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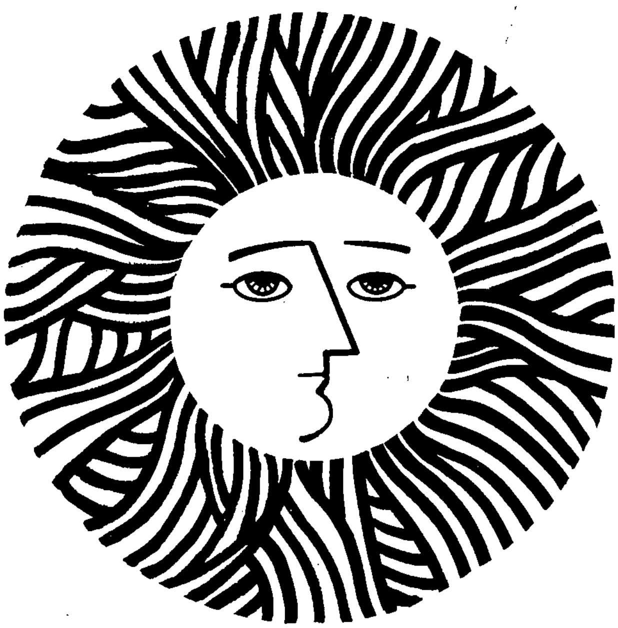

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ABSTRACT

There are a number of methods that can be used to estimate the annual energy consumption of a house, ranging from simple hand calculation of heat loss under steady-state conditions, to exhaustive computer calculations of hour-by-hour heat loss and heat gain. This paper introduces a scorecard method which utilizes processed results of computer calculations. Scores are awarded either in terms of annual heating or cooling load, or in terms of arbitrary "points". The scorecard is easy to use, yet embodies the results of hour-by-hour calculations. The theoretical basis for the point system scorecard is developed, and its limitations discussed. A points scorecard for single family houses in Minneapolis is presented.

INTRODUCTION

There are at present a number of methods to estimate the average annual energy use of a residence. The simpler methods tend to be rather inaccurate, while the more accurate ones tend to be rather expensive. However, within limited ranges the heat loss through all the house components can be treated as independent. Thus it is possible to process the results of computer-based calculations to construct a scorecard for energy use estimation that is both accurate and simple, yet has wide-scale applicability. The processing method is a development of the effective degree day method.

ENERGY ESTIMATING METHODS

Design Heat Loss and the Degree Day Method

It is not easy to estimate the annual heating load of a house, since heat loss and gain are complex and dynamic. The traditional method used is the degree day method [1], which assumes that on the average free heat (solar heat and waste heat from appliances and occupants) will offset heat losses as long as the average outside temperature is greater than 65^{o}F, or some other "base temperature". The general equation for the method is:

$$L = (H/t) \times DD \times 24$$

where L = annual heating load, Btu per year
H = design heat loss, Btu per hour
t = design temperature difference, ^{o}F
DD = number of degree days, base 65^{o}F
Note:H/t includes infiltration losses; it is equivalent to UA, the overall heat transfer coefficient, Btu per hour per ^{o}F

The number of degree days to base 65^{o}F is defined as:

$$DD = \sum 65 - \frac{Tmax + Tmin}{2}$$

$$\text{for all days where } \frac{Tmax + Tmin}{2} < 65^{o}F$$

This method is admirably simple but not particularly accurate. Today's tighter houses retain more of their free heat, so that the number of degree days to base 65^{o}F is not directly proportional to the heating load as calculated by hour-by-hour computer models (which include free heat explicitly). This is illustrated in Figure 1, which shows the results of calculations using DOE-2.1, the U.S. Department of Energy's building energy use model [2,3]. It is clear that although the load as calculated by DOE-2.1 does vary almost linearly with design heat loss per ^{o}F, it does not pass through the origin as expected from the degree day method; tighter houses have progressively fewer degree days. On the assumption that the hour-by-hour calculation is more accurate than the degree day method, we explored simple interpolation methods to improve the agreement.

