

CALCULATED AND MEASURED ENERGY CONSUMPTION FOR "LOW ENERGY" HOUSES

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ABSTRACT

An increased awareness of residential space-heating energy costs has stimulated the development of a new type of housing technology often referred to as "low energy" construction. These houses incorporate a number of special features including air-tight vapor barriers, high levels of insulation, and mechanical ventilation systems.

A microcomputer-based residential energy-analysis program named HOTCAN 2.0 has been developed in Canada and has become widely used for energy budget calculations. HOTCAN 2.0 incorporates a number of algorithms for calculating monthly heat flows through various building components and allows the building designer to evaluate the effect of changes in the basic building elements prior to construction.

This paper outlines the results of a two-year energy analysis (HOTCAN 2.0 simulations) and field measurement study of 28 low-energy houses. The space heating, domestic hot-water heating, and interior electrical consumptions were individually measured on a monthly basis. Ventilation rates were monitored and occupant-related inputs were documented using a questionnaire. These data are compared with HOTCAN 2.0 calculated values. Various methods of analysing the data are discussed.

Good agreement between the average measured and calculated overall heat transfer coefficients was observed. However, the calculated below-grade heat losses were consistently low. Since the below-grade heat losses were a substantial component of the total space heating load, the calculated annual space heating requirements were also significantly lower than the measured values. The results highlight the importance of being able to input reliable data into an energy analysis program. The effect of an error in estimating the soil thermal conductivity is discussed.

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INTRODUCTION

During the past five years, thousands of "low energy" houses have been constructed in Canada. Features of these houses include high levels of insulation in the ceilings (\geq RSI 7) and walls (\geq RSI 3.5), primarily triple glazed windows and tightly sealed air-vapour barriers (\leq 1.5 ach @50 Pa as measured by the fan depressurization test) [1]. Although the technology of building these types of houses is becoming accepted building practice [2,3] detailed measurements of their in situ thermal performance is limited.

A residential energy-analysis computer program called HOTCAN 2.0 [4] has become widely used as a design tool to predict the thermal performance of low-energy houses. The program provides a summary of the monthly heating power requirements based on the average indoor/outdoor air-temperature differences and also estimates the total annual heating load. Versions of this program are used by various agencies, owners and contractors to establish design criteria for houses.

A study by Dumont et al [5] reported monthly energy consumption measurements on twenty-seven low energy houses using readings from the utility supplied energy meters. Of this group, four houses had additional sub-metering to separately measure the energy input to the space heating and domestic hot water systems. For the other houses, the average summer total energy readings were used as an energy baseline and these values were subtracted from winter measurements to obtain the calculated space heating energy consumption. HOTCAN 2.0 was used to calculate the space heating consumption and reasonably good agreement (within +24% and -17%) between the measured and calculated values was obtained for a sample of 14 of the houses.

Another study [6] compared the measured energy consumption of four unoccupied test huts with HOTCAN 2.0 calculations. Again, good agreement between the measured and calculated values was reported.

Since detailed field studies of energy utilization in low energy houses in cold Canadian climates are limited, this study was undertaken in Manitoba on electrically heated houses to expand the data base of information on low energy house performance and explore some aspects of energy consumption in low energy residences. The study sites are located in the Canadian prairie region which has a continental climate [7]. Although relatively sunny (2321 sunshine hours/year), the heating season is severe (5923°C day/year, 18°C base).

The purpose of this report is to present measured performance data for a group of 28 low energy houses and compare the results with HOTCAN 2.0

calculations. The comparisons include the overall heat-loss coefficients for the buildings and the long-term heating energy consumptions.

Since HOTCAN 2.0 is designed to accept monthly input data, the experimental data were collected on an approximately monthly basis between October, 1983 and March, 1985. The "months" used in HOTCAN 2.0 were adjusted to correspond to the field monitoring periods.

HOUSE DESCRIPTION

All of the houses were new, wood framed, single family residences with full depth cast-in-place concrete basement walls. The floor slabs were 75 mm concrete, cast over 150 mm of gravel placed on undisturbed soil. All of the basements were insulated from the inside using wood studs with glass fibre batt insulation between the studs. A continuous 150 μ m polyethylene vapor barrier was applied over the inside face of the studs and the walls were sheeted with 12 mm gypsum board.

