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LOW–ENERGY HOUSES: MEASURED ENERGY–CONSUMPTION FIGURES

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RÉSUMÉ

Ce document présente les valeurs mesurées de la consommation d'énergie pour le chauffage des locaux et de la consommation totale d'énergie d'un groupe de 27 maisons peu énergivores, situées à Saskatoon (Saskatchewan, Canada) et ayant fait l'objet d'une étude échelonnée sur un an. La consommation moyenne d'énergie pour le chauffage des 27 maisons a été de 43,7 kJ/m^2•°C-j (2,1 btu/pi^2•°F-j) pour la période comprise entre mai 1980 et mai 1981. La consommation totale d'énergie s'élevait en moyenne à 365 MJ/m^2 (32 200 btu/pi^2) alors que la consommation d'énergie pour le chauffage des locaux atteignait, en moyenne, 228 MJ/m^2 (20 100 btu/pi^2). Ces maisons à faible consommation d'énergie ont un certain nombre de caractéristiques leur permettant d'économiser l'énergie et les distinguant des loge ... l'air, ventilation contrôlé ... res face au sud pour ... et niveaux élevés d'is...

No. 2753

Low-Energy Houses: Measured Energy-Consumption Figures

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ABSTRACT

Measured space heating and total energy-consumption values are presented for a one-year monitoring period for a group of 27 low-energy houses in Saskatoon, Saskatchewan, Canada. The average space heating energy consumption for the 27 houses was 43.7 kJ/m·°C-d (2.1 Btu/ft^2·°F-d) for the period from May 1980 to May 1981. The total energy consumption averaged 365 MJ/m^2 (32,200 Btu/ft^2); and space heating energy consumption averaged 228 MJ/m^2 (20,100 Btu/ft^2). These low-energy houses have a number of energy-conserving features -- air tightness, controlled ventilation, air-to-air heat exchangers, use of south windows for passive solar gain, and high insulation levels -- that distinguish them from conventional housing stock.

INTRODUCTION

Measured energy-consumption values are presented for a group of houses whose annual space-heating requirements are significantly lower than those of pre-1970 stock. The houses are located in Saskatoon, Saskatchewan, Canada, which has a climate classified as "continental" and experiences annual average degree-days of 6077°C-days, basis 18°C (10870°F-days, basis 65°F). The mean temperature in January is -18.7°C (-1.7°F); average annual sunshine hours are 2403, with average annual solar radiation on a horizontal surface equal to 5.0 GJ/m^2 (441,000 Btu/ft^2). The houses have been variously described in a number of publications as "superinsulated," "energy-efficient," "lo-cal," and "low-energy" houses.[1-4]

The term that will be used in this paper is "low-energy." The adjective "superinsulated" is thought to be incomplete in that well-designed low-energy houses have a number of features -- air tightness, controlled ventilation, use of south windows for passive solar gain -- that are not encompassed by the "superinsulated" description.

The energy-conservation features used on the major portion of the low-energy houses in Saskatoon are described in the pamphlet Energy Efficient Housing - A Prairie Approach.[2] Three key energy-conservation features for space heating are identified: air tightness with controlled ventilation, using an air-to-air heat exchanger; insulation levels considerably greater than the minimum standards; and placement of windows to the south for passive solar gain.

Air tightness is achieved in the houses primarily by means of a 150-μm (6-milli-in.) thick vapor barrier installed in a continuous manner. Special care was taken at all joints to ensure continuity. Some 40 houses in Saskatoon that were constructed using these air-tightness techniques have been pressure tested.

