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HEAT BALANCE RELATIONS IN FUEL–HEATED HOUSES

by C.P. Hedlin

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RÉSUMÉ

Le bilan thermique d'une maison dépend des apports et des pertes de chaleur. En combinant les mesures de consommation de combustible pour le chauffage et l'eau chaude avec les apports thermiques dus aux occupants, au rayonnement solaire et aux appareils électriques, on a pu évaluer l'apport thermique total dans l'espace habitable en fonction des températures extérieures. Les pertes de chaleur ont aussi été calculées en fonction des températures extérieures. On a pu ainsi estimer le rendement d'installations de chauffage à partir des résultats présentés sous forme de graphiques.

Les modifications dans la relation entre la consommation de combustible et les températures extérieures sont présentées pour plusieurs maisons dont l'isolation thermique a été améliorée. Dans deux cas, la mise en place d'un isolant de
valeur RSI 2 les murs du
sous-sol (pr 30 pour cent
la consommat

No. 2839

Heat Balance Relations in Fuel-Heated Houses

C.P. Hedlin, Ph.D.
ASHRAE Member

ABSTRACT

The heat balance in a house depends on heat inputs and heat losses. By combining measured fuel consumptions for the furnace and hot water system with estimated heat gains from occupants, solar radiation, and electrical appliances, total useful space heat inputs were estimated as a function of outdoor temperature. Heat losses were also calculated as a function of outdoor temperature. From the resulting graphical relationships, estimates were made of heating system efficiencies.

Changes in the fuel consumption-outdoor temperature relationship are given for several houses to which insulation was added. In two cases, addition of RSI 2 insulation to the attic and RSI 1.5 to basement walls (previously uninsulated) reduced fuel consumption by about 30%.

INTRODUCTION

In Canada a large part of the energy supplied to houses is used for space heating. As a consequence, there is a long history of study of heat loss and its control. Much of this work has involved laboratory investigation of individual components whose performance can be studied in isolation. Houses can also be studied as systems under field conditions, in which case a wide variety of interactive effects comes into play. Although some individual effects may be obscured, results are based on practical field conditions and constitute an important complement to controlled studies.

A comfortable interior environment requires maintenance of proper balance between heat loss and heat input. House-to-house variations in heat loss will occur even for houses of the same size. The type and state of repair of the heating system, the management or occupancy condition, and the condition of the structure all affect the result. On the other hand, houses in the same geographical area are subject to substantially the same weather conditions and the same basic heat loss phenomena (e.g., stack effect) and thermal conduction apply to all of them. Consequently, heat-balance relations that apply to one will, within limits, be applicable to others.

The heat input to houses in cold weather normally includes fuel and electricity purchased from (and metered by) utility companies for space heating and other purposes, heat input from occupants, and solar radiation. Under conditions of equilibrium, net heat inputs are balanced by heat loss from the structure. The house, including its components (and occupants), comprises a system that can be subjected to analysis. In this study, the energy inputs and losses are considered in combination with meteorological data in the development of a

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graphical heat-balance relationship for housing systems of a type widely used in Canada (Hedlin and Orr 1977). Such a graph portrays the relationship between the variables over the range of outdoor temperatures and permits some deductions about their individual characteristics or about their interactions with other components of the graph. For example, the relation developed here can be used to estimate a thermal efficiency of the system at a given outdoor temperature and for a season.

Thus, this report explores relationships that may complement those developed in other studies and contribute to the solution of existing questions about heat balance in houses.

Results for three Saskatoon houses are used as examples. In these houses, natural gas is used for space and domestic water heating and electricity is used for other household needs including cooking.

House A is a four-level split design with a plan area of 110 m^2; houses B and C are full basement bungalows with plan areas of 93 and 100 m^2, respectively. The overall thermal resistances for walls and ceilings were about RSI 1.8 (2.1 $m^2 \cdot C/W$), except for the ceiling of house C, which was RSI 3.8. All are heated with natural gas furnaces having pilot lights. None have stack dampers. The combustion efficiency measured with an efficiency meter was 78% for house A and 76% for house C. It was not measured for house B.

Energy values are given in megajoules. Electrical quantities have been converted from kWh by multiplying by 3.6 (1 kWh = 3.6 MJ). Natural gas quantities were converted assuming a heat equivalent of 37.3 MJ/m^3.

The heat-balance relation involved the total heat loss from the structure on the one hand and all of the heat inputs on the other. Inputs include contributions of the occupants (E_O), electrical equipment (E_E), and the sun (E_{Sr}). The major contribution comes from natural gas (E_G), most of which goes to the space heating system (E_F); the remainder is used to heat water. The fraction of E_F that is converted into useful space heat equals ηE_F. Part of the heat from the water heating system (E_{HW}) also shows up as useful space heat. The remainder (E_{HWW}) is wasted.

The three main factors in the heat balance relationship are the weather variable, heat losses, and heat inputs.

THE WEATHER VARIABLE

In this study, the energy inputs are given as daily average (MJ/day) and plotted against a temperature (T) defined by the number of heating degree days (basis 18 C) as:

$$T = 18 - HDD \qquad (1)$$

HDD is the average number of heating degree days for the period involved -- one or more days.