Houses 1 - 4 were located in Pinawa, Manitoba (approximately 100 km north-east of Winnipeg) and were constructed by contractor 1. Houses 5 - 12 were also located in Pinawa, Manitoba but were constructed by contractor 2. The remaining houses 13 - 28, were located in Winnipeg, Manitoba and were constructed by contractor 1.

The contractor 1 houses had above-grade walls constructed using the double-stud technique [3]. Air-to-air heat exchangers (ATAHE) were used to supply outside air and circulate air within the houses. The units had interlocked supply and exhaust fans with the ON/OFF operation controlled by a humidistat. The exhaust air was removed (via ductwork) from the kitchen and bathroom. The outside air was supplied into the centre of the basement and allowed to migrate through the house. Floor registers were cut through the main floor to facilitate air movement between the main floor and basement. Electric baseboard heaters (convective) were used for space heating.

The contractor 2 houses had conventional single-stud above grade walls. All other construction materials and techniques were similar to those used by contractor 1. Electric forced-air heating systems (20-kW input) with ducts supplying air into every room and two centralized main floor return air grilles were used. Outdoor air was supplied via a 125-mm diameter duct connected to the return air plenum. The single-speed furnace fan (\approx 400 L/s) operation was controlled by heating demand.

Details of the houses including occupancy are given in Table 1.

Table I. House details.

	House code	Year of const.	Const. style	Total int. floor area incl. bsmt. (m ²)	Heated vol. (m ³)	Insulation levels RSI (m ² °C/W)			Space heating system*	ATAHE ⁺	No. of occup. adults/ children	Air tightness (ach @ 50 Pa)
						Wall	Ceil.	Bsmt. wall				
Contractor 1 - Pinawa	1	1982	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	0/0	0.18
	2	1982	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	0/0	0.14
	3	1982	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	2/1	0.16
	4	1982	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	3/0	0.15
Contractor 2 - Pinawa	5	1982	Bungalow	191.2	477.0	3.5	7.0	2.1	EFA	N	2/0	N/A
	6	1982	1½ Storey	174.9	451.9	3.5	7.0	2.1	EFA	N	4/1	1.61
	7	1982	Bungalow	204.2	507.5	3.5	7.0	2.1	EFA	N	2/1	1.23
	8	1982	Bungalow	220.4	545.0	3.5	7.0	2.1	EFA	N	2/1	1.54
	9	1982	Bungalow	191.2	477.0	3.5	7.0	2.1	EFA	N	2/2	1.54
	10	1982	Bungalow	220.4	545.0	3.5	7.0	2.1	EFA	N	2/1	1.96
	11	1982	1½ Storey	174.9	451.9	3.5	7.0	2.1	EFA	N	0/0	2.12
12	1982	Bungalow	204.2	507.5	3.5	7.0	2.1	EFA	N	2/2	2.04	
Contractor 1 - Winnipeg	13	1981	Split L.	178.7	513.0	7.3	9.0	3.5	EB	Y	4/0	0.25
	14	1981	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	2/2	0.22
	15	1982	Bungalow	204.3	513.6	7.6	10.4	4.2	EFA	Y	2/0	0.67
	16	1981	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	2/3	0.19
	17	1982	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	2/0	0.27
	18	1981	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	2/2	0.32
	19	1982	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	2/0	0.32
	20	1983	Split L.	118.6	304.2	7.3	9.0	3.5	EB	Y	1/0	0.39
	21	1982	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	2/2	0.23
	22	1981	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	2/1	0.15
	23	1981	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	2/1	0.35
	24	1981	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	2/2	0.27
	25	1981	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	2/1	0.28
	26	1981	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	2/2	0.24
	27	1981	Split L.	178.7	513.0	7.3	9.0	3.5	EB	Y	4/0	0.49
	28	1981	Bungalow	183.3	464.5	7.3	9.0	3.5	EB	Y	2/0	0.16

*EB = Electric baseboard; EFA = Electric forced air

+ATAHE = Air-to-air heat exchanger

MEASUREMENTS

The air tightness of the houses was measured using the fan depressurization method [1]. The values for the air leakage at 50 Pa of differential pressure are given in Table 1. The test involved blocking the ventilation ducts penetrating the house envelope, depressurizing the house using an exhaust fan and measuring the air flow, Q (L/s), and corresponding value of the differential pressure across the building envelope, ΔP (Pa) for a range of different pressures. Values for the flow coefficient, C (L/sm²(Pa)ⁿ), and flow exponent, n (dimensionless), were then calculated using the expression:

$$Q = CA (\Delta P)^n \quad (1)$$

where

A = area of the building envelope (m²)

The total ventilation rate (V_T) for the houses was calculated as:

$$V_T = V_M + V_I \quad (2)$$

where

V_M = average mechanical ventilation flow rate (ach)

V_I = infiltration flow rate (ach)

Equation (2) is an approximation. However, since the houses were very airtight, the mechanical system provided most of the total ventilation air.