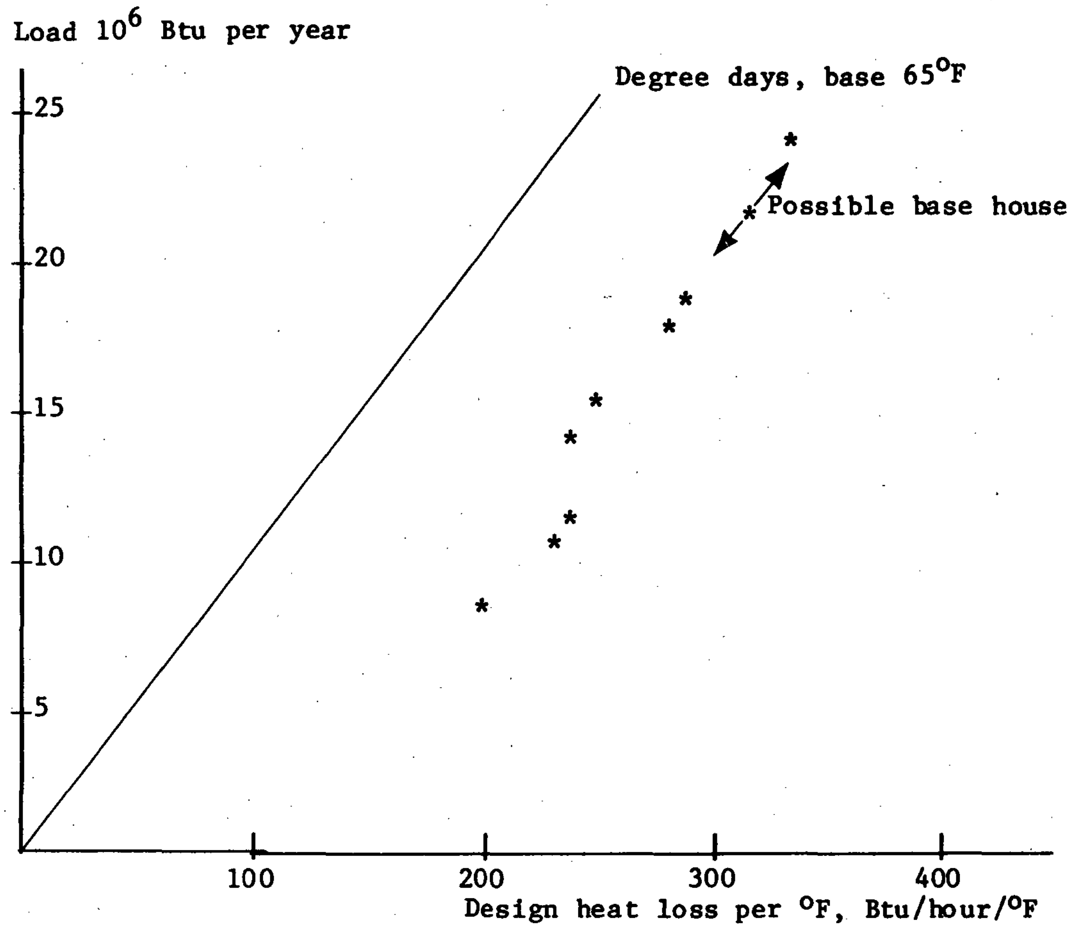


Figure 1. Variation of annual heating load with design heat loss per °F for a series of houses in Washington, DC. Results of calculations with the DOE-2.1 building energy use model.

Interpolation Methods

Agreement can be improved by introducing an empirical constant to correct for the difference between degree days and heating load. A much greater improvement is possible by making use of the computer to calculate the load of a base house, for example the possible base house marked in Figure 1, and then using the base 65 degree day model to extrapolate to other designs. The change in load is calculated as:

$$\Delta L = \Delta(H/t) \times DD \times 24$$

A better fit may be achieved if a base other than 65°F is used. By interpolating between two computed values of L an empirical value of DD, i.e. the local slope of Figure 1, can be found. The empirical DD is called the number of effective degree days. Closer analysis reveals that it varies from component to component in a house. For example, while Washington, DC, has 4247 degree days to base 65°F, for the house shown in Figure 1, the ceiling has approximately 5400 effective degree days, while the walls have approximately 4200 effective degree days. This suggests a final improvement; the load is best predicted by an equation of the form:

$$L = L_{base} + \sum \frac{\Delta H_i}{t_i} \times D_i \times 24$$

where L_{base} = load of a base house, Btu per year

ΔH_i = difference in design heat load of component i compared to the base house, Btu per hour

t_i = design temperature difference for component i, °F

D_i = number of effective degree days for component i

This equation is an interpolation formula, and can be expected to hold over small ranges where the contributions of all the components to the total load can be regarded as independent.

Extension of the Interpolation Formula

The linearity shown in Figure 1 suggests that the interpolation formula might hold over wide ranges of load. To test this hypothesis for commonly installed insulation values, the formula was rewritten:

$$L = L_{base} + f_1(R_{ceiling}) + f_2(R_{walls}) \cdots$$

Here f_i is a change in load from the base case caused by a change in component i. The functional form of f_i was not considered; it may be expected to be complex, since R_i is a proxy for the heat transfer coefficient of the whole component. It is clear by comparing the two forms of the interpolation formula that if the design heat loss per °F had been chosen as the variable, f_i would have been equal to $24D_i$ times the difference in heat transfer coefficient. Table 1 shows a typical set of values of the interpolation function, f_i, for ceiling insulation for a 1540 ft^2 light construction ranch house in Minneapolis, Minnesota. The floor plan and elevation are shown in Figure 2.

TABLE 1

Variation in annual heating load (10^6 Btu per year) caused by a change in ceiling insulation level in a Minneapolis house.

Insulation level	R19	R30	R38	R49	R60
Heating Load change	8.1	3.3	1.5	0.0	-1.0
Cooling Load change	0.7	0.3	0.1	0.0	-0.1

The house with R49 in the ceiling was chosen as the base house, and therefore the function is zero for this level of insulation. If a measure varies the load imperceptably, several successive values may be identical. The numbers in Table 1 were obtained from five computer runs in which all the house parameters except ceiling insulation level were kept constant at their base case values. The f_i for all other components can be found in the same way. The variables used need not be R-value; for windows the parameters could be window area, window glazing and window orientation; for night thermostat setback the parameters could be simply yes or no for a well-defined setback.

