DEFINITION AND CALCULATION OF A NORMALIZED BUILDING ENVELOPE THERMAL LOAD

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ABSTRACT

The recently completed Minnesota Energy Efficient House Research Project required the analysis of the energy performance of over 100 houses of 25 design types. In order to compare the various energy efficient design strategies employed in these houses, a technique for calculating a normalized thermal load that would be independent of occupant usage patterns was developed. Of the various thermal load measures in use today the model developed in this paper is most like the Iowa Home Heating Requirement described at the 1984 ACEEE Summer Study.

The method developed uses a simple linear load line to model the increase in envelope thermal load that occurs with decreasing ambient temperature. The slope and intercept of this load line are found by using a least squares technique to fit the total metered energy thermalized within the envelope to the ambient temperature for each measurement period for which the average ambient temperature is below the balance temperature of the house. If the total metered energy were the only energy thermalized within the envelope, and if it were thermalized only to ambient temperature, then this load line would have an intercept equal to the setpoint temperature for the house. Analysis of metered data show, however, that the intercept may be below or above the setpoint temperature indicating that additional sources and sinks of energy are present within the house envelope. These additional contributions are conjectured to be solar and metabolic gains, and below grade and gray water losses of energy. By quantifying the metabolic and gray water values, and using measured interior temperatures to make a setpoint temperature adjustment, a normalized thermal load may be determined for each house.

For this study the parameters required for determining the normalized thermal load were obtained by applying the Princeton Scorekeeping Method (PRISM) to metered data for each house. Calculation of the standard errors for the normalized thermal loads found using this method, plus an examination of the method using heating season data only, indicated that this application of the PRISM program was reliable for the houses examined in the study.

Because the proposed method divides envelope losses into ambient temperature dependent and ambient temperature independent components, a more detailed thermal load signature emerges. Sample results are presented to illustrate the effects that solar apertures and varying below grade losses have on the total thermal energy required by a building envelope.

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INTRODUCTION

The recently completed Minnesota Energy Efficient House Research Project required the analysis of the energy performance of over 100 houses of 25 design types (Hutchinson, et al., 1984). In order to compare the various energy efficient design strategies employed in these houses, a technique for calculating a normalized thermal load that would be independent of occupant usage patterns was developed. This load is defined to equal the annual sum of all metered energy thermalized within the house that is utilized for space heating, exclusive of the solar energy collected by the house, but including corrections for the gains and losses due to occupancy. Of the various thermal load measures in use today the model developed in this paper is most like the Iowa Home Heating Requirement described at the 1984 ACEEE Summer Study (Hodges, 1984).

DEFINITION OF NORMALIZED THERMAL LOAD

The definition of the normalized thermal load is based on the observation that as the outside temperature decreases the heating load of a building increases. This is shown by the building load line in Figure 1. In this figure the total energy thermalized within the envelope is plotted as a function of the average ambient temperature. If the building being modeled in Figure 1 were unoccupied, windowless, and built on insulated stilts all of the energy thermalized within the building envelope would be thermalized to the outside temperature. In this case the temperature T' at which the building would require heat from some source of energy would be equal to the setpoint of the thermostat within the building envelope. Below T' the energy that is required to be thermalized within the envelope increases with decreasing temperature with a slope proportional to the thermal loss coefficient for the building envelope.

Next assume that the envelope being modeled in Figure 1 is set into the ground or built on conducting stilts. Beyond the ambient temperature dependent load discussed above, the envelope now experiences an ambient temperature independent load due to thermal conduction into the nearly constant temperature soil mass supporting the structure. This will uniformly increase the building thermal load for all ambient temperatures and move the intercept temperature T' to some new value above the setpoint temperature as shown in Figure 1. Physically, for ambient temperatures above the setpoint temperature, but below T', the building's below grade thermal losses are being met by thermal gains due to the conduction of heat through the above grade portions of the building envelope. This is unlikely to occur in practice, since most occupants would simply ventilate the building so that the required heat would be provided by convection rather than conduction.