In cold weather, T will be the same as the average outdoor temperature (T_a); however, if the period includes days when the average temperature exceeds 18 C, T and T_a will differ. T as defined by equation 1 can never exceed 18 C, while T_a may exceed 18 C.

Month-long averages of T_a and T for Saskatoon are plotted in figure 1. This relationship would probably vary with climate. The difference between T_a and T is about 2 C for T = 18 C, but decreases to approximately 0.5 C when T = 15 C. Since the following discussion is confined to temperatures generally lower than 15 C, T_a and T can be regarded as interchangeable with very little error.

The slope-intercept relationship

$$E = I + S\,(18 - T) \qquad (2)$$

is used to relate heat energy E (MJ/day) and temperature T (C) for heat inputs. I is expressed in MJ/day and S in MJ/day·C. Subscripts are used to identify the component referred to: E_G, I_G, and S_G would apply to all the natural gas consumed. Nomenclature is listed following the summary.

STRUCTURAL HEAT LOSS

In houses A and C, air infiltration was measured with a tracer gas (SF_6) unit, with which continuous monitoring can be done (Kumar et al. 1979). Decay measurements were also done with N_2O. With the first method, measurements were made over three-day winter periods. Some variability was found due to wind, but the averages of 0.2 and 0.18 air changes per hour (ac/h) (for houses A and C) were judged to be close enough for the purpose of this study. This represents all of the air exchange, without distinguishing between exit paths. In the calculation of infiltration heat loss, air was assumed to leave at house temperature. Furnace wastage associated with air exchange would be applied to chimney exfiltration losses, using the house temperature as a base.

For houses A and C, the average indoor temperature was 19 C, based on measurements taken on all four levels with a chart recorder. For house B it was estimated at 19 C, but was not measured. A computer program was used to estimate house heat losses for each month of the year (Dumont et al. 1982). The coefficients I and S of the equation

$$E_{St} = I_{St} + S_{St}(18-T) \qquad (3)$$

are given in table 1 for each house.

HEAT INPUTS

Heat sources include occupants, solar gain through windows, and by-product heat from electrical equipment and from the burning of natural gas.

Heat from occupants varies with the size and number of persons and with activity (ASHRAE 1981). The occupants of houses A and C were estimated to contribute 20 MJ/day and for house B, 30 MJ/day.

All of the heat from electrical equipment (measured by the utility company's meter) was assumed to be converted into useful space heat. In fact, a fraction of it would be lost by the use of exterior lights, occasional use of the car block heater, and a clothes dryer vented to the outside. These losses were not measured but were judged to be negligible compared to the total energy use. The coefficients for

$$E_E = I_E + S_E\ (18-T) \qquad (4)$$

are given in table 1 for the three houses. In all cases S_E was positive, reflecting increased use of electricity in winter time. Values for house A are shown in figure 2 for illustrative purposes.

In this study the effect of solar gain on walls and roofs was not considered. Useful gains through windows were estimated using a computer program (Dumont et al. 1982). Monthly estimates of solar gains are given in figure 2 for house A. Average values for the year, excluding June, July, and August are given in table 1.

Natural gas was burned in two separate units, a domestic water heater and a forced air furnace. From gas meter readings, daily average energy consumptions (E_G) were found. Each point in figure 3 (for houses A and B) represents a period of about two weeks. These are plotted against T. Intercept, slope and coefficients of correlation are given in table 1 for

$$E_G = I_G + S_G\ (18-T) \qquad (5)$$

for the three houses.

The above inputs can be combined to find the total heat input (E_{Tot}, table 1). This combination of inputs and losses is shown graphically in figure 4 for house A. For convenience, two groupings were used.

1. The heat from occupants (E_O), electrical appliances (E_E), and solar radiation (E_{Sr}) were added together (table 1):

$$E_D = E_O + E_E + E_{Sr} = I_D + S_D\,(18-T) \qquad (6)$$

2. The natural gas used for water heating in houses A and C (E_W) was estimated by recording the on-time of the water heaters and measuring their consumption rates. These were approximately 100 and 120 MJ/day, respectively. For house B the estimate was 160 MJ/day. Based on observations (personal communication with S. Barakat, National Research Council Canada), it was estimated that the useful heat from the hot water system amounted to 9 MJ/day + 8% of the gross input to the system. This amount added to E_D constitutes all of the miscellaneous space heat derived from sources other than the furnace. It was represented by E_M.

$$E_M = E_D + E_{HW} = I_M + S_M\,(18-T) \qquad (7)$$

Scatter and seasonal variation in the miscellaneous inputs were not taken into account in the analysis. Their effects should result in increased or decreased fuel consumption. No attempt was made to quantify such influences; however, the points in figure 3 differentiate between the January-to-June period and the July-to-December period.