To test the range over which the interpolation formula is accurate, a model ranch house (Figure 2) was set up for the DOE-2.1 computer program, and a number of calculations made for Minneapolis, MN, and Riverside, CA, weather. A very wide range of component thermal resistances was used, although it was expected that the formula, with its implicit assumption that the heat loss through any component is independent of the total load, would only hold for a moderate range of loads. If the house were a steady-state enclosure with no internal heat sources except the thermostatically controlled furnace, then each exterior surface could be considered as a test specimen in a hot box. The heat loss of the steady-state house would be the sum of the heat losses through the test specimens, calculated independent of the total load. However, this is not the case. As the house becomes thermally tighter, more of its load is met by free heat. The number of effective degree days therefore decreases with the total house load, and f_i should become commensurately smaller. The results of the computer calculations for Minneapolis are shown in Table 2.

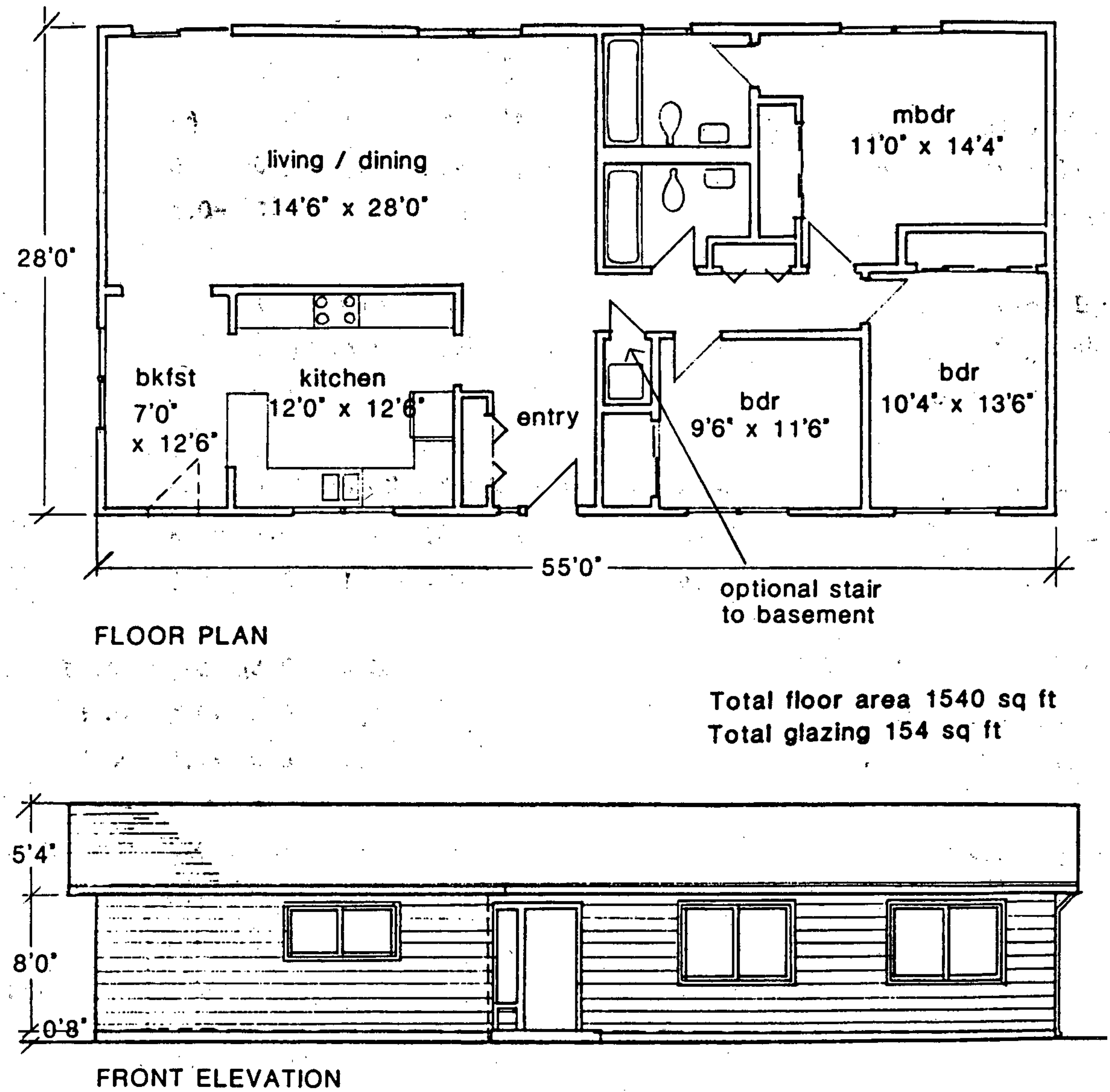


Figure 2. Floor plan and elevation of the one story ranch house used for calculations with the DOE-2.1 building energy use model. The house was modelled with a basement in Minneapolis, MN, weather and with a slab in Riverside, CA, weather.