For the houses with ATAHE, elapsed time meters were interlocked to the ATAHE fans to record ON time. The supply and exhaust flow volume rates were calculated from heated probe anemometer traverse measurements in the ducts. V_M was calculated by dividing the total volume of air through the ATAHE during each monitoring period (total running time multiplied by the average duct air volume flow rate) by the total time of each monitoring period. The ATAHE heat recovery effectiveness was assumed to be 50% [8]. In most cases, the supply and exhaust air flows through the ATAHE were not equal, so the larger of the two values was used. This would normally result in a mechanically induced pressure difference which would upset the infiltration, however, since the initial calculated values of V_I were relatively small, no attempt was made to correct them. The value of V_M for the houses with fresh air intakes was calculated by multiplying the furnace ON time by the average measured fresh air flow rate through the intake duct with the furnace fan ON (≈ 35 L/s for all houses) and dividing by the total time of the monitoring period. The furnace ON time was approximated as the total measured furnace electrical energy consumption (kWh) divided by the rated heat output (20 kW).

Shaw's [9] method was used to calculate the infiltration rate (V_I) using the values from the fan depressurization test. No correction was made for additional infiltration through the air intake and/or exhaust ducts when the mechanical systems were not operating.

When the outdoor wind speed was <3.5 m/s and the indoor/outdoor temperature difference was >20 K, V_I was calculated using the expression:

$$V_I = 0.32 CA (\Delta T^n)/V \quad (3)$$

where

V = house volume (m^3)

ΔT = average indoor/outdoor temperature difference (K)

When ΔT was <20 K and the wind speed was >3.5 m/s, V_I was calculated as:

$$V_I = 0.76 CA v^n/V \quad (4)$$

where

v = wind speed (m/s)

The summer values of V_T will not represent the total ventilation rate since windows were frequently opened.

In each house, the total electrical energy and water consumption were read from the utility installed meters. Additional meters were installed to measure the electrical energy supplied to the space heating (SH) and domestic hot water (DHW) systems and to measure the DHW flow volume. An aspirating psychrometer was used to measure the mid-height temperature and relative humidity at each floor level in the houses. All of the meter, air flow, temperature and humidity measurements were taken at approximately one month intervals. The total electrical energy consumption through each meter was divided by the elapsed time for each monitoring period to calculate the average power consumption.

The outdoor air temperature data were taken from local airport weather station records [7].

Solar radiation data were taken from the standard long term design values contained within the HOTCAN 2.0 program. Comparison of long term and actual monthly total global radiation data [10] indicated an average difference (actual - long term) of -1.6% with a standard deviation of 7.4%.

An independent engineering consultant was hired to provide construction quality control for the houses. The consultant ensured that the houses were constructed in accordance with the blueprints.

MEASURED PERFORMANCE

The average measured heating power input to a house for each monitoring period, Q_{MT} (kW), can be determined by the expression:

$$Q_{MT} = Q_{SH} + Q_{NE} + Q_{DHW} + Q_{PEOPLE} + Q_{SOLAR} \quad (5)$$

where

Q_{SH} = average power supplied by the space heating system (kW)
 Q_{NE} = average net electrical power input to the house (kW)
 Q_{DHW} = average space heat gain from the domestic hot water system (kW)
 Q_{PEOPLE} = average net sensible heat gain from the occupants (kW)
 Q_{SOLAR} = average space heat gain from solar energy (kW)

The average net electrical power input to the house was calculated as:

$$Q_{NE} = Q_E - Q_{SH} - Q_{DHW} - Q_{OUT} \quad (6)$$

where

Q_E = average total electrical power usage (kW)
 Q_{OUT} = average outdoor electrical power usage (kW)

Homeowners were asked to estimate the average number of hours of use of outdoor lights and appliances (including block heaters) so that this power could be deducted from the average total electrical power consumption.

It was assumed that 8% of the DHW power is given up as heat to the space and that the system has a 100 watt standby loss. This assumption is consistent with the calculation procedure in HOTCAN 2.0.

