Development of a Simple Model to Relate Heating and Cooling Energy to Building Envelope Thermal Characteristics

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ABSTRACT

A new energy efficiency code for nonresidential buildings is being developed in Canada. This code will have three compliance paths for building envelope requirements-simple prescriptive tables, a trade off procedure, and whole-building energy performance modelling. A simple means of estimating the relationship between building envelope characteristics and energy consumption was needed both for economic analyses to select prescriptive envelope values, and as the basic energy model for tradeoff compliance software.

A simplified energy model has been derived from a database of 5,400 DOE-2 simulations for 25 Canadian locations. Correlations developed from this database allow prediction of annual heating and cooling energy loads based on location, building envelope characteristics (area, wall and fenestration U-values, and shading coefficients), and internal gains (people, lights, and equipment). This paper describes the development of the energy database and the correlation equations, and compares the correlations' predictions of heating and cooling energy with those of the original DOE-2 simulations.

INTRODUCTION

Canada is developing a new code for energy efficiency in buildings; during development, the need for a simple energy model emerged. The code will contain alternate compliance paths to provide flexibility to designers while maintaining minimum levels of energy efficiency. The simplest, prescriptive compliance, will consist of showing that individual building envelope components satisfy the minimum thermal requirements (such as U-value and shading coefficient) tabulated in the code. More flexibility is permitted by the tradeoff route. This allows combinations of envelope components to differ from those specified by the prescriptive path if they can be shown, using a simple computerized tradeoff procedure, to be at least equivalent in terms of energy use. Finally, the performance path allows any combination of envelope, lighting, and mechanical systems if it can be shown, using computer simulation, that this would result in energy use no greater than a target value based on the prescriptive requirements.

Energy simulation plays a role not only in the performance path, but also in the other two compliance paths. The prescriptive values in the code are set at the life-cycle cost optimum taking into account specific costs and economic assumptions for each region of Canada. This

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analysis requires calculating construction and energy costs for a large number of combinations—further emphasizing the need for a simple energy model. A simple energy model is also needed as the basis for comparison of energy characteristics in an envelope tradeoff compliance tool, which is intended to be an interactive tool widely distributed to users of the code.

The requirements of the energy model for these purposes are that it be quick and simple, and accurately predict changes in heating/cooling energy due to changes in envelope characteristics. It is not intended to predict building energy consumption; therefore its absolute accuracy in predicting energy consumption is not as important as its sensitivity to envelope variations.

A correlation method for predicting changes in energy consumption due to changes in envelope characteristics is presented in *ASHRAE/IES Standard 90.1-1989* (ASHRAE 1989a) and implemented in computer software (ENVSTD) that is provided with the standard. However, our investigations revealed that using these correlations for Canadian constructions and climates could force them beyond the valid ranges of their use (Crawley 1992). It was also deemed desirable to try to derive simpler, more rational equations (the correlations and coefficients cover more than nine pages of Standard 90.1).

ENERGY DATABASE DEVELOPMENT

For these reasons, a new energy database was developed and a new set of correlations derived for the Canadian code. Our first step was to select parameters that would effectively cover the wide range of possible combinations of wall and window thermal characteristics, and heat gains from lights, occupants, and equipment. After reviewing possible solutions, we decided to define the characteristics of the building in terms of three factors—transmission, solar, and internal gains:

transmission, W/m²K $U = [A_w * U_w + A_g * U_g]/A_t$

solar, dimensionless $V = A_g * SC_g / A_t$

internal gains, W/m² $W = I * A_f / A_t$

where:

A_w = opaque wall area, m²
A_g = window area including frame, m²
A_t = gross wall area in m², sum of opaque wall area (A_w) and window area (A_g)
A_f = floor area associated with envelope, typically 4.5 m deep, m²
U_w = opaque wall U-value, W/m²K
U_g = window U-value including frame, W/m²K
SC_g = window shading coefficient including frame
I = design heat gain from lights, people, and equipment, W/m² floor area