TABLE 2

Difference in Annual Load (10^6 Btu/year) for a Minnneapolis house as compared to the Base House (Annual Heating Load 50.6 10^6 Btu, Annual Cooling Load 6.9 10^6 Btu)

Ceiling insulation		R19	R30	R38	R49	R60	
Heating difference		8.1	3.3	1.5	0.0	-1.0	
Cooling difference		0.7	0.3	0.1	0.0	-0.1	
Wall insulation			R11	R19	R27		
Heating difference			9.7	3.4	0.0		
Cooling difference			0.5	0.1	0.0		
Basement insulation	None	4´ R5	4´ R10	8´ R5	8´ R10	R19	
Heating difference	16.6	8.9	5.5	4.9	0.0	-1.6	
Cooling difference	0.6	0.3	0.2	0.1	0.0	0.5	
Infiltration,ach				0.67	0.50	0.33	0.17
Heating difference				9.6	0.0	-9.5	-18.6
Cooling difference				0.2	0.0	-0.2	-0.3
Setback thermostat					Yes	No	
Heating difference					0.0	2.3	
Cooling difference					0.0	0.0	

Table 2 (continued)

Glazing as a percentage of floor area

(a) North+East+West

		Single	Double	Triple
2.5% glazing	Heating Difference	3.5	-0.3	-1.5
	Cooling Difference	-2.0	-2.2	-2.3
5% glazing	Heating Difference	9.1	1.5	-0.8
	Cooling Difference	-0.6	-1.0	-1.2
7.5% glazing	Heating Difference	14.8	3.5	0.0
	Cooling Difference	0.9	0.3	0.0
10% glazing	Heating Difference	20.4	5.4	0.8
	Cooling Difference	2.4	1.6	1.2
15% glazing	Heating Difference	31.7	9.3	2.4
	Cooling Difference	5.6	4.4	3.8

(b) South glass

		Single	Double	Triple
2.5% glazing	Heating Difference	4.6	1.0	0.0
	Cooling Difference	0.3	0.1	0.0
5% glazing	Heating Difference	8.3	1.2	-0.8
	Cooling Difference	1.8	1.2	1.2
7.5% glazing	Heating Difference	12.1	1.5	-1.6
	Cooling Difference	3.3	2.7	2.4
10% glazing	Heating Difference	15.9	1.8	-2.3
	Cooling Difference	4.8	4.4	3.7
15% glazing	Heating Difference	23.6	2.8	-3.3
	Cooling Difference	8.3	7.1	6.5

RANGE OF VALIDITY OF THE INTERPOLATION FORMULA

If the interpolation formula were to apply accurately to all combinations of the variables given in Table 2, then this table would be able to predict the energy consumption of Minneapolis houses with several thousand different combinations of components, provided they were similar in construction to the base house. To see how the tables would be used, consider a Minneapolis house similar to the base house but with R19 in the ceiling, R11 in the walls, no basement insulation, an infiltration rate of 0.67 air changes per hour, no night setback thermostat, with windows on the North, East, and West sides totalling 15% of its floor area, with a South window of 2.5% of its floor area, all windows being single glazed. This house would, according to Table 2, have an annual heating load greater than the base house by:

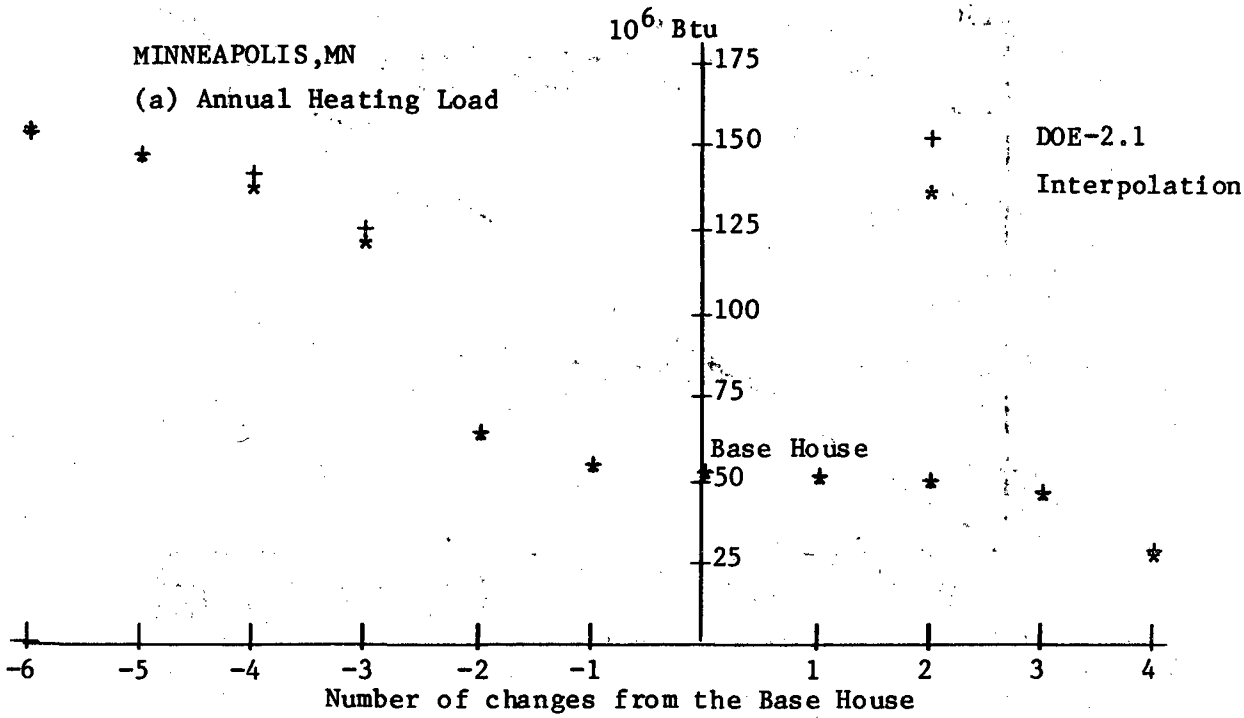
$$[\ 8.1 + 9.7 + 16.6 + 9.6 + 2.3 + 31.7 + 4.6\ ]\ 10^6 \text{ Btu per year}$$