One comprehensive study [11] that has explored the relationship between cold water supply temperature and usage in addition to DHW usage suggests that for light DHW users (<200 L/day), apart from the standby loss, the net heat input from the domestic water (hot and cold) may be negligible. For occupied houses, lifestyle differences with time and from house to house can cause significant variations in the DHW heat gain, which are difficult to quantify.

Occupancy time for people was determined from questionnaires administered to the homeowners. They were asked to estimate who occupied the house and for how long. For each occupant, the heat gain was assumed to be 0.065 kW for adults and 0.033 kW for children.

The average space heat gain from solar energy was not measured. The values calculated by HOTCAN 2.0 were used. Utilization factors [12] are applied to Q_{SOLAR} to account for the building's ability to use the available solar radiation.

The term "free heat" (Q_F) is often used to describe the heating power input to a building from sources other than the heating plant and can be calculated as:

$$Q_F = Q_{NE} + Q_{DHW} + Q_{PEOPLE} + Q_{SOLAR} \quad (7)$$

CALCULATED PERFORMANCE

HOTCAN 2.0 was used to model the thermal performance of the houses for the

monitoring periods. The standard design data contained within the program were replaced with measured data for the outdoor air temperature and deep ground temperature to accurately represent the prevailing conditions.

The required program inputs include building envelope component sizes and insulation values, infiltration and mechanical ventilation rates, Q_{NE} and DHW energy consumption, and indoor air temperature.

The basic energy balance in HOTCAN 2.0 equates the average total calculated heating power input to the building, Q_{CT} (kW) with the required auxiliary space heat (Q_{AUX}) and the available "free heat" sources:

$$Q_{CT} = Q_{AUX} + Q_{NE} + Q_{DHW} + Q_{PEOPLE} + Q_{SOLAR} \quad (8)$$

By inputting field measured values of the net electrical power consumption and DHW energy consumption, relative errors in these inputs have been removed. For reference, Table II gives the values obtained in this study and the average values suggested in HOTCAN 2.0.

ANALYSIS

The energy balance equations for a house (equations (5) and (8)) can be illustrated as shown in Figure 1. This figure can be developed by plotting the total heating power input (Q_{MT} and Q_{CT}) vs. the corresponding average indoor/outdoor air temperature difference for each monitoring period. The non-space heating power inputs (Q_F) offset the building power loss until the balance point temperature difference (ΔT_B) is reached. Beyond this point ($\Delta T > \Delta T_B$) additional space heating power must be input to satisfy the heating load. Below this point, ($\Delta T < \Delta T_B$), the excess internal gains must be removed or the house temperature will rise.

For the analysis, the same values of Q_{SOLAR} , Q_{PEOPLE} , Q_{DHW} and Q_{NE} were used in the measured and calculated energy equations. Therefore, from equations (5) and (8), the values of X and Y in Figure 1 represent Q_{AUX} and Q_{SH} .

In HOTCAN 2.0, the heat loss of a structure is composed of the sum of the heat losses due to above grade conduction, infiltration, ventilation and below grade conduction. When the outdoor air temperature (T_o) is greater than or equal to the average indoor air temperature (T_i), the only heat loss is assumed to be due to the below grade surfaces. Mitalas [13] has shown that the below grade component of the heat loss is related to the ground surface temperature but can have a time lag in the order of months. Because of this, linear expressions that relate the building heating energy load with the indoor/outdoor air temperature difference (ΔT) will contain some element of error. As the ratio of the below grade heat loss to the total heat loss becomes larger, the validity of the linear expressions becomes more questionable. Despite this shortcoming, one popular method of describing the heat loss characteristics of

houses is to define an overall calculated heat loss coefficient U_C (W/°C) or U_M (experimentally determined) such that:

$$Q_{CT} = U_C \Delta T + B_C \tag{9}$$

or

$$Q_{MT} = U_M \Delta T + B_M \tag{10}$$

Table II. Suggested values in HOTCAN 2.0 and measured values for internal gain parameters.