For the analyses, we fixed a number of assumptions about the building and its systems. The fixed building assumptions were:

- 4 zones (each 4.5 x 30.5 m) facing N, E, S, and W
- no interzone heat transfer
- medium level thermal mass
- fixed infiltration rate
- internal loads on 6-day office-type schedules
- typical system operating schedules (heating setback to 15 C; fans, and cooling off when unoccupied)

In evaluating HVAC systems for the database, we decided they must be reasonably efficient and sensitive to zone loads (i.e., not a lot of reheat). The HVAC system assumptions that were fixed:

- variable air volume (VAV) system with terminal reheat
- 13 C supply air
- free cooling (enthalpy controlled airside economizer)
- minimum ventilation set to *ANSI/ASHRAE Standard 62-1989* (ASHRAE 1989b) requirements, 9.4 l/s·person (20 cfm/person)

We selected the DOE-2.1E hourly energy simulation program (LBL 1992) to generate the values for the energy database. The base input file was developed based on the above set of assumptions. The parametric features of DOE-2 allowed us to incrementally move through the combinations of values for transmission, solar, and internal gains. We used a combination of six values each for the three factors, ranging from low (or 0) to high cases, resulting in 216 simulations (6 x 6 x 6 cases) per location. The range of values used are shown in Table 1.

We then selected 25 locations throughout Canada to represent the variety of weather conditions, from the mild Atlantic maritime and the temperate Pacific coast to the extremes above the Arctic Circle. A new set of weather data for use with building energy simulation programs, called Canadian Weather for Energy Calculations (CWEC) (WATSUN 1992), was developed for the 25 Canadian locations.

The 216 simulations in each of the 25 locations (5400 DOE-2.1E simulations) were automated using procedures that automatically created the input files, ran the simulations, and extracted energy results that comprise the energy database. The results that we focused on for the correlations were the monthly and annual values for both peak demand and energy consumption due to heating, cooling, and fans, by orientation. The heating and cooling values are coil loads, i.e., they do not include plant efficiencies—we account for these externally.

COOLING ENERGY EQUATIONS

Cooling energy can be expressed as a function of internal gain; solar gain; infiltration, ventilation, and system effects; and transmission gain/loss. Figure 1 shows how cooling energy typically varies with changes to internal and solar gains. This example is for an east facing zone located in Ottawa, and for one value of transmission parameter U (0.227 W/m^2K). This figure shows that cooling energy is almost directly proportional to parameters V and W.

Figure 1 also shows that cooling does not go below a minimum value, C_{min}. The minimum cooling is determined by the way the system is assumed to operate. The VAV system assumed for this analysis cannot reduce air flow below the minimum required for adequate ventilation. Since the supply air temperature is also fixed, this results in some minimum cooling which may be made up by reheat in the zone when the zone does not require cooling. This value of C_{min} is climate dependent. The form of equation indicated by Figure 1 is:

$$C_0 = MAX(C_{min}, a_0 + a_1 * V + a_2 * W) \qquad (1)$$

Figure 2 shows that an increase in the transmission parameter, U, reduces cooling energy. This is true in most Canadian climates since transmission heat losses tend to outweigh transmission gains; in a hotter climate the reverse would be true. Given that the overall effect of U is less than 10% of total cooling energy (comparing Figure 2 with Figure 1), it can be considered a minor correction term to C_0.

This correction term, ΔC, accounts for the change in cooling with the variation in U. Figure 3 shows that the magnitude of ΔC increases with increasing U and goes to zero as C approaches C_{min}. This indicates a correction term of the form:

$$\Delta C = a_3 * U * [1 - C_{min} / C_0] \qquad (2)$$

where a_3 is a location and orientation dependant coefficient.

The cooling energy, in MJ, for a zone having gross wall area, A_t, can therefore be simply calculated as:

$$C = A_t * MAX[C_{min}, C_0 + \Delta C] \qquad (3)$$

where C_0 and ΔC are obtained from equations (1) and (2) using the coefficients for the applicable location and orientation. Table 2 shows coefficients for the four principle orientations for Ottawa.