The above division of the building load modeled in Figure 1 into ambient temperature independent and ambient temperature dependent parts allows for the definition and calculation of a normalized thermal load. The normalized thermal load is defined to equal the annual sum of all metered energy thermalized within the building envelope that is utilized for space heating to maintain the interior temperature at a normalized setpoint temperature of T_n. In order to calculate this load three additional ambient temperature independent terms need to be considered. These are gains due to solar radiation, and metabolic gains and gray water losses due to occupancy. Solar gains reduce the amount of metered energy required to heat the building envelope, and are therefore directly included in the model where they are quantified as a temperature independent gain. In contrast to the effect of below grade losses that increase the temperature T', solar gains are assumed to uniformly lower the thermal load line shown in Figure 1 and therefore act to decrease T'. Metabolic gains and gray water losses due to occupancy, however, require the direct addition of a correction factor to the temperature independent component of the normalized thermal load. This correction will be discussed in detail in the calculation section of this paper.

Based on the above discussion and using Figure 1 we may develop an expression for the normalized thermal load. The temperature dependent thermal load is set equal to the slope β times the number of degree days for a base temperature equal to the normalized setpoint temperature, T_n. The setpoint temperature, T_n, is arbitrary but should be set equal to a reasonable temperature for comfort, such as 68° F. Use of a degree day base temperature equal to the comfort setpoint temperature is appropriate in this case, since all metered energy sources thermalized within the building envelope are included in the determination of the load line. That is, internal gains do not explicity appear in this model, since the thermal gains provided by either a furnace or by internal sources are considered to be indistinguishable.

The temperature independent thermal load is set equal to the daily average temperature independent thermal load times the number of days for which the average temperature is below the normalized comfort setpoint temperature, T_n. The daily average temperature independent load is defined as the value of ε shown in Figure 1, where ε is equal to the daily average temperature independent thermal load based on a building setpoint temperature T_{set}. In Figure 1, ε is equal to the vertical offset in the load line that causes the difference between the values of T_{set} and T' discussed earlier.

From the above discussion we may write the following expression for the normalized thermal load (NTL) as the sum of the temperature dependent and temperature independent thermal loads.

$$\text{Normalized Thermal Load} = H_o\,(T_n)\,\beta + D_o\,(T_n)\,\varepsilon \qquad (1)$$

where

T_n - Normalized thermostat setpoint temperature

$H_o(T_n)$ - Number of heating degree days below T_n

$D_o(T_n)$ - Number of days for which average temperature is below T_n

The value of β in Equation 1 is equal to the slope of the load line shown in Figure 1, and is a measure of the conduction and infiltration losses of the building envelope. The value of ε in Equation 1 may be found by geometry from Figure 1, and is written as follows,

$$\varepsilon = \beta\,(T' - T_{set}) \qquad (2)$$

As discussed above, the temperature T_{set} in Equation 2 is the setpoint temperature for the particular building being analyzed. The setpoint temperature normalization represented by Equation 2 yields an ε that is independent of the difference between T_{set} and the normalization temperature, T_n, chosen in Equation 1, and thus assumes that below grade losses for any particular building are independent of this temperature difference. This is shown by the normalized building load line in Figure 1. Finally, occupancy effects are accounted for by the direct adjustment of ε for metabolic gains and gray water losses.

The slope and intercept of the load line shown in Figure 1 may be calculated using a least-squares technique to find the load line that best fits the thermal energy consumption to the average temperature during each measurement period. For a typical building the thermal energy consumption data required for this analysis would be equal to the sum of the thermal energy provided by combustion appliances plus electrical energy thermalized within the building envelope for any given measurement period.