SYSTEM EFFICIENCY

Studies indicate that the efficiency with which furnace fuel is converted to useful space heat is affected by a variety of factors including oversizing (Janssen and Bonne 1977; Chi and Kelly 1978; Sonderegger et al. 1980; Hise and Holman 1977; Kweller and Mullis 1981). The furnaces in both houses A and B were oversized, judged by the input needed to offset heat loss. The full-load balance-point temperatures (T_B), estimated using equation 8, were -72, -60, and -88 C for houses A, B, and C, respectively,

$$T_B = T_0 - \frac{(T_0 - T)}{L} \qquad (8)$$

where L is the percentage on-time at an outside temperature T. T_o is the temperature when $E_{St} = E_M$, i.e., when the structural heat loss is balanced by heat input from miscellaneous sources. Using figure 5, system efficiency can be defined as:

$$\eta = \frac{E_{St} - E_M}{E_F} \qquad (9)$$

where $E_{St} - E_M$ is the space heat required from the furnace, and E_F is the heat equivalent of the fuel supplied to the furnace. This is shown in figure 6 for the temperature range of +13 to -60 C.

An estimate of seasonal efficiency (η_y) can be made using the equation

$$\eta_y = \frac{\sum_{i=1}^{N} \eta_x E_F}{\sum_{i=1}^{N} E_F} \qquad (10)$$

In the present case, a computer was used to find η_y and E_F for each of the N days of the heating season. The temperatures, taken from meterological records, were averges of the mean daily temperatures for a 30-year period. For houses A, B, and C, the seasonal efficiencies were 69, 67, and 58%, respectively. The length of the heating season (N) ranged from about 250 to 270 days.

The method of computing efficiency is very sensitive to errors in the estimates of miscellaneous heat and structural heat loss and to errors in measurement and representation of fuel consumption. For example, if E_M was 50 MJ greater than the amounts given here, estimated seasonal efficiency would be approximately 10 percentage points lower in each case. If E_M were 50 MJ lower than indicated, the estimated seasonal efficiencies would be approximately 10% higher.

At full load, steady-state conditions, the efficiency (η_o) for the system is achieved. If this efficiency were maintained at all load conditions, the furnace fuel consumption could be represented by a line $E_F{}^1$ passing through the point where the structural heat loss line (E_{St}) meets the miscellaneous heat line (E_M, figure 6). It would have a slope

$$S_F{}^1 = (S_{St} - S_M)/\eta_o \ . \tag{11}$$

If S_M is zero, then

$$S_F{}^1 = S_{St}/\eta_o \ . \tag{12}$$

If extended in the other direction, this line would theoretically meet the $E_F + E_M$ line at the full-load balance-point temperature (T_B).

If $S_F = S_G$, then a simple relationship can be developed between S_G and S_{St}.* In figure 6 the intersection of E_{St} and E_M is used as the origin corresponding to temperature T_o. Then

$$E_F = A_G + S_G\ (T_0-T) \qquad \text{MJ/day} \tag{13}$$

where A_G is the apparent furnace consumption at T_0.

$$A_G + S_G\ (T_0-T) = \frac{(S_{St} - S_M)(T_0-T)}{\eta_o} + A_G \frac{(T - T_0)}{(T_0 - T_B)} \tag{14}$$

then

$$\frac{(S_{St} - S_M)}{(\eta_o)}\ (T_0-T) = S_G\ (T_0-T) + A_G \left[1 - \frac{(T - T_0)}{(T_0 - T_B)}\right] \tag{15}$$

and

$$S_{St} - S_M = \eta_o \left[S_G + \frac{A_G}{(T_0 - T_B)}\right] \tag{16}$$

If $S_M = 0$

$$S_{St} = \eta_o \left[S_G + \frac{A_G}{(T_0 - T_B)}\right] \tag{17}$$

LINEARITY OF NATURAL GAS CONSUMPTION/HEATING DEGREE-DAY RELATIONSHIPS

The intersection of E_{St} and E_M lines (figure 6) suggests that the transition from the heating to nonheating season occurs abruptly at about 13 C. Above 13 C, fuel would be consumed only by the furnace pilot light and the domestic water heater. That would be inconsistent with the fact that the $E_F + E_M$ line intersects the E_M line at a higher temperature ($T_M{}^1$). In practice, there appears to be a transition period between the regular heating season and the nonheating season that has unique heating requirements. Some space heat may be used to take the chill off the house in the morning during the transition interval (Reeves 1981; Myer and Benjamini 1978). The temperature span for this transition region is short and there are not many points in the interval above 10 C (figure 3). Though fine detail is missing, points in the vicinity of T = 10 appear to fall somewhat below the line of best fit. The existence of such a deviation was demonstrated by a statistical treatment of data for a large number of houses - similar to those described in this report. In that (unpublished) report, the departure from linearity was shown to begin when the temperature exceeded about 8 C.

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*In this model $S_F = S_G$, provided that the amount of fuel consumed by the water heater is independent of T.

In the nonheating season, the furnace would not come on; all the natural gas used would be for hot water and the furnace pilot light. Properly speaking, the data points for that period should not be included. However in this study, their inclusion does not greatly affect the results. Dropping off all the points corresponding to outside temperatures above 10 C for eight sets of data, including the six most populous sets in figures 3 and 7, produced differences in slope of up to 4%. The absolute average was 1.7% and the arithmetic average was +0.2%.