Figure 4 shows the cooling energy calculated using equation (3) and coefficients from Table 2 against the original DOE-2 simulation results for east orientation in Ottawa. This graph contains the entire range of parametric values for U, V, and W. This simple model produces results that are within 10% of the DOE-2 simulations except at the very lowest values of cooling.

HEATING ENERGY EQUATIONS

Heating energy can be expressed as a function of transmission loss; losses due to infiltration and ventilation; solar gain; and internal gain. Figure 5 shows typical heating energy when there are no internal gains or solar gains through glazing (i.e., V=0 and W=0) for the four orientations of a building located in Ottawa. Note that heating energy is nearly a linear function of U and that the effect of orientation (due to solar radiation on the opaque walls) is relatively small. Similar to cooling, there is a minimum value of heating at U=0 because of infiltration and ventilation assumptions.

Therefore, heating energy, in MJ per m^2 of gross wall area, A_t, corresponding to V=0 and W=0 is:

$$H_{0,0} = b_0 + b_1 * U \qquad (4)$$

where b_0 and b_1 are location and orientation specific coefficients.

Figure 6 illustrates the effect of solar gains through windows in reducing heating energy. This example is for the east orientation, located in Ottawa, and with zero internal gains (W=0). The heating corresponding to the condition of a non-zero solar coefficient, V, and zero internal gains, $H_{V,0}$, can be expressed as a modification of $H_{0,0}$ to account for the useable solar gains (Sander and Barakat 1983). Figure 7 shows that when the ratio $H_{V,0}/H_{0,0}$ is plotted against $V/H_{0,0}$, the values of U can be approximated by a single curve. This curve may be expressed by the equation:

$$H_{V,0} = H_{0,0} * \frac{1}{[1 + \alpha_1 * X + \alpha_2 * X^2 + \alpha_3 * X^3]} \qquad (5)$$

where X is the ratio of V to $H_{0,0}$.

Normally, the condition of interest is $H_{V,W}$, when both internal and solar gains are non-zero. For this case, it is necessary to account for the interaction of internal and solar loads (Barakat and Sander 1986). We found that by introducing an additional parameter, Y, to account for this interaction it is possible to plot the ratio $H_{V,W}/H_{V,0}$ versus Y as a single curve for all values of U, V, and W. This is shown in Figure 8. The curve can be expressed by the equation:

$$H_{V,W} = H_{V,0} * [\frac{(1 + \beta_1 * Y)}{(1 + \beta_2 * Y + \beta_3 * Y^2)}]^2 \qquad (6)$$

where:

$Y = b_2 * (W/H_{0,0}) + (1 - b_2) * (W/H_{V,0})$

The heating energy for a zone having a gross wall area, A_t, and any combination of parameters U, V, and W, can then be calculated as:

$$H = A_t * H_{V,W} \qquad (7)$$

where $H_{V,W}$ is calculated from equations (4), (5), and (6) using the appropriate coefficients for the orientation and location (Table 3 gives coefficients for the primary orientations for Ottawa).

Figure 9 shows heating energy calculated using equation (7) and coefficients from Table 3 compared with the DOE-2 simulation results for the east orientation in Ottawa. The points on the graphs represent the entire range of parametric values for U, V, and W. The simple model for heating also produces results that are within 10% of the DOE-2 simulations, except at very lowest values of heating.

CONCLUSIONS

A simple model has been developed to satisfy the needs of the Canadian energy code for fast, simple, and accurate prediction of changes in heating/ cooling energy due to changes in envelope thermal characteristics. These correlations are not intended to estimate the absolute energy consumption of a building, but instead to compare the energy impact of variations in envelope thermal characteristics.

The simple model described in this paper requires location-specific coefficients. Automated procedures have been developed to make it relatively easy to generate these coefficients for all the locations necessary for the intended energy code application.