ANALYSIS OF METERED DATA

The analysis required is actually more complex than simply fitting a straight line to the metered data for any particular house because the metered base energy use per day does not go to zero at T' as shown in Figure 1. Typically the base metered energy use will be equal to some average summer value as shown by the dashed line in Figure 1. The intersection of this base use line with the load line in Figure 1 occurs at the balance point temperature of the house being examined. At this temperature the thermal load of the envelope exceeds the internal gains provided by the base use, and the heating system turns on to provide the additional heat required. It needs to be remembered that while the furnace will not come on until the ambient temperature is equal to the balance temperature, the house still requires thermal input from some source of energy to provide space heat between the setpoint and balance temperatures. Excess thermal input not required for space heat between these temperatures is not included in the present analysis, since the NTL as defined by Equation 1 is designed to include only the total useful energy required to maintain the space temperature at the setpoint temperature T_{set}.

Because of the above observation, the intercept T' cannot be obtained directly, but must be determined by extrapolation of the load line from the point (T_{bal}, α) as shown in Figure 1. Thus, beyond a simple least squares fitting routine, a procedure for determining the (T_{bal}, α) point is required as a part of the analysis. While a less sophisticated program could have been written, the ability of Princeton University Scorekeeping Method (PRISM) program to determine the best balance point temperature, plus its availability and reliability made this program the logical choice for performing the required analysis (Fels, 1984). The PRISM program calculates the α, β, and T_{bal} parameters shown in Figure 1 so that a value for the Princeton normalized annual consumption (see definition in Fels, 1984) is best determined in the least squares sense. The current work uses the T_{bal} and α values provided by the PRISM program to define the (T_{bal}, α) point shown in Figure 1. Together with the β value provided by PRISM this point completes the point-slope specification required for the determination of the load line defined in the present study. From the geometry of Figure 1, the temperature T' required to complete the present analysis may be written as follows,

$$T' = T_{bal} + \alpha / \beta \qquad (3)$$

The Princeton PRISM program is designed to find a value for T_{bal} that yields the greatest r-squared statistic for the calculation of the normalized annual consumption. Because of the difference between the definition of the normalized annual consumption (NAC) as calculated by the PRISM program and the normalized thermal load as defined in this paper, additional analysis was done to examine the reliability of PRISM program for this application. From an examination of Figure 1 it can be seen that the NTL should in theory be independent of those data points for which the average outside temperature is above T_{bal}. That is, because the NTL is a heating only model, it should be independent of summer consumption data. This was demonstrated by repeating PRISM runs for data sets from which the summer data had been removed. These additional PRISM runs showed that the NTL model yielded nearly the same results whether full or truncated data sets were used for the analysis. A complete discussion of this analysis appears in the final project report (Nelson, et al., 1986).

Also examined in the final project report is the precision of the method presented in this paper. It is well documented that the NAC as calculated by the PRISM program is better determined than the individual α, β or T_{bal}

fitting parameters due to the presence of internal cancellations within the calculation for the NAC (Fels, 1984). Thus, a slope β with a 10 percent standard error can be used along with the corresponding α and T_{bal} to calculate an NAC with a standard error of 5 percent or less. A central question in the present analysis is whether or not the normalized thermal load as defined in Equation 1 is an equally reliable measurement of building performance. The answer to this question appears to depend on which of the fitting parameters are considered to be independent. Using an analysis that assumes a zero covariance between all the parameters except T_{bal} and α, yields values for the NTL that have about twice the percentage error as the NAC. Because the NTL is usually smaller than the NAC, the absolute errors of the NTL are somewhat better than this. If non-zero covariances are assumed between all parameters, as is done for the calculation of the NAC, then the NTL has about the same percentage error as the NAC (Hurvich, 1986). If the temperature independent thermal load and the temperature dependent thermal load are assumed to be independent variables for the envelope performance model describe here, the appropriate standard error for the NTL is then about twice the standard error of the NAC.