FUEL CONSUMPTION COEFFICIENT AS A MEASURE OF HOUSE THERMAL PERFORMANCE

The fuel consumption coefficient (S_G) is approximately equal to both the heat input coefficient (S_{Tot}) and the furnace consumption coefficient (S_F). If S_G is used to represent S_{Tot} the percentage error is

$$\left[\frac{S_D}{S_{Tot}}\right]100 \ . \qquad (18)$$

In the case of house A, represented in figure 3, that error would be

$$\left[\frac{-0.3}{25.1}\right] 100 = -1.2\%.$$

For houses B and C, the errors would be 3.0% and 0.5%, respectively.

S_F and S_{Tot} are indicators of energy use for space heating in houses.* As their approximate equivalent, S_G can serve as a measure of house thermal performance. It should be nearly independent of interior temperature. It might be used for comparing one house with another or to estimate the improvement achieved by adding insulation to a house. In the former case, it should be noted that S_D will play a part. For example, two houses may have identical heat input coefficients; however, since

$$S_{Tot} = S_G + S_D$$

the value of S_G will be affected by S_D.

The effect of adding insulation to three houses is illustrated in figure 7. In house B, insulation with RSI 1.2 was added to half of the interior basement wall, from the top of the wall to approximately 1.2 m below grade. Insulation was also added in the attic. In house C (a 100 m^2 bungalow), insulation with RSI 1.5 was added to the previously uninsulated basement walls. Approximately RSI 2 was added to the attic. In house D (a 106 m^2 bungalow) RSI 2.1 was added to the attic, reducing fuel consumption to E_{G2}. Then the basement was insulated and fuel consumption was reduced further to E_{G3}. For house B, S_G was reduced by only about 6%. For C and D, it was reduced by about 30%.

SUMMARY

Heat loss from houses is partly balanced by heat inputs from miscellaneous sources such as occupants, solar radiation, electricity, and the hot water heating system. The remaining requirement is met by the space heating system. The combination of energy inputs on one hand and heat losses on the other represents the heat balance for the house.

In this study, energy inputs and heat losses were estimated as functions of heating degree days (18 C base). A temperature scale is superimposed on the heating-degree-day scale. That temperature (T = 18 -HDD/day) is the same as average outdoor temperature (T) unless the average temperature for individual days exceeds 18 C. Locally, this occurs mainly in June, July and August. It makes the temperature scale too low by about 0.5 C at 15 C and by about 2 C at 18 C.

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*Multiplying S_F by the appropriate number of heating degree-days (calculated from the appropriate base) should give approximately the energy consumption calculated using the relationship in the <u>ASHRAE Handbook-1981 Fundamentals</u>, (equation 1, p. 28.2).

In many homes on the Canadian prairies, natural gas is used for space heating and domestic hot water. For space heating, the year may be divided into three segments, the heating season, the nonheating season, and a transition period. In spite of discontinuities in the demand for space heat, the relationship between natural gas consumption and temperature is nearly linear for the houses used in this study. When the outdoor temperature exceeds 10-12 C, space heat may be needed only intermittently or not at all in warm weather.

A variety of criteria might be used to express the thermal performance of a house, including fuel consumption by the furnace (E_F) and the total heat input to the house (E_{Tot}). In the houses considered in this study, fuel consumed for domestic hot water and space heating is designated E_G. E_F, E_{Tot}, and E_G can each be expressed in terms of outside temperature using the slope intercept relationship,

$$E = I + S\ (18 - T)\ .$$

This results in slopes S_F (furnace consumption coefficient), S_{Tot} (heat input coefficient), and S_G (fuel consumption coefficient).

S_G is approximately equal to both S_F and S_{Tot} and is related to the structural heat loss coefficient (S_{St}). Because of close links to these parameters of energy use and heat loss, S_G is a useful measure of house thermal performance. It is substantially independent of the interior temperature and also of fuel consumption for other purposes, if the latter does not vary seasonally.

Fuel consumption data were obtained for several houses before and after addition of insulation. These results showed reductions in the fuel consumption coefficient (S_G) of up to 30%.

The efficiency with which the complete system used heat supplied to it is affected by the combustion efficiency of the furnace and "off-time" stack losses up the hot chimney. An approximate expression for efficiency of the system was developed. Seasonal efficiencies for three houses calculated in this way ranged from 58% to 69%. This calculation is subject to a number of uncertainties and must be regarded as very approximate.

NOMENCLATURE

E = $I + S\ (18 - T)$ general slope-intercept equation relating heat energy E (MJ/day) and temperature (T)
I = intercept (MJ/day)
S = slope (MJ/day • C)
T = 18 - HDD/day, temperature based on the heating-degree-day scale (C)
HDD/day = average heating degree days/day for the period presented by the data point
kWh = Kilowatt hours
MJ = megajoule
T_a = average outdoor temperature (C)
T_i = indoor temperature (C)
T_{o1} = temperature at which structural heat loss equals miscellaneous heat supply (C)
T_M = temperature (C) where $E = 0$ (no fuel supplied to furnace except for pilot light)
η = efficiency of the heating system
η_o = full-load efficiency of the heating system
A_G = apparent furnace fuel consumption at T_o (MJ/day)
θ = $\tan S^{-1}$ (where S = slope)
ac/h = air changes per hour
m = metre (length)
RSI = thermal resistance ($M^2 \cdot C/W$)

Subscripts

Subscripts are used to identify the heat component.