We found that the coefficients for cooling (C_{min}, a_0, a_1, a_2, and a_3) can be correlated to statistical climate parameters such as cooling degree-days and vertical solar radiation. We are also examining ways of modifying the heating model to incorporate correlations to climate parameters. This would result in a much more general model that could be used where location-specific coefficients are not available. Other possible future work includes examining the suitability of the models for other locations in North America that are more cooling dominated.

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Table 1
Parametric Cases for DOE-2 Energy Simulations

Factor	Parametric Values					
U (W/m²K)	0.227	0.568	1.136	1.703	2.271	2.839
V	0.0	0.2	0.4	0.6	0.8	1.0
W (W/m²)	0.0	13.46	26.91	53.82	80.73	107.64

Table 2
Cooling Coefficients for Ottawa

Coefficients	North	East	South	West
C_{min}	87.7	87.7	87.7	87.7
a_0	15.103	22.034	19.473	24.824
a_1	506.31	857.66	789.25	816.93
a_2	4.1754	4.0757	4.1151	4.1113
a_3	-52.06	-41.26	-43.62	-46.52

Table 3
Heating Coefficients for Ottawa

Coefficients	North	East	South	West
b_0	721.39	728.88	729.16	722.14
b_1	463.32	431.26	421.10	444.92
b_2	0.974	0.951	0.966	0.943
α_1	1415.6	2403.1	3473.7	2361.3
α_2	-309378	-465466	2882129	-529143
α_3	3.55E+08	1.18E+09	2.66E+09	1.25E+09
β_1	-5.42768	-4.60259	-4.47212	-5.45598
β_2	1.193782	2.145594	3.741244	1.329969
β_3	24.30558	33.15287	28.4294	25.35017

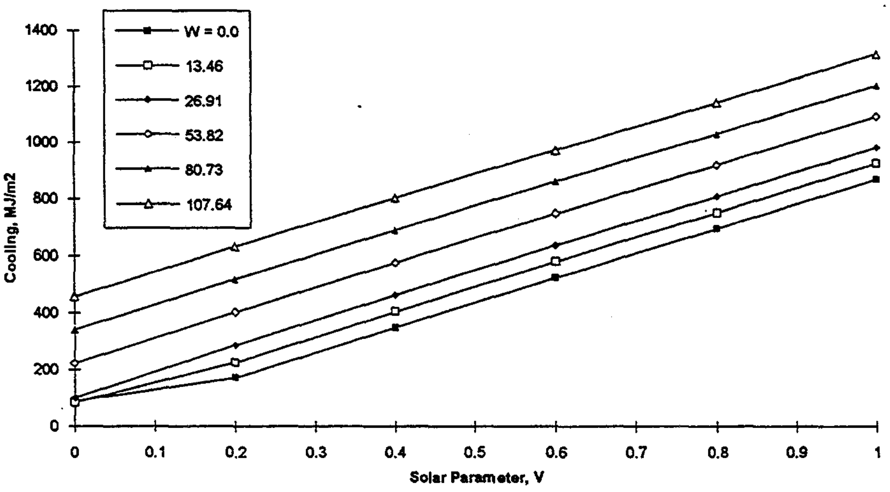

Figure 1
Cooling Energy v. Solar Parameter, V, and Internal Gain Parameter, W, for East Orientation in Ottawa (U=0.227)