$$= 82.6\ 10^6 \text{ Btu per year more than the base house}$$

$$= 133.2\ 10^6 \text{ Btu per year}$$

Similarly, the cooling load would be 14.8 10^6 Btu per year. The tables make available the sophistication of the hour-by-hour computer program in a simple format. The posible advantages for energy auditors are obvious; a walk through audit could produce the same results as an individualized computerized audit, provided the interpolation formula holds. It is therefore of some importance to examine the range over which it is accurate.

One systematic way doing this is to construct a series of houses, ranging from very loose to very tight, and to compare the load predicted by Table 2 with the value obtained by an individualized DOE-2.1 run. Two series of ranch houses were modelled, in Riverside, CA, and Minneapolis, MN, starting with a house with the most energy consuming options in the Tables. These house were transformed, one component at a time, into the base houses, and then transformed, again one step at a time, into about the tightest houses possible. The steps are not equal in size. The base houses are rather tight, so that the steps taken to tighten them are smaller than those taken to loosen them. Details are



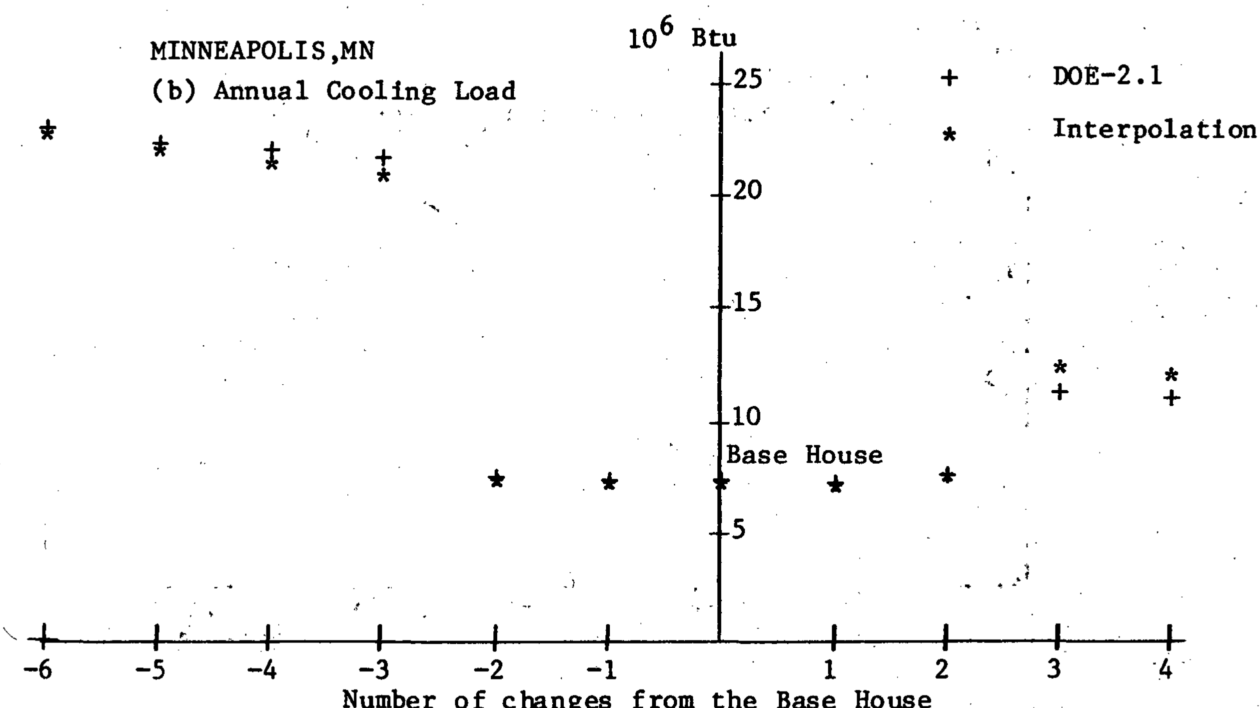
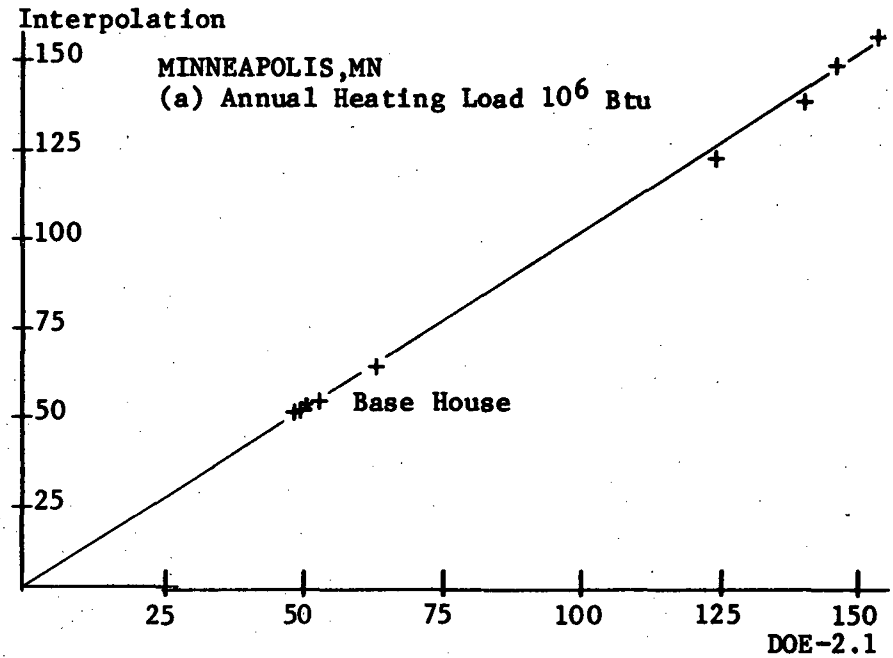