St = structure
Tot = heat energy supplied to house from all sources
G = all natural gas

F = furnace
E = electricity
O = occupants
Sr = solar
D = occupant + electrical + solar total
W = all energy used by domestic hot water
HW = hot water heat converted to space heat
HWW = heat from domestic hot water wasted
M = miscellaneous space heat (D + HW)

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TABLE 1

Estimated Structural Heat Losses and Energy Inputs for Houses A, B and C

[Given as intercepts (I) and slopes (S) of $E = I + S\ (18-T)$ or as constant values.]

Energy Components	House A			House B			House C		
	I (MJ/day)	S (MJ/day•C)	r*	I (MJ/day)	S (MJ/day•C)	r*	I (MJ/day)	S (MJ/day•C)	r*
E_{St} (structural)	90	20.5		77	17.8		88	14.2	
E_O (occupants)	20	-	-	30	-	-	20	-	-
E_E (electricity)	68	0.4		70	0.5		86	0.1	
E_{Sr} (solar)	80	-	-	68	-	-	56	-	-
E_G	53	24.9	0.98	109	21.0	0.99	59	20.1	.99
E_W	100	-	-	160	-	-	120		
E_{HW}	17	-	-	21	-	-	18	-	-
$E_D=E_O+E_E+E_{Sr}$	168	0.4	-	168	0.5	-	162	0.1	
$E_M=E_D+E_{HW}$	185	0.4		189	0.5	-	180	0.1	
$E_F + E_M$	138	25.4		135	21.5		119	20.2	
E_{Tot}	221	25.4		277	21.5		221	20.2	

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*Coefficient of correlation for E_G.

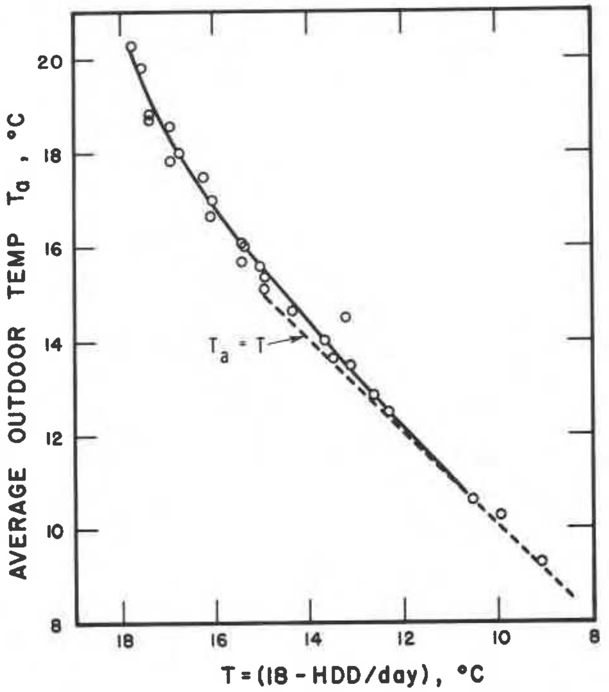

Figure 1. *Outdoor temperature T_a versus T. T is based on monthly averages of HDD/day for May to September 1975-80, Saskatoon*

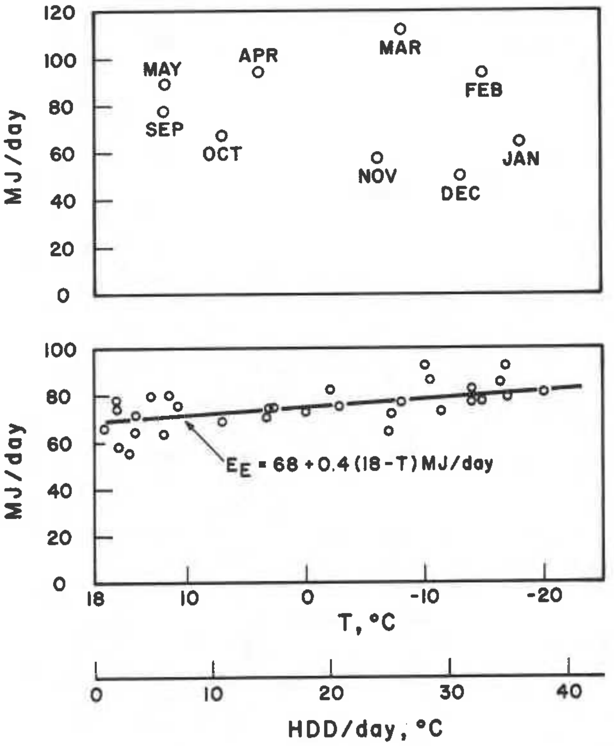

Figure 2. *Measured electricity consumption and estimated solar gains versus T, House A*

