.41									
GST	2.67	4.17	-2181.82								
GC	.97	3.65	2787.00	-389.29							
LIT	.53	2.25	190.91	180.00	-113.14						
LS	.80	4.50	254.55	-453.33	-145.99	-44					
OA	-.13	-.50	-4.55	-15.32	21.90	-18.00	-36.00				
TH	0.00	-.09	2.27	-13.33	4.56	-5.75	5.00	1.5			
TC	-.03	-.22	-9.09	-13.33	10.95	-2.0	32.00	1..13	-.19		
THS	-.04	-.38	27.27	-108.0	11.68	-7.00	-7.20	2.90	-1.00	-.20	

Table C.5. Taylor Series for Cooling Energy Use Predictions

	RR	RW	WWR	GST	GC	LIT	LS	OA	TH	TC	THS
$\frac{\partial E}{\partial P_i}$	0.6	2.0	591	507	-174	206	564	-37.0	7.0	-39.8	1.0
$\frac{\partial^2 E}{\partial P_i^2}$	0.0	-0.25	413	266.7	384	51.0	-1512	8.75	0.02	2.31	0.16

Table C.6. Taylor Series Mixed Partial Derivatives $\left[\frac{\partial^2 E}{\partial P_i \partial P_j}\right]$ for Cooling Energy Use

	RR	RW	WWR	GST	GC	LIT	LS	OA	TH	TC	THS
RR	-										
RW	-0.61	-									
WWR	-0.61	-1.14	-								
GST	+0.44	+8.33	2424	-							
GC	-0.74	-6.48	-909	-296	-						
LIT	+0.27	+1.25	45.5	80	-44.4	-					
LS	1.07	3.5	+72.7	+240	-163	+272	-				
OA	-0.07	-0.25	-4.55	-16.7	12.96	-12.5	-26	-			
TH	-0.0	-0.06	2.27	1.67	0.0	2.5	-5	-0.75	-		
TC	0.0	0.0	-27.3	-16.67	0.0	-9.5	-16	1.0	-0.81	-	
THS	-0.0	-0.03	+1.82	101	0.74	0.6	+2.4	-0.3	0.0	-0.2	-

TECHNICAL INFORMATION DEPARTMENT
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