Figure 3. Annual Heating and Cooling Loads for a Series of Houses in Minneapolis, MN. Predictions from DOE-2.1 and from the Interpolation Formula. Note that changes are not of equal magnitude.



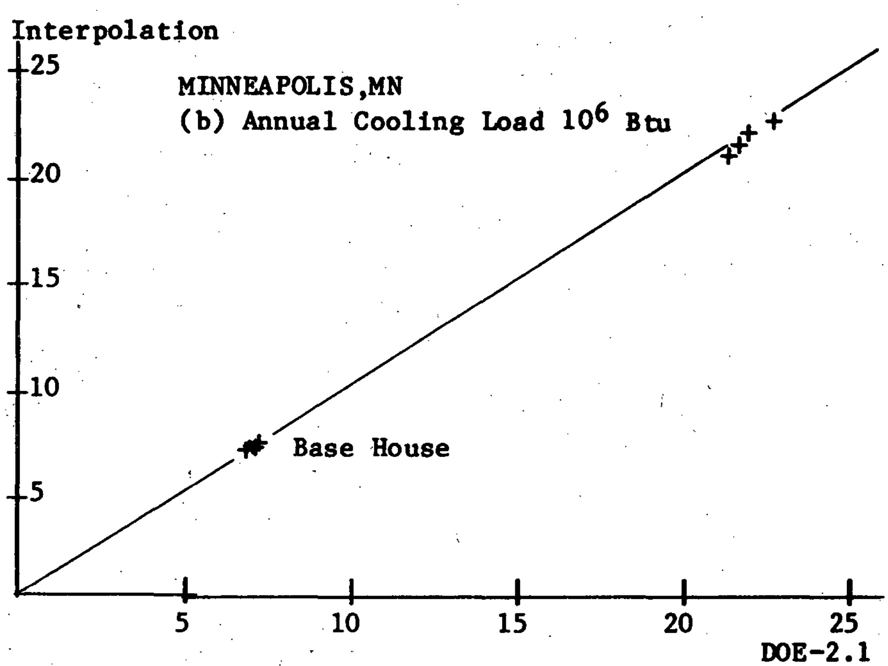


Figure 4. Annual Heating and Cooling Loads for a Series of Houses in Minneapolis, MN. Predictions from DOE-2.1 and from the Interpolation Formula. The solid line indicates perfect agreement.

TABLE 3

Characteristics of the Minneapolis Houses

House #	-6	-5	-4	-3	-2	-1	BASE	1	2	3	4
Ceiling R-value	19	49	49	49	49	49	49	60	60	60	60
Wall R-value	11	11	27	27	27	27	27	27	27	27	27
Floor measure #	0	0	0	4	4	4	4	4	5	5	5
Window area, South	15	15	15	15	2.5	2.5	2.5	2.5	2.5	15	15
Window area, N+E+W	15	15	15	15	7.5	7.5	7.5	7.5	7.5	2.5	2.5
Window glazing	1	1	1	1	3	3	3	3	3	3	3
Infiltration,ach	0.7	0.7	0.7	0.7	0.7	0.5	0.5	0.5	0.5	0.5	0.2
Night setback	no	no	no	no	no	no	yes	yes	yes	yes	yes

Notes
(a) The floor measures for basement insulation are defined as:
FM0 = None
FM4 = Eight feet of R10 on the exterior wall
FM5 = R19 on the floor
(b) Window area is measured as a percentage of floor area.
(c) The thermostat setback is from 70°F to 60°F from midnight to 6am.

given in Table 3. The results of the DOE-2 runs for Minneapolis are shown in Figure 3, with the same results plotted in a slightly different format in Figure 4.