The paper "Air Tightness Measurements of Detached Houses in Saskatoon" gives a detailed description of the pressure test results for these houses.[5] Compared with houses of the same age but not incorporating special air-tightness measures, the low-energy house sample achieved a 58% reduction of air leakage in a pressure test. For the 40-house sample, the pressure test result at a negative pressure of 50 Pa (0.2 in. of water) was equal to 1.5 air changes per

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hour. As typical winter pressures on the houses are in the order of 5 Pa or less, the uncontrolled air movement into and out of the houses has been reduced to a small value. Virtually all the low-energy houses have air-to-air heat exchangers as part of a controlled-ventilation strategy. Typically, the heat exchangers have an effectiveness of approximately 50% to 70%. Flow rates of about 40 L/s (80 cfm) are used on most of them. In most of the houses a relative humidity sensor is used to control operation of the ventilation system; in a few, the heat exchanger is cycled manually. To control frost buildup inside the heat exchangers, a defrost cycle is used. Generally, defrost action is achieved by shutting off the outside air intake fan until the exhaust air from the house has defrosted the exchanger.

The second element of the low-energy strategy is the use of significantly higher levels of insulation than the present minimum standards. The booklet Energy Efficient Housing: A Prairie Approach[2] gives the recommendation listed in Tab. 2 for insulation levels in low-energy houses in the southern Canadian Prairie climate.

The third element in the low-energy strategy is the use of windows facing south for passive solar gain. Typically in new house construction, the design places roughly 75% of the windows on the south side of the building. In most of the low-energy houses additional mass has not been added and, consequently, only a modest amount of south-facing glazing can be used without having the house overheat on sunny days. Typically, a maximum of 6% south window area to total floor area is used. Improved performance of the south windows can be achieved by the use of triple-glazing or insulating nighttime shutters. To prevent excessive heat gain during the summer months, roof overhangs or awnings can reduce the direct solar radiation incident on the south windows.

SAMPLE OF HOUSES CHOSEN FOR STUDY

In the present study 27 houses were monitored. The prime criterion was a wall thermal resistance level exceeding 4.4 $m^2 \cdot °C/W$ (25 $ft^2 \cdot °F \cdot hr/Btu$). Houses using wood heat were included in a larger sample of monitored houses, but because of the difficulty of quantifying the space-heating contribution from wood they were excluded from this report. Thermal characteristics of the sample of houses are presented in Tab. 2.

Measurements of the utility-supplied meters were made once a month over a 12-month period from May 1980 to May 1981. On a number of the low-energy houses additional meters were installed to sub-meter the energy consumption of the space-heating system and water heater. These houses were B6, G5, H1, and W4. The outside temperatures, heating degree-days, and measured solar radiation on a horizontal surface are presented in Tab. 3. These meteorological data were collected by the Saskatchewan Research Council.[6]

ENERGY-CONSUMPTION FIGURES

Of primary interest on the low-energy houses are the figures for space heating and total energy consumption for the year.

Case Study

The energy-consumption figures for house W4 are presented in Fig. 1. The space-heating requirement for the electric forced-air furnace is clearly not a simple linear function of the degree-day values, based on a reference temperature of 18°C (65.3°F). For such a house a degree-day base of approximately 8°C (46.4°F) would be required to allow a more adequate linear relation between furnace space-heating supply and heating degree-days. The water-heating energy consumption, as shown in Fig. 2, is relatively independent of degree-day figures. Total energy consumption as a function of degree-day values is presented in Fig. 3.

Values for 27 Houses

Values for total energy consumption of the residences over a one-year period are presented in Tab. 4 and Fig. 4. To provide a basis of comparison the values are presented in the units of energy consumption per unit floor area (including basements, but excluding crawlspaces and other unheated areas such as greenhouses or garages). The average total energy consumption for the 27 houses was 365 MJ/m^2 (32,200 Btu/ft^2).