Value	HOTCAN 2.0	Measured	
		\bar{x} (average)	s (std. dev.)
Daily base electrical consumption (kWh/d)	14	26.0	8.1
Daily hot-water energy consumption (kWh/d)	14	13.0	4.7

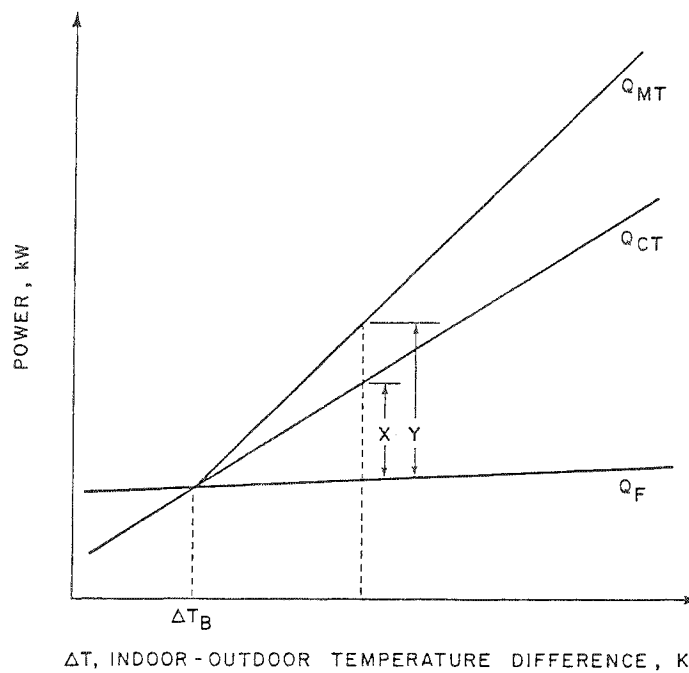


Figure 1. Typical heating power balance schematic.

The value of U combines the heat loss coefficients for the above grade conduction, infiltration and ventilation with a portion of the below grade heat loss coefficient. The constant B represents the heat loss that will occur when the indoor/outdoor air temperature difference is ≤ 0 K. This is the average below grade heat loss for the summer months.

Using a least squares regression technique, linear expressions of the forms of equations (9) and (10) were fitted through the values of Q_{CT} and Q_{MT} for $\Delta T \geq 10$ K and values for U_C and U_M and B_C and B_M were calculated (Table III). Values of the index of determination (r^2) for the linear regressions are also given in Table III. The $\Delta T = 10$ K cut-off point was arbitrarily chosen based on observations of the plotted data. For most occupied houses, the power consumption rate became non-linear for $\Delta T < 10$ K (Figure 2). Since almost all of the heating requirement exists when $\Delta T \geq 10$ K, this technique can be used to accurately model the houses under actual conditions.

To make decisions about building components, heating system configurations and fuel types, house designers require accurate information about the long term space heating energy requirements. A standard HOTCAN 2.0 output provides an estimate of the annual space heating energy consumption. The values of the measured and calculated total space heating energy consumption for the individual houses within the three house groups are shown in Figures 3, 4 and 5. Since the monitoring periods and house sizes varied, the total space heating energy consumption for each house was divided by the total floor area and the elapsed heating degree days (18°C base) for the monitoring period.

DISCUSSION

There are a number of possible uses for the results from a HOTCAN 2.0 calculation. These include:

- 1) comparison of the relative effect of changes in the building envelope (i.e. insulation levels, window geometry, etc.) on the thermal performance of the structure prior to completing the final design.
- 2) calculation of the heating power requirement as a function of the indoor/outdoor temperature difference.
- 3) energy budget estimations of heating energy use. These are often used to estimate utility energy demand requirements and the relative energy costs associated with various heating system configurations.

Since the experimental data are "whole house" measurements, no specific conclusions regarding use 1 can be made. For the houses in this study, a representative annual heat loss distribution as calculated by HOTCAN 2.0 is shown in Figure 6.

Table III. Measured and calculated values of overall heat loss coefficients and constants.