It can be seen that the values predicted by the interpolation formula are very close to those predicted by DOE-2.1 runs. For the Minneapolis house, the heating loads agree to within 5%, while the cooling loads agree to within 10%. For Riverside, CA, the heating loads agree to within 15% except for the very tightest house. (For this house, the interpolation formula predicts a negative heating load. This is clearly impossible; however, the heating load for this house is so low, approximately 200,000 Btu per year, that this result is of no practical consequence.) The cooling loads in Riverside agree to within 5%. It was not expected that the agreement would be so good, nor that it would hold over such a broad range of loads. To find a more sensitive test for the accuracy of the formula, a series of runs was made for a very tight house in Riverside, CA. It was found that the load reduction from thermostat setback was predicted least accurately. This result was expected; thermostat setback takes the house furthest away from the hot-box model. It was decided to use thermostat setback to examine the errors of the interpolation formula for the whole range of houses for Riverside and Minneapolis. The results of the computer runs for Minneapolis are shown in Figure 5.

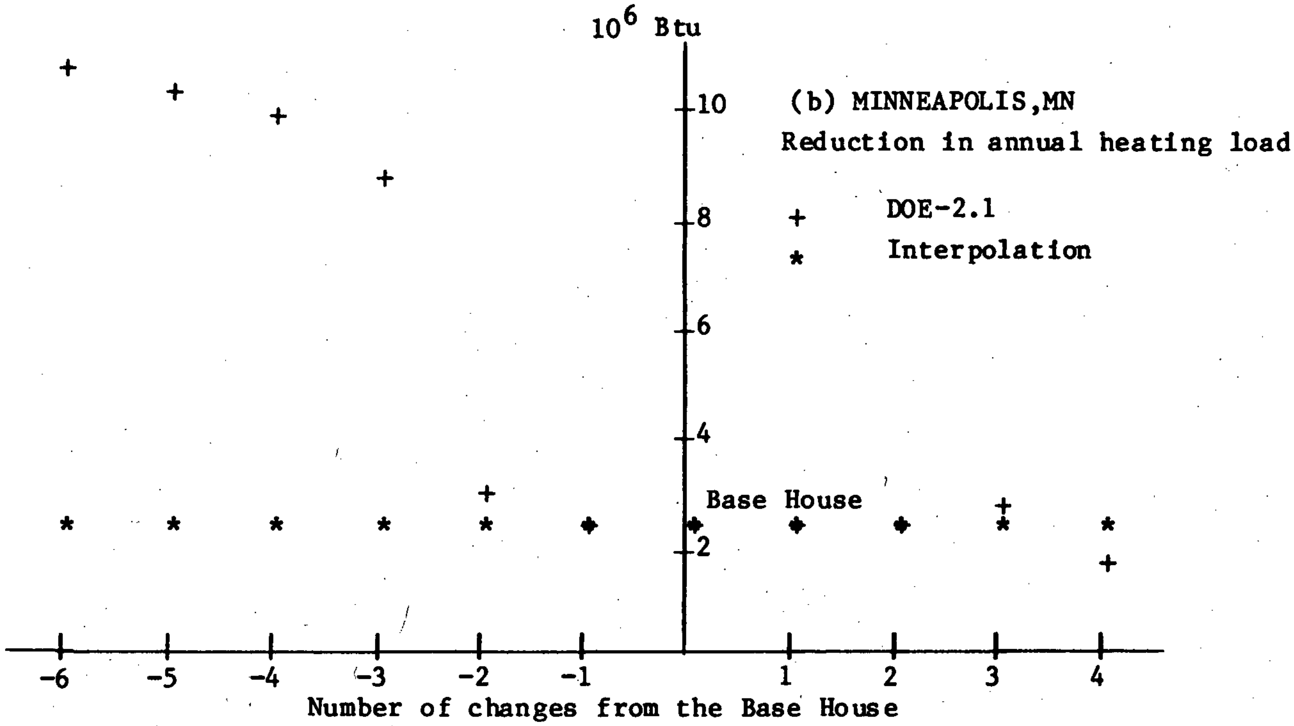


Figure 5. Load reduction in Minneapolis houses caused by use of a thermostat setback. The houses are those defined in Table 3. Note that house #-6 has an annual heating load of 154 10^6 Btu.

The change in load that results from a thermostat setback is clearly not independent of the total load of the house. On the contrary, it is almost directly proportional to the heating load. For Riverside, the setback reduces the load by about 20%, while for Minneapolis the reduction is about 6%. However, the error in the interpolation method's prediction appears small when expressesed as a percentage of the total load; 8% error for the loose house and 3% for the tight house. It is for this reason that figures 3 and 4 show such excellent agreement.