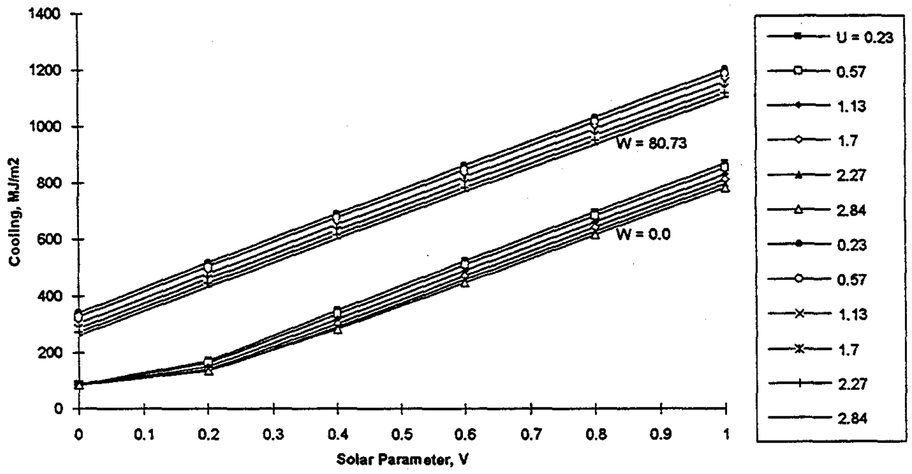

Figure 2
Cooling Energy v. Transmission Parameter, U, for Two Internal Gain Cases for East Orientation in Ottawa

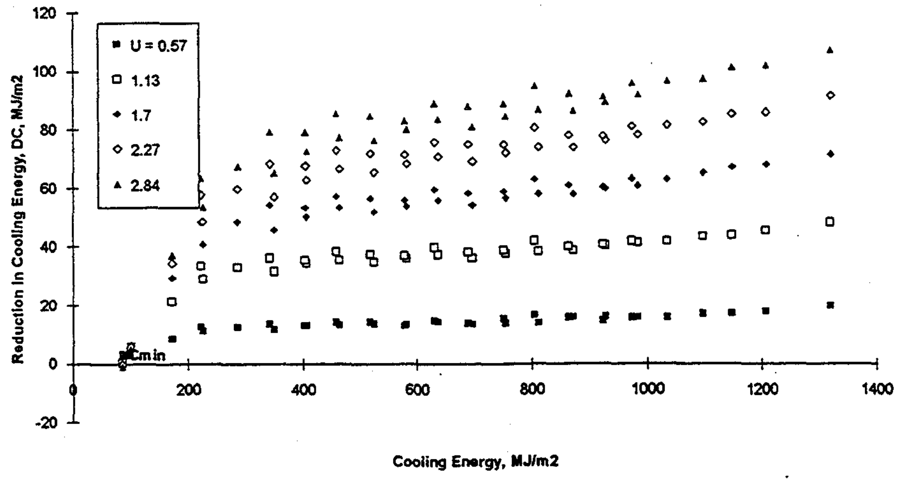

Figure 3
Effect of Transmission Parameter, U, on Cooling Energy for East Orientation in Ottawa

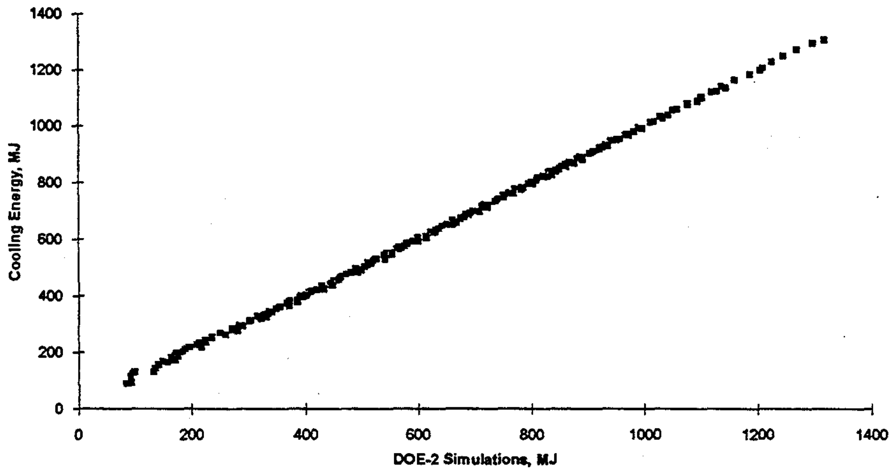

Figure 4
Predicted Cooling Energy for Correlation v. DOE-2 Simulations
for East Orientation in Ottawa