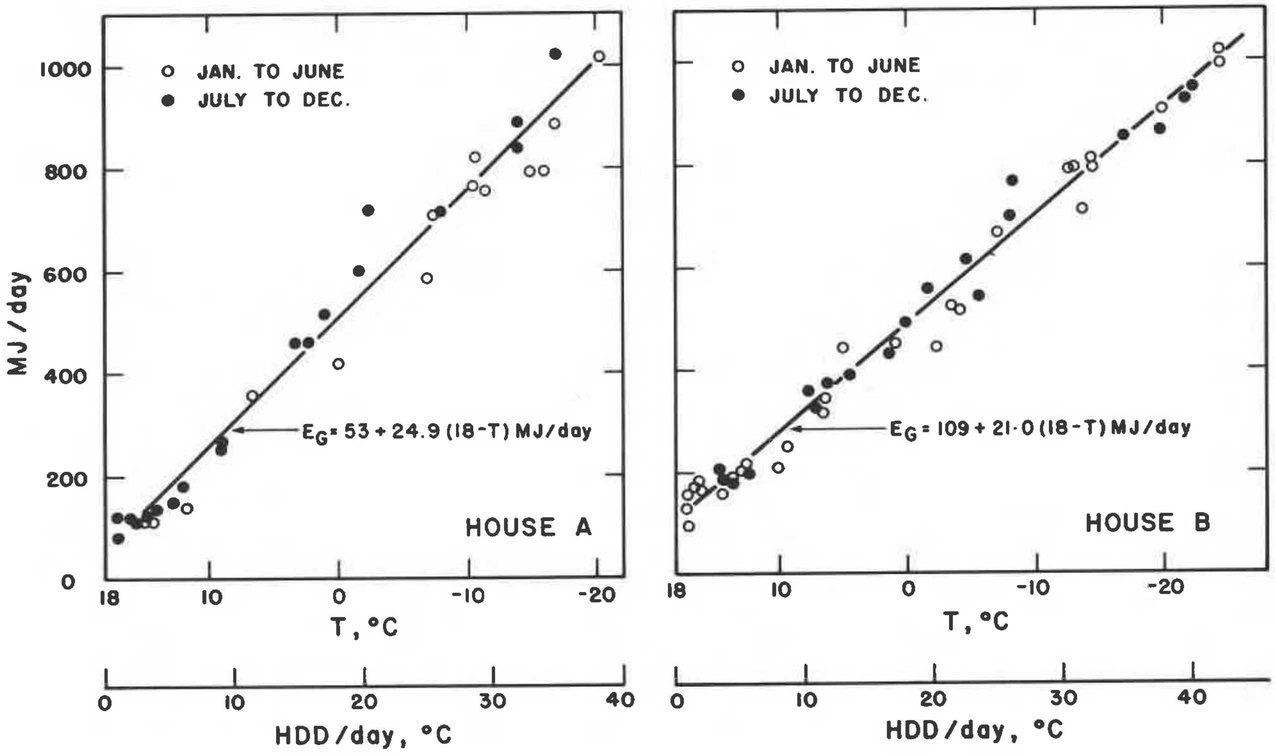

Figure 3. *Natural gas consumption versus T, Houses A and B*

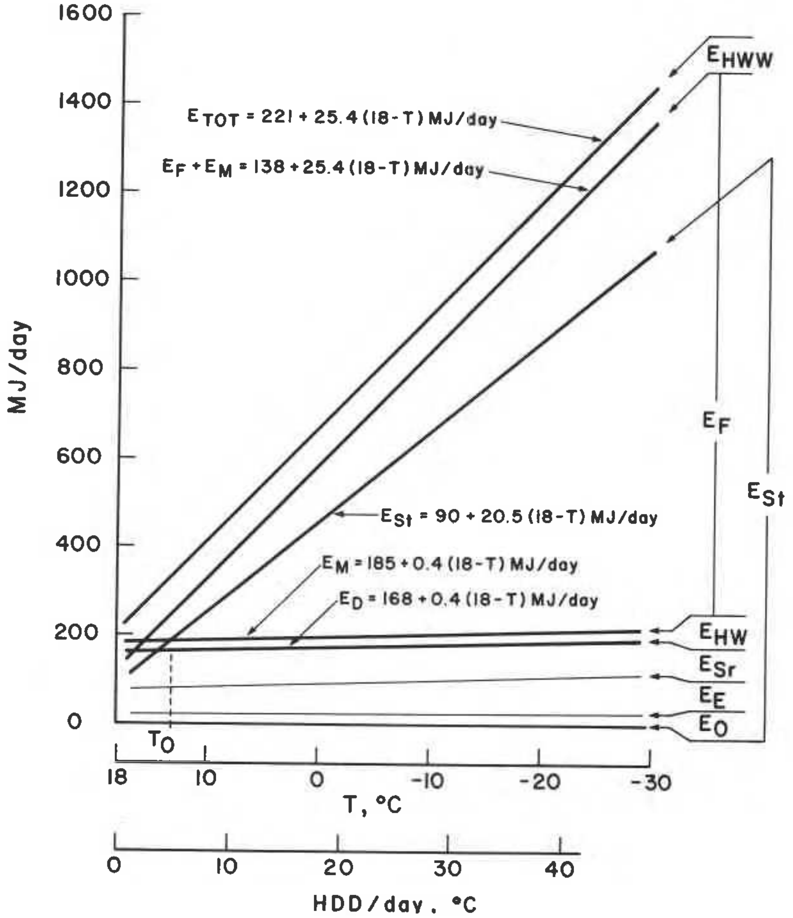

Figure 4. Heat inputs and losses versus T, House A

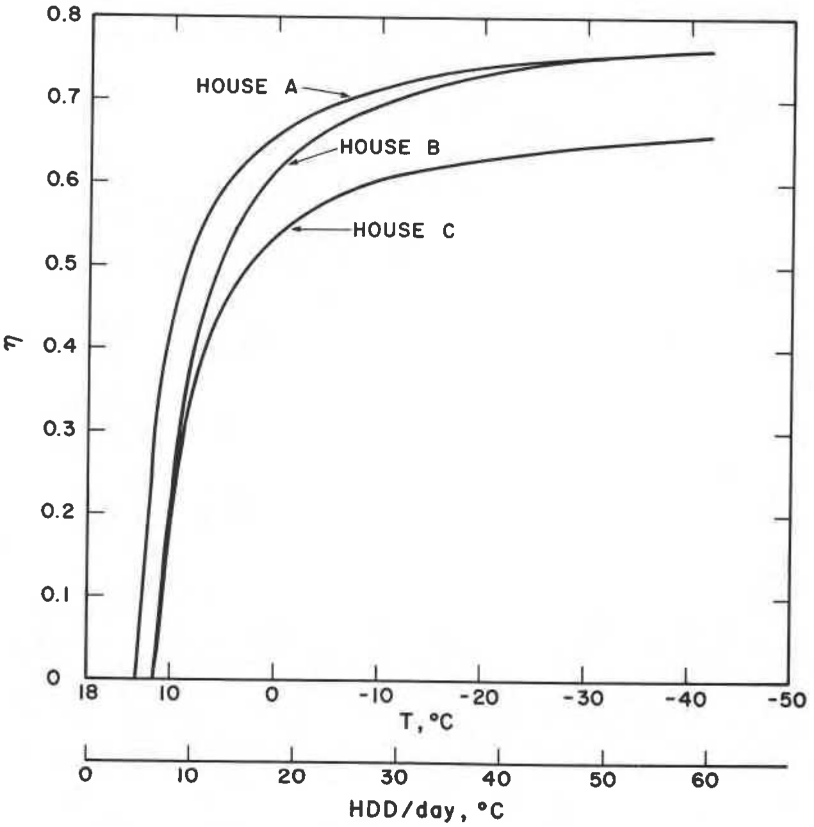

Figure 5. Estimated system thermal efficiencies versus T, Houses A, B, and C

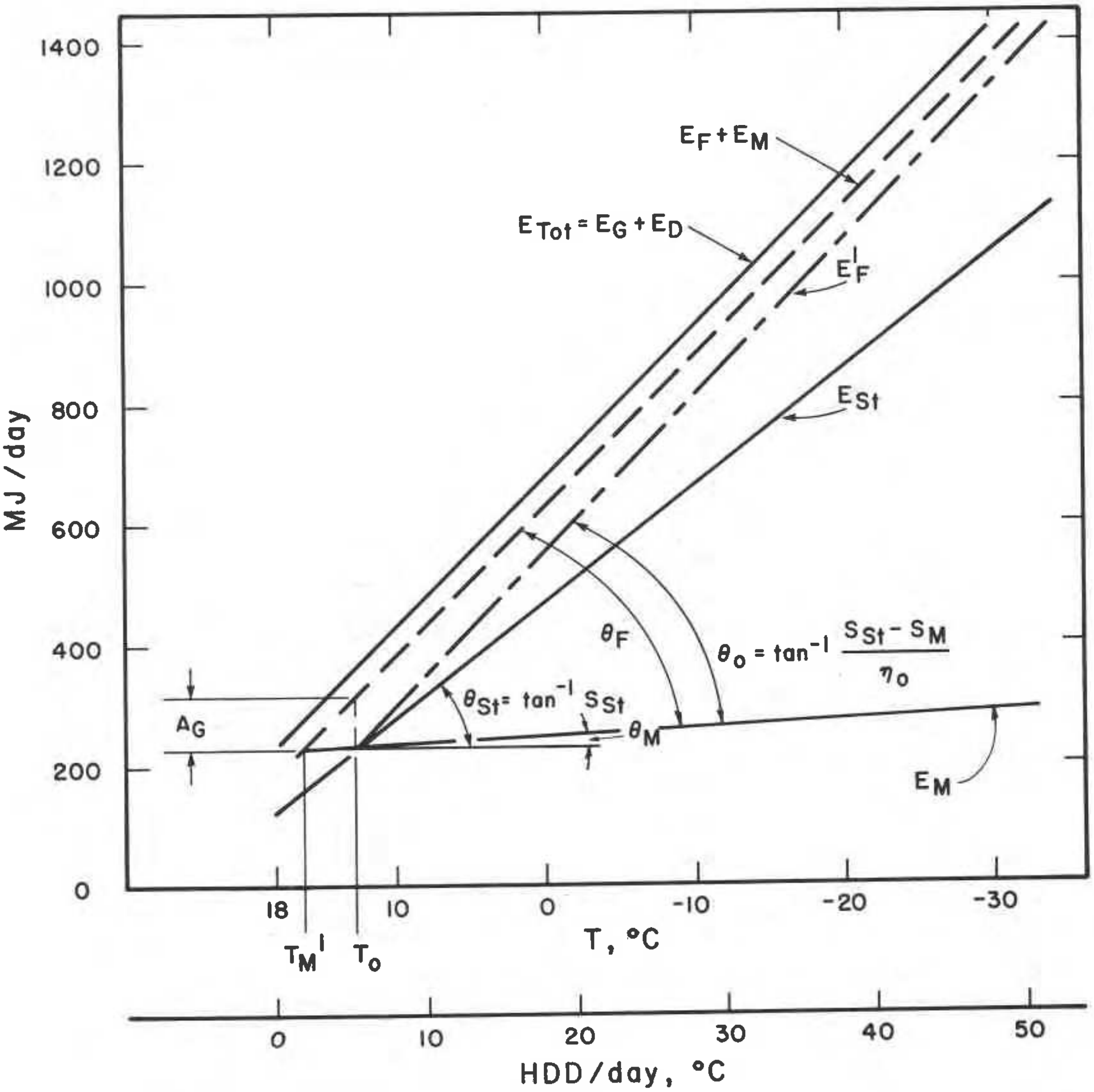

Figure 6. Construction used in developing equation (17)
Note: $\theta_m = \tan^{-1} S_M$ and $\theta_F = \tan^{-1} S_G$

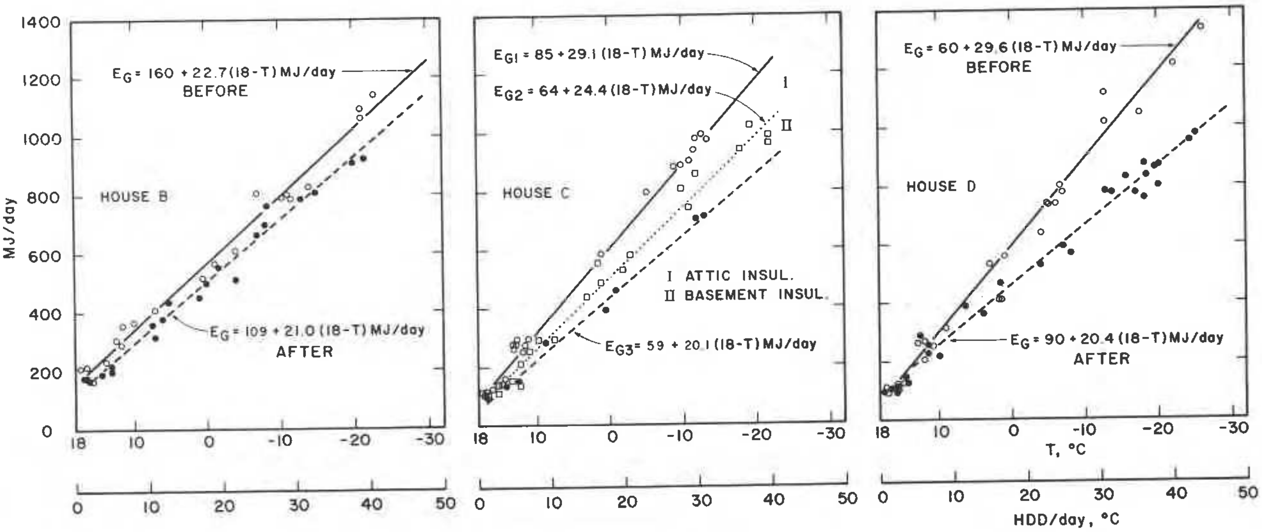

Figure 7. Natural gas versus temperature plots for houses B, C, D before and after adding insulation

DISCUSSION

R. RUNDQUIST, Ross & Bruzzini, St. Louis, MO: What were furnace heating capacities relative to calculated heating loads in each of the test houses, and how does this relate to apparent seasonal efficiencies?