CALCULATION OF THE NORMALIZED THERMAL LOAD

Application of PRISM Program to Metered Data

The definition of the normalized thermal load requires that the parameters describing the envelope load line in Figure 1 be calculated using the sum of all energy that is thermalized within the envelope. For the purposes of the present study, 100% of the electric energy plus 70% of the energy due to gas combustion was used as the PRISM input energy for each meter reading period. These numbers were assumed to describe the entire group of houses, and could be refined for each house through a more detailed analysis of appliance efficiency. As a part of the Energy Efficient House Research Project paid and volunteer meter readers provided weekly simultaneous electric and gas meter readings on 65 houses for a period of one year. Areas served by the same utility for both electric and gas service provided an additional 12 houses, yielding a total of 77 houses with simultaneous meter readings. Overall, including utility data, good metered data were available for 127 of the houses in the research program. These data were then analyzed using the PRISM program installed at the University of Minnesota Computer Center. For these data, the quality of fit for determining the normalized annual consumption as calculated by the PRISM program was quite good. For the 127 PRISM runs completed for this study, the majority , 97 (76 percent of the total), had a standard error for the NAC of less than 5 percent, with only four having a standard error greater than 10 percent.

Using the results of the above PRISM analysis and Equations 1 to 3, the normalized thermal load was calculated for each house in the research program. These results are shown in Table I for a portion of those houses for which simultaneous gas and electric meter readings were available. For those 50 houses for which only separate readings were available, the PRISM analysis was applied to only the gas meter readings, and then the average winter electric consumption was added to ε before the NTL was calculated using Equation 1. This second technique corresponds most closely to that used in the calculation of the Iowa Home Heating Requirement, and a complete table of these results (similar to Table I) appears in the final project report.

Overall the NTL was calculated for 119 houses. For these houses the majority, 67 (56 percent of the total), had a standard error of 5 to 10 percent. Of the remaining houses, 27 (23 percent of the total) had a standard error of less than 5 percent, and 25 (21 percent of the total) had a standard error of greater than 10 percent.

As discussed earlier for any given house, the percent standard error of the NTL is about twice as large as the percent standard error of the NAC, but less than the percent standard error of the slope, β . Because the NTL is smaller than the NAC, the absolute errors of the NTL are actually better than this, and range fom one and one-half to two times greater than the absolute errors of the NAC.

Setpoint Temperature Correlation

The calculation of the NTL as shown in Table I requires that the setpoint temperature in Equation 2 be known for each house. For this study 47 of the 119 houses were equipped with battery driven strip chart temperature recorders, and the setpoint temperatures for these houses were taken to be the measured interior temperatures averaged over three winter months. For the rest of the houses in the program the setpoint temperatures were based on the following correlation formula,

$$\begin{array}{c}\text{Average}\\ \text{Setpoint}\\ \text{Temperature}\end{array} = 16.35 + .33\ T_{setup} + .46\ T_{setback} \qquad (4)$$

where T_{setup} and $T_{setback}$ were self-reported thermostat setup and setback temperatures obtained from a homeowner survey conducted during the research project. The correlation shown in Equation 4 was found by multiple regression using the measured and self-reported data from the set of 47 submetered houses mentioned above. It is interesting to note that for equal setup and setback temperatures of 68^{o}F that Equation 4 yields an average setpoint temperature of 70^{o}F, in good agreement with the belief that actual setpoint temperatures tend to be a few degrees higher than self-reported temperatures.