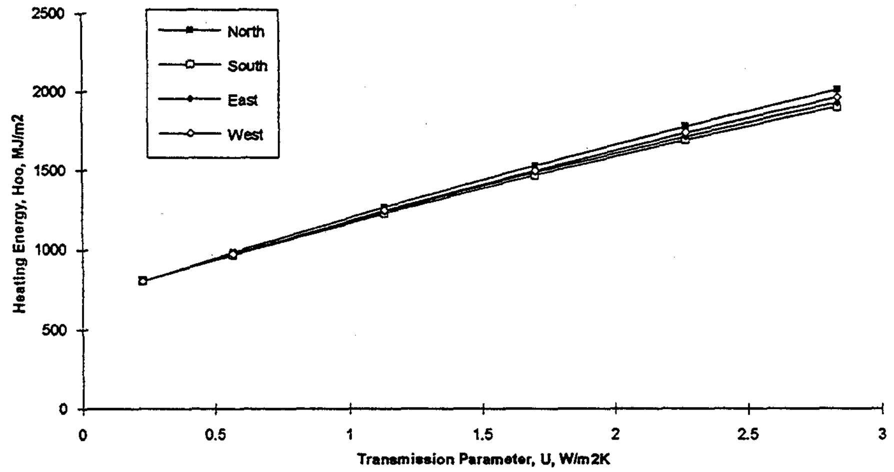

Figure 5
Heating Energy v. Transmission Parameter, U, for V and W =0
for Ottawa

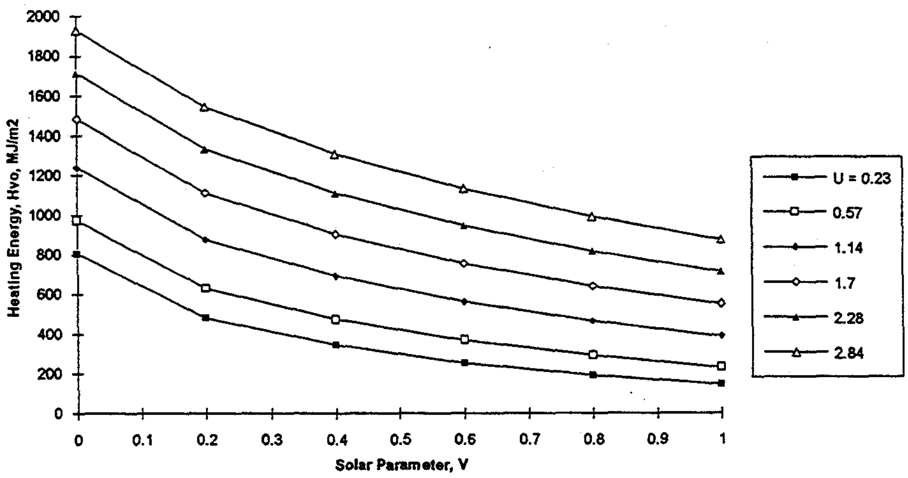

Figure 6
Heating Energy v. Solar Parameter, V, for W=0
for East Orientation in Ottawa