Values for the space-heating energy consumption of the residences over a one-year period are presented in Tab. 4 and Fig. 5. In houses for which the space-heating energy consumption was not measured by a separate meter, these values were estimated by subtracting the energy for water heating and lights and appliances, based on the summertime values of the latter quantities. The average value for the space-heating energy consumption of the 27 houses was 228 MJ/m^2 (20,100 Btu/ft^2). A number of variables within the houses, such as inside temperature and internal heat gains, can affect the space-heating requirements. To measure the inside temperatures, clock-driven hygrothermographs were placed in each of the houses for a one-week period during the spring of 1981. A histogram of the temperature distribution in the houses is presented in Fig. 6. The mean temperature inside was 21.9°C (71.4°F), with a standard deviation of 1.8°C. The summer-period energy consumption of the houses was measured; a histogram of the average energy consumption rate is presented in Fig. 7. The average energy-consumption rate for the summer period for the occupied houses was 1098 W, and the standard deviation was 540 W. As Saskatoon has relatively cool summer nights, the majority of low-energy houses do not use summer air-conditioning. The balance-point temperatures and the slope of the energy consumption versus degree-day per day curves were calculated using plots similar to those of Fig. 3 for each of the houses. The results are presented in Tab. 5.

Comparisons with Computer Model Prediction

A computer model, HOTCAN, has been developed at the Division of Building Research, National Research Council Canada.[8] The HOTCAN model uses a month-by-month calculation technique to estimate the annual space heating requirement of houses. Features of the model are as follows:

1. Passive solar gains through windows are accounted for by means of a technique developed by Barakat and Sander.[9]

2. Internal heat gains from lights and appliances, from the hot water heater, and from people are included explicitly.

3. The effect of overhangs on south windows is included.

4. An improved basement heat loss model developed by Mitalas is included.[10]

5. The model can be run on a microcomputer.

The HOTCAN model was used in making a comparison of predicted and measured space-heating energy consumption for a group of the low-energy houses for the period May 1980 to May 1981. As may be seen in Fig. 8, agreement between predicted and measured values was quite good, within +24% and -17% over the range of houses tested. Both internal temperatures and internal gains were known for each house, as was the air-tightness level. None of the houses used wood heat.

DISCUSSION

The energy consumption of the low-energy house sample may be compared with that of a group of pre-1974 houses not incorporating extra energy-conservation features. Hedlin and Orr have presented energy consumption figures for 209 Regina houses built between 1970 and 1973.[7] Regina is located 250 km (150 m) southeast of Saskatoon and has a closely similar elevation and annual heating degree-days. Energy-consumption figures are presented in Tab. 6 along with those for the Saskatoon low-energy house sample.

The non-low-energy house sample has an annual space-heating consumption equal to 3.03 times that of the low-energy houses if the samples are compared without regard for type of space-heating system. If only natural-gas-heated houses are compared, the non-low-energy house sample used 2.19 times as much energy for space heating as the low-energy house sample.

A number of the houses (F1, G3, L2, R1) had space-heating energy-consumption values more than one standard deviation larger than the average for the low-energy sample. Several design features are believed responsible for this higher energy consumption:

1. Low basement wall insulation levels (F1, G3, R1) and no floor insulation (F1, G3, L2, R1).

2. Relatively poor air-tightness (L2, R1) and no air-to-air heat exchanger (F1, G3, R1).

3. Excessive glass area (L2). This house has 32.5 m^2 (350 ft^2) of south windows that are double-glazed. Heat loss from these windows accounts for approximately 40% of the total loss. As the house has a low thermal capacity, it also tends to experience large temperature swings on sunny days, necessitating use of reflective blinds to reduce overheating.

4. Poor orientation of the major windows on the house. Houses G3 and R1 have the major portion of their windows on non-south walls.

5. Use of double-glazing (G3, L2, R1) instead of triple-glazing or double-glazing with night insulation.

6. Higher inside temperatures than average (F1, G3, L2).

As may be seen from histograms of inside house temperatures and summer energy-consumption values, there is a significant variation in the two variables among the houses. Thus, two identical houses with equal numbers of occupants may have radically different energy-consumption figures for space heating, depending on inside temperatures and internal use of electricity by the occupants.

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TABLE 1

Typical Thermal Resistance Levels, Low-Energy Houses

	$m