Occupancy Effects

Variation in occupancy among units requires that the metabolic gains and gray water losses be determined for each house. For much of the original study these values were assumed to cancel exactly, since they are opposite in sign and roughly similar in magnitude (Hodges, 1984). However, in completing the study it was demonstrated that this was a rather poor assumption, since the gray water loss per person was found to be about three times larger than the metabolic gain. This net loss due to occupancy was found using two methods. The first was based on the observation that the energy required to heat domestic hot water decreases as the supply water temperature increases. In this analysis a least squares technique was used to fit the energy required for domestic hot water to the average water supply temperature for each measurement period. If the water heater efficiency is known it can be shown that the slope of the best fit line is a measure of the average volume of hot water delivered at any temperature above the supply temperature, and that the intercept is a measure of the average temperature of this water (Nelson, et al., 1986). Given these average consumption values (325 gallons/person-week delivered at 101°F), plus the annual average supply water temperature, the annual average gray water loss may be readily found. For an average supply water temperature of 55°F, the average gray water loss can be shown to equal about 17,800 Btu/person-day. Metabolic gains were estimated using the ASHRAE metabolic value of 360 Btu/hour for an adult at rest, and assuming an average occupation time of 14 hours per day, to yield an estimated average gain of 5,000 Btu/person-day. For the 287 day heating season assumed in this analysis, the above factors yield a net loss of 37 therms/person per year. The second method used a multiple regression analysis to examine the dependence of the temperature independent energy on the number of occupants in each house. When this was done using a subgroup of houses with stable occupancy, a significant correlation of 39 therms/person per year was found, in excellent agreement with the above calculated value.

From the above analysis a value of 35 therms/person per year for the net loss due to occupancy was chosen as an adjustment factor for the normalized thermal loads shown in Table I. This value was chosen to be somewhat smaller than the above numbers since it is likely that some of the gray water energy remains within the house envelope. The occupancy adjustment for each house was calculated based on the occupancy factor shown in Table I. This factor is equal to the number of adults in each house plus one-half the number of children under the age of 12, and is based on data obtained from the homeowner survey mentioned earlier. The total occupancy correction was then calculated by multiplying the average annual loss of 35 therms/person by the occupancy factor for each house. This correction was then subtracted from the annual temperature independent load, $D_0(T_n)\,\varepsilon$, in Equation 1 to yield the temperature independent load values shown in Table I. As discussed above, as the temperature independent load decreases, T' also decreases, and this is shown by the reduced values for T' in the column labeled "ADJUSTED T PRIME" in Table I.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

As discussed in the INTRODUCTION the building load model described in this paper was developed as an analysis tool for the evaluation of a specific group of cold climate energy efficient houses. The reliability of the method as applied to this set of houses is verified in the final project report (Nelson, et al., 1986). It needs to be emphasized, however, that the PRISM program application described in this paper differs from that developed by the program authors, and that the general applicability of the analysis presented here requires further evaluation.

Table I presents a variety of results that yield insight into the use of space heat in residential envelopes. From Table I it can be seen that one-half of the houses have T' temperatures that exceed the setpoint temperature. Since T' is the ambient temperature at which the house requires space heat, we can make the physical interpretation that for these houses space heat is required at ambient temperatures above the setpoint temperature. This requirement for space heat above the thermostat setpoint could explain in part the anecdotal observations that houses seem cold in the fall and the spring. This effect was dubbed "The mental-thermal lag effect" at the 1984 ACEEE meeting where it was a lively source of spontaneous speculation. Because the requirement for space heat above the setpoint temperature is most likely due to thermal losses to the below grade portions of the structure, the coupling between the above and below grade portions of a house becomes an important factor for maintaining comfort during the fall and spring seasons.

The results in Table I for units 1 - 8 by builder A provide an interesting example of the normalized thermal load model. For these houses the temperature independent load varies over a large range from -131 to 146 therms/year, yet the total normalized thermal load is relatively well behaved and clearly shows the end, middle, middle, and end locations of units 1 - 4 and 5 - 8 in these two quadplexes. It would be interesting to return to these houses to see why their energy consumption signatures are so varied.

The houses by builder M in Table I had the largest solar apertures of all the houses in the research study. From survey data, all the homeowners in this development used window insulation at night except the owner of unit 84. Does the large negative temperature independent load balanced by a large temperature dependent load indicate the presence of an uncontrolled thermal flux due to solar energy input during the day and a large aperture loss at night?