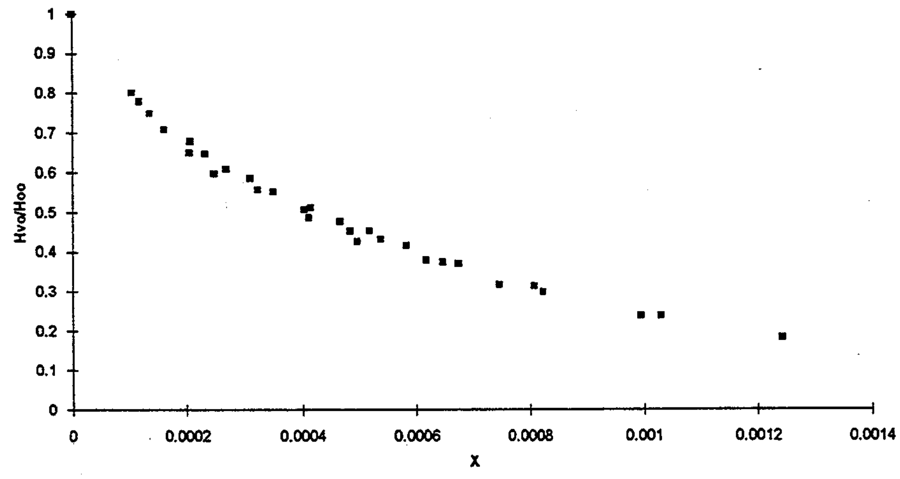

Figure 7
Ratio of Heating with Solar to Heating without Solar v. Parameter X for W=0 for East Orientation in Ottawa

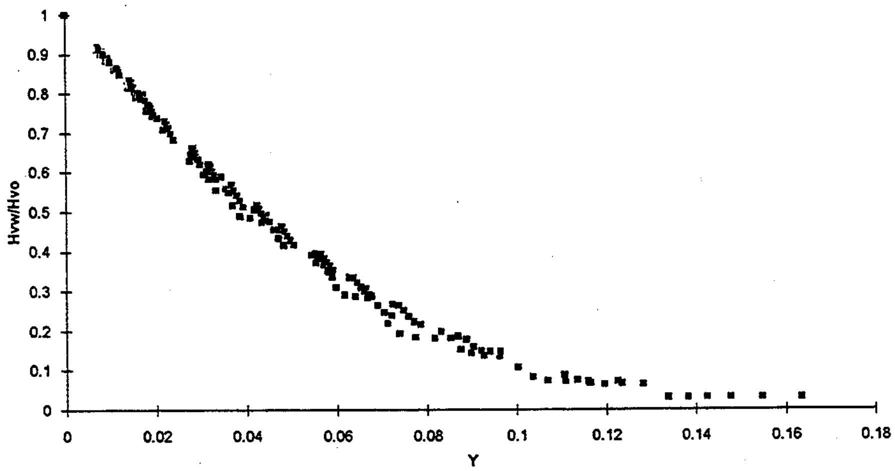

Figure 8
Ratio of Heating with Internal Gain and Solar to Heating with Solar Only v. Parameter Y (b_2*W/$H_{0,0}$ + (1-b_2)*W/$H_{V,0}$) for the East Orientation in Ottawa

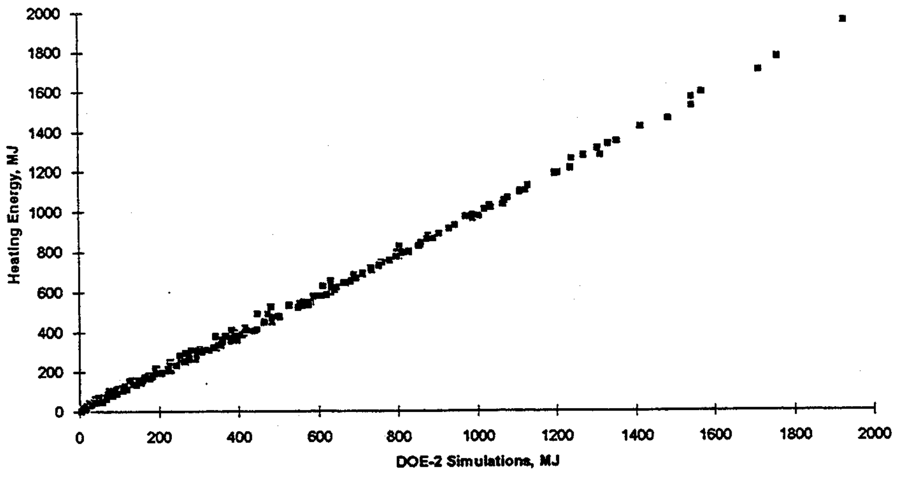

Figure 9
Predicted Heating Energy for Correlation v. DOE-2 Simulations for East Orientation in Ottawa