	House code	U_M (W/°C)	U_C (W/°C)	B_M (W)	B_C (W)	r^2_M	r^2_C
Contractor 1 Pinawa	1	49.2	60.8	1477	1083	0.47	0.77
	2	39.6	42.5	1448	1188	0.95	0.89
	3	92.1	59.2	463	838	0.98	0.97
	4	93.8	106.3	962	566	0.98	0.99
Contractor 2 Pinawa	5	107.5	101.7	646	757	0.99	0.98
	6	135.0	100.8	578	900	0.95	0.99
	7	111.3	109.2	1177	699	0.95	0.99
	8	105.0	113.3	1070	738	0.93	0.97
	9	111.7	110.0	1019	573	0.89	0.99
	10	110.4	125.8	1320	685	0.94	0.99
	11	142.9	127.9	276	386	0.98	0.97
	12	120.4	118.8	1172	750	0.91	0.99
Contractor 1 Winnipeg	13	82.9	87.9	1028	765	0.93	0.98
	14	76.3	68.3	679	633	0.96	0.94
	15	105.4	85.8	1128	1002	0.96	0.94
	16	67.9	85.0	1093	647	0.76	0.96
	17	81.7	60.0	937	718	0.93	0.79
	18	76.7	71.7	1039	654	0.82	0.80
	19	83.8	89.2	835	804	0.91	0.97
	20	80.4	65.8	829	695	0.78	0.93
	21	79.2	80.8	1305	873	0.86	0.94
	22	85.4	93.3	753	538	0.90	0.94
	23	104.6	100.0	410	561	0.78	0.98
	24	97.5	78.8	728	733	0.92	0.95
	25	85.8	93.3	930	546	0.86	0.97
	26	95.4	89.2	861	595	0.92	0.98
	27	96.7	66.7	927	1044	0.89	0.79
	28	81.7	69.6	802	597	0.94	0.79

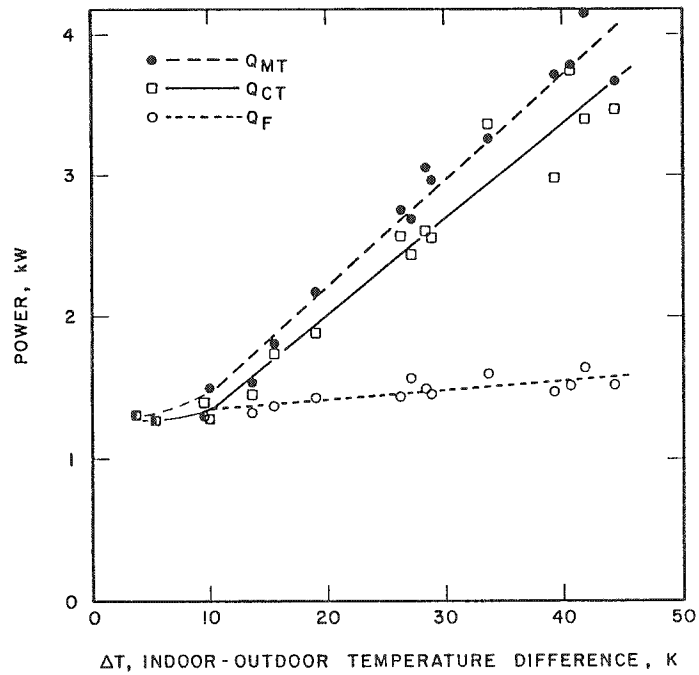


Figure 2. Heating power balance for house 14.

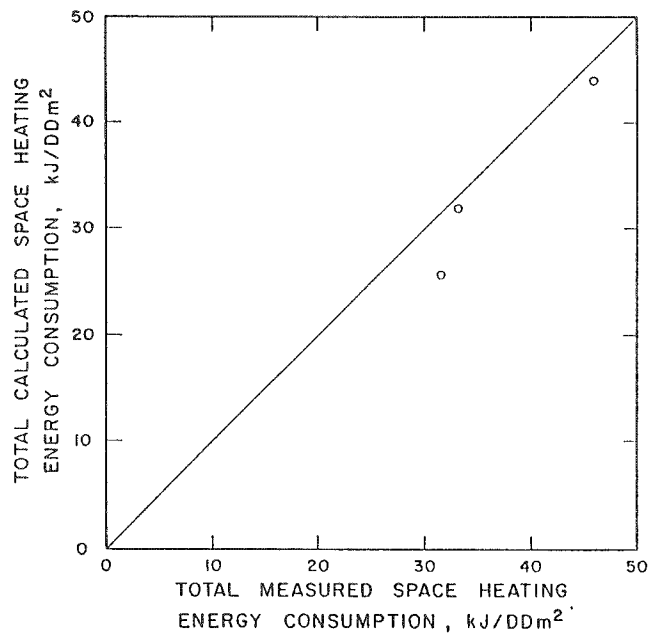


Figure 3. Calculated vs. measured space heating energy consumption for unoccupied contractor 1 and 2 houses.