Finally, the houses by builder N show the effect of varying house design. Units 94 and 95 by this builder are of split entry design and have shallow below grade areas, while units 96 and 97 are walkout rambler designs that have a larger portion of their envelope below grade. As can be seen in Table I the total normalized thermal loads for this group of houses are somewhat comparable. However, an examination of the ambient temperature independent and dependent loads indicates that these two designs perform differently with the rambler designs showing greater temperature independent loads. From the above examples, it appears that the normalized thermal load and its temperature independent and temperature dependent subcomponents may reveal information about energy use in houses that is not available using other techniques.

Beyond the above building signature analysis, a principal advantage of the normalized thermal load as defined in this paper is that it is a true heating only model, and because of this can be used to evaluate the total space heating performance of a building envelope.

As discussed earlier, the building load model developed in this paper has been shown to yield a reliable energy use index for the specific set of cold climate houses examined in this study. Further work is required to establish the general applicability of the method, and to evaluate the more detailed building energy signature that has emerged. Specifically, the standard error of the NTL needs to be examined in detail, including the measurement errors inherent in the setpoint temperature and occupancy normalization factors (Hurvich, 1986). The value of the normalized thermal load compared to other measures of building energy performance, in particular the Princeton normalized annual consumption, needs to be examined by applying these methods to a diverse group of houses located in different climates. A comparison of the NTL calculated with and without using total consumption values is needed to yield insight into the necessity and value of using simultaneous gas and electric meter readings for the evaluation of building performance. A follow-up study using the present set of data to make a detailed comparison of the normalized thermal load developed here with the Princeton normalized annual consumption would be a good start at the above tasks.

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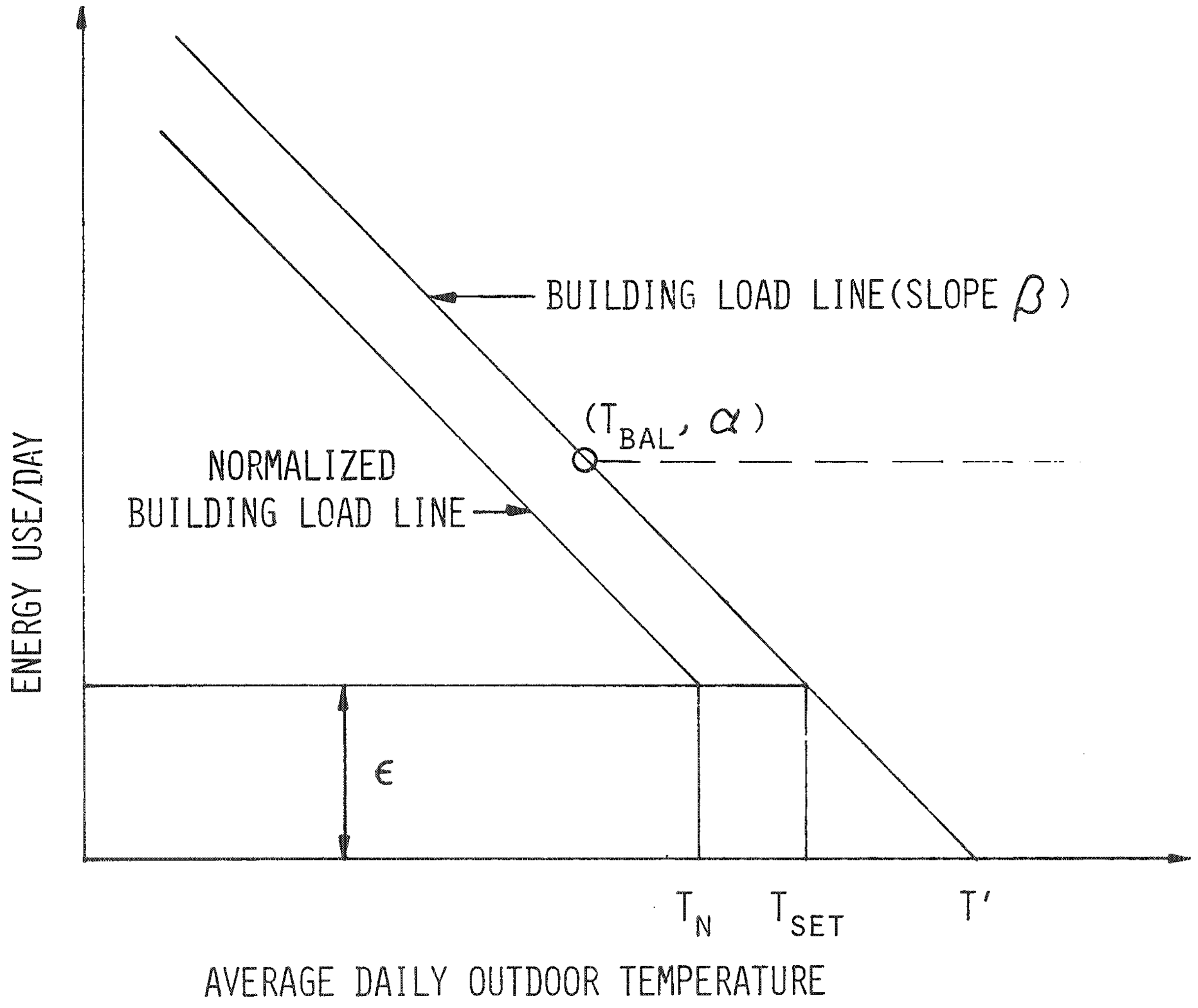