C.P. HEDLIN: The rated output capacities of the furnaces were approximately 95, 72, and 95 MJ/hr for houses A, B, and C respectively. Following the same order, the estimated space heating loads at a design temperature of -35°C were 1320, 1110, and 1130 MJ/day. Thus the furnace oversizing was most marked for house C which also had the lowest efficiency.

J.A. NATION, CAER, Inc., Golden, CO: Did you attribute loss of efficiency with decreasing degree-days to:
a. infiltration?
b. part-load furnace efficiency?
c. Did furnaces have continuous pilot or intermittent?
d. Were vent dampers installed?

HEDLIN: Loss of efficiency with decreasing days may have been caused by a combinations of these factors. The furnaces all had pilot lights which consumed energy at the rate of 15-20 MJ/day. An increasing fraction of this would be lost as with decreasing degree days thus, contributing in a small way to reduced efficiency values. None of the furnaces had vent dampers, and heat loss due to furnace-associated exfiltration following firing periods could also be a factor. No direct measurements of chimney loss were made.

HEDLIN: There was a third question asked at the meeting in Kansas City. The inquirer asked if data for retrofitted houses, shown in figure 7, had been investigated to see whether calculated efficiencies changed with increased insulation. The answer is that this was not done though it would be interesting to do so. Also, I said that these houses were not the same as houses A, B, and C discussed earlier in the paper. In fact two of the three (B and C) are the same. I want to apologize for my error.

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