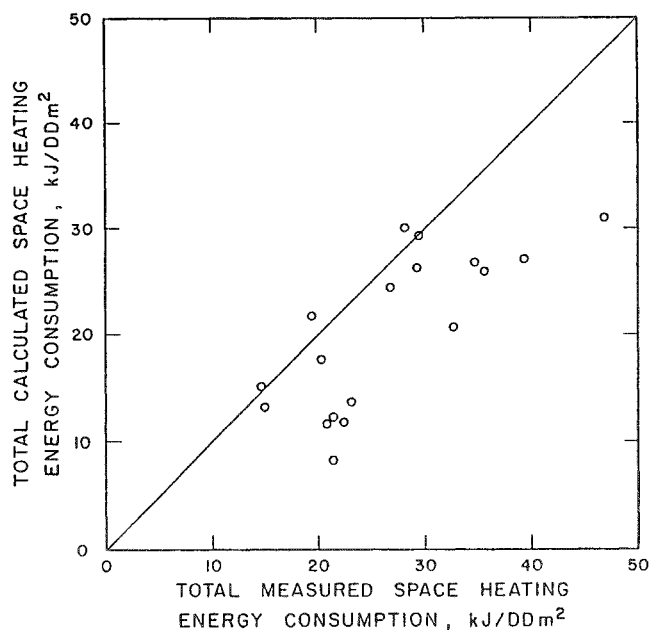


Figure 4. Calculated vs. measured space heating energy consumption for occupied contractor 1 houses.

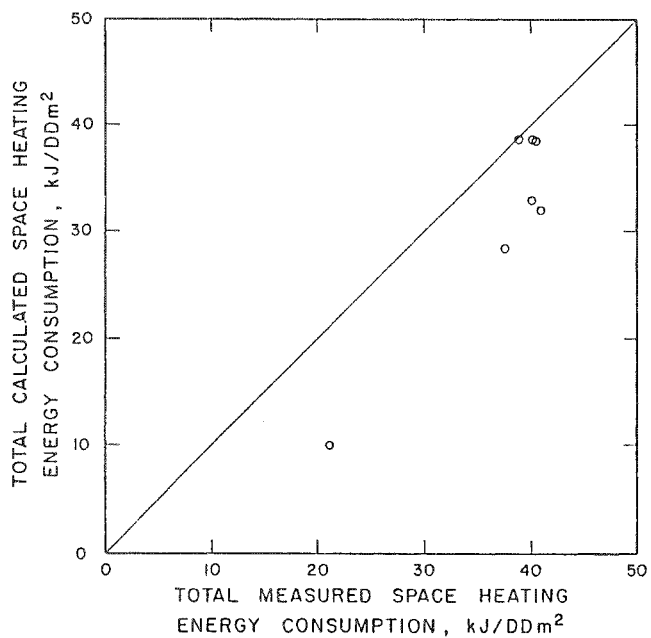


Figure 5. Calculated vs. measured space heating energy consumption for occupied contractor 2 houses.

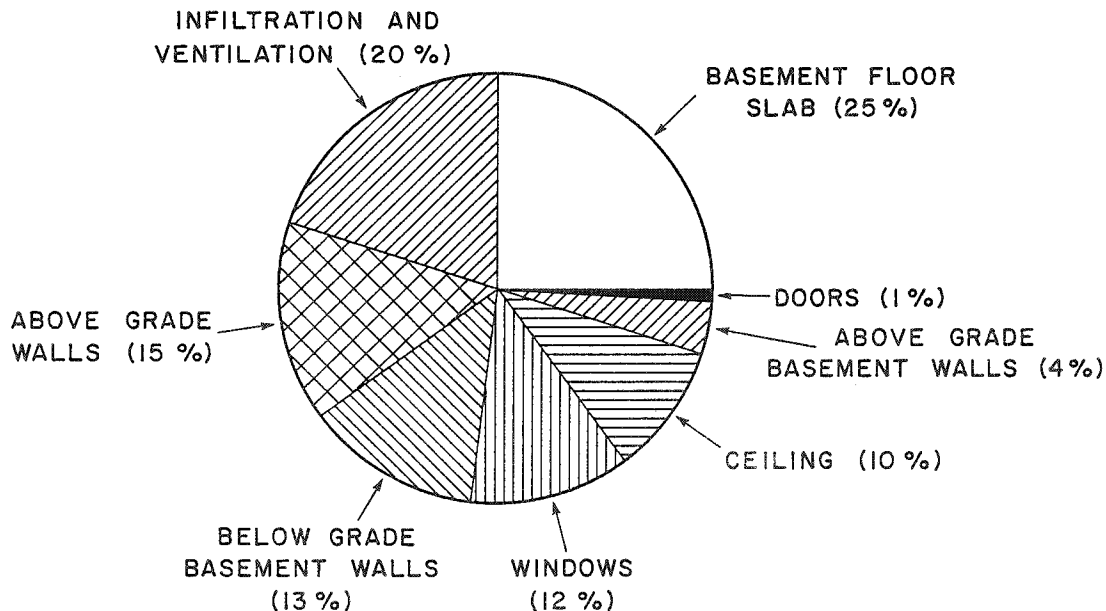


Figure 6. Annual heat loss distribution for a typical house.