This suggests that the interpolation formula may be used in a narrow range to predict accurately the load change produced by a component change, but that it may also be used with the same percentage accuracy over a much wider range to predict the total load of a house.

For example, the total load of Minneapolis house #-6 is predicted to within less than 8%, with or without the thermostat setback, while the predicted load change for a thermostat setback for the same house is in error by almost a factor of five. It should be noted that this conclusion applies strictly only to those measures considered here, viz. ceiling insulation; wall insulation; floor insulation; window size, glazing and orientation; infiltration rate; and thermostat setback. There are a number of parameters which were not varied, including thermostat setting (except for night setback), cooling schedule, thermal mass, floor area, and shading. Such parameters could interact more strongly than those we studied. For example, exploratory DOE-2.1 runs for cooling loads in Davis, CA, indicate a strong interaction between infiltration rate and cooling schedule, and systematically higher cooling loads per unit area for smaller houses.

POINT SYSTEMS

For houses within the region where the total house load is well predicted, the interpolation formula may be used as the basis of a simple rating system [4]. If the system is required to predict the heating and cooling loads, the figures in Table 2 can be used. If the system is required to produce an overall figure of merit for heating and cooling energy use, the values in the tables can be multiplied by appropriate conversion factors to account for heating and cooling system efficiency. For example, if the chosen figure of merit is the resource energy used per square foot of floor area per year, the conversion factors are:

$$\text{Heating factor} = \text{Area}^{-1} \times \text{Efficiency}^{-1} \times \text{Resource constant}$$

$$\text{Cooling factor} = \text{Area}^{-1} \times \text{COP}^{-1} \times \text{Resource constant}$$

For the house in Minneapolis, with gas heating (efficiency 70%) and electric cooling (SEER 5.3) and an area of 1540 ft^2, these factors are 0.93 and 1.23 respectively. The units of the figure of merit are thousands of Btu of resource energy per ft^2 per year, with electricity counted at 11600 Btu per kWh. For the sake of brevity, this unit is called one "point", and the method used to produce it a "point system". A table of points for the Minneapolis house is given in Table 4.

This table, with sub-tables to correct for different heating and cooling system efficiencies, may now be used to rate Minneapolis houses, with over 150,000 different combinations of components. The points for each component are simply added. For the vast majority of these houses, the rating provided by such a point system will be within 10% of the rating that would have been produced had an individualized DOE-2.1 run been made, providing that there are no gross differences between the base house and the rated house in parameters for which points are not awarded. These parameters include, for example, size, shape, and window shading. For an area with a mixture of housing types, separate point systems might have to be developed, for example for ranch houses and town houses.

TABLE 4

A Point System for Minneapolis Single Family Homes, Gas or Oil heated.

Ceiling insulation		R19	R30	R38	R49	R60	
		8.4	3.4	1.5	0.0	-1.1	
Wall insulation			R11	R19	R27		
			9.6	3.3	0.0		
Basement insulation	None	4´ R5	4´ R10	8´ R5	8´ R10	R19	
	16.2	8.6	5.4	4.7	0.0	-0.9	
Infiltration				Loose	Normal	Tight	V. Tight
				9.1	0.0	-9.1	-17.7
Setback thermostat					Yes	No	
					0.0	2.1	

Glazing as a percentage of floor area

(a) North+East+West	Single	Double	Triple
2.5%	0.8	-3.0	-4.3
5%	7.7	0.2	-2.2
7.5%	14.9	3.6	0.0
10%	22.0	7.0	2.2
15%	36.4	14.1	6.9

(b) South glass	Single	Double	Triple
2.5%	4.6	1.1	0.0
5%	9.9	2.6	0.7
7.5%	15.3	4.7	1.5
10%	20.7	7.1	2.4
15%	32.2	11.3	4.9

Note:
R19 basement insulation is in floor
Thermostat setback is from 70°F to 60°F from midnight to 6am.

Since accuracy tends to decrease the further the rated house diverges from the base house, new houses, being more uniform in construction, are easier to rate than existing houses.

The point system does not account for behavioural and other effects which tend to make actual energy use rather different from calculated energy use. It is no more and no less than a simplified method of presenting processed results of energy use calculations, and reflects the accuracy of the calculational model. There is no limitation on the energy model used to construct the point system. As long as the measures considered do not interact substantially over the range of houses to be considered, any model may be employed [5,6].

CONCLUSION

The point system presented can be used for ranch houses in Minneapolis. It would be extremely simple to develop a similar system for another house type in another weather zone, perhaps using another building energy model. The interpolation method on which the system is based was tested for a series of houses in Riverside, CA, and Minneapolis, MN, weather. The hypothesis of linear additivity of load contributions from all components of the house was found to hold over a rather wide range, though thermostat setback was better predicted as a multiplier. It predicted heating and cooling loads within 15% of those predicted by individualized DOE-2.1 runs, except for some negative heating loads. However, the difference in load caused by a change in one component is less well predicted. The predicted load changes from thermostat setbacks in loose houses in both Riverside and Minneapolis were in error by almost a factor of five. The method could be improved, at the expense of added complexity, by the addition of cross terms to account for the interaction between components.

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