FIGURE 1. Heating only model used to calculate the normalized thermal load. The energy use per day consists of all metered energy thermalized within the building envelope. T_{set} is the actual building setpoint temperature, and T_n is the normalized setpoint temperature. The daily average temperature independent energy, ε, is calculated based on T_{set} and is assumed to be independent of T_n. The point(T_{bal}, α) and the slope β are found using the Princeton University PRISM program. This point-slope specification is then used to determine the building load line shown.

TABLE I. PRISM program results and normalized thermal load (NTL) values for three house groups with simultaneous gas and electric meter readings. Results for all builders are shown in the final report. Houses by builder A are attached and differ in the number of common walls. Houses by builder M are large aperture detached houses of identical design. Houses by builder N are detached, and are split level and walkout rambler designs. Thermal load values have been normalized for setpoint temperature and occupancy (see text).

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	SETPOINT TEMP (F)	T PRIME (F)	OCCUPANCY FACTOR	ADJUSTED T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)	STD ERROR OF THERML LOAD (CCF/YR)
BUILDER A											
1	58.01	.794	.0413	70	77.24	2	71.42	17	367	384	34
2	41.46	1.006	.0346	67	70.54	2	63.60	-34	308	274	18
3	47.12	.548	.0338	65	63.33	1	59.78	-51	300	250	22
4	52.01	1.103	.0365	68	82.23	2.5	74.01	63	324	387	26
5	57.68	.638	.0423	66	72.76	1	69.93	48	376	424	30
6	42.61	.909	.0349	68	68.66	4	54.90	-131	310	179	19
7	61.07	.767	.0266	72	89.90	3	76.37	33	236	270	20
8	70.01	.809	.0292	70	97.72	2.5	87.44	146	260	406	36
BUILDER M											
84	51.06	1.035	.0864	70.27	63.04	3	58.87	-283	768	485	98
82	47.57	.359	.04	59.15	56.55	2	50.55	-99	356	257	30
83	55.8	.864	.0516	69.35	72.54	2	67.89	-22	459	437	28
85	60.74	.459	.0534	69.81	69.34	2	64.84	-76	475	398	27
BUILDER N											
94	45.29	1.332	.05	67	71.93	2	67.13	2	444	446	36
95	48.89	.871	.0461	67	67.78	2	62.58	-59	410	351	30
96	59.01	1.082	.0347	68	90.19	4	76.36	83	308	392	43
97	54.22	1.197	.0418	68	82.86	2.5	75.68	92	372	464	41