With respect to the second use, the individual house data from Table III were divided into 3 groups:

- 1) unoccupied contractor 1 houses
- 2) occupied contractor 1 houses
- 3) occupied contractor 2 houses

and group average values of U_M , U_C , B_M and B_C were calculated (Table IV).

Table IV. Average values of overall heat loss coefficients and constants for the house group.

House	U_M (W/°C)	U_C (W/°C)	B_M (W)	B_C (W)
Contractor 1 & 2 (unoccupied)	77.1	77.1	1088	888
Contractor 1 (occupied)	86.3	80.3	893	713
Contractor 2 (occupied)	114.6	111.7	996	729

For the unoccupied contractor 1 houses, the average of the calculated and measured values of U were 77.1 W/°C. This suggests that the algorithms in HOTCAN 2.0 can estimate the heat loss associated with the above grade building components and outdoor air exchange and predict the utilized solar radiation.

The average calculated overall heat loss coefficients for both groups of occupied houses were slightly lower than the measured values (7% for contractor 1 and 3% for contractor 2).

The average value of B_M for the unoccupied contractor 1 houses was 18% higher than the calculated value, suggesting that the calculated basement heat loss may be low. The B_M values were also higher than the calculated values for the occupied contractor 1 houses (20%) and occupied contractor 2 houses (27%). The calculated values were obtained using the HOTCAN 2.0 suggested values for the upper/lower soil thermal conductivity of $k = 0.8 - 0.9 \text{ W/m}^\circ\text{C}$. Detailed soil investigations were not conducted, however, general observations indicated soils [14] that should have conductivities in the range of $k = 1.2 - 1.35 \text{ W/m}^\circ\text{C}$. The HOTCAN 2.0 calculations for house 1 were re-done using the higher soil conductivities and the value of B increased from 1.08 to 1.25 kW, reducing the difference between the measured and calculated values from 27% to 16%. Thus, much of the initial difference between the calculated and measured values of Q could have resulted from the low soil conductivities used in the calculation.

Figures 3, 4 and 5 show that for all of the house groups, the measured space heating energy consumption exceeded the predicted values. For the unoccupied contractor 1 houses, the average ratio of Q_{SH}/Q_{AUX} (\bar{x}) was 1.11 with a standard deviation (s) of 0.11. For the occupied contractor 1 houses, $\bar{x} = 1.37$ and $s = 0.42$ and for the occupied contractor 2 houses, $\bar{x} = 1.29$ and $s = 0.39$.

Possible reasons for the HOTCAN 2.0 under-prediction of the total space heating energy consumption are:

- 1) undocumented closing of window shades (reducing possible solar gain)
- 2) undocumented opening of windows and doors (increased heat loss from infiltration)
- 3) inaccurate estimation and/or incomplete utilization of internal gains.

For the unoccupied houses, a low calculated basement heat loss could account for the Q_{SH}/Q_{AUX} ratio of 1.11. With the occupied houses, the previously outlined occupancy and basement effects could be responsible.

CONCLUSIONS

The results from this study lead to a number of observations concerning energy studies on residential buildings:

- 1) HOTCAN 2.0 estimated the thermal performance of the houses, the exception being the below grade heat loss. This highlights the importance of having accurate, detailed data on in situ soil conditions and a validated below grade heat loss algorithm.

- 2) It is difficult to account for occupancy effects in houses. Increased natural ventilation and variations in the utilization of solar and internal gains introduce errors that are beyond the building designers control. The total measured space heating energy consumptions were substantially higher than the total calculated values. This fact is significant when economics and the impact of "low energy" housing technology on energy consumption are considered.
- 3) Substantial variations in the measured vs. calculated thermal performance occurred from house to house. Although these variations occurred, the physical phenomena causing them could not be determined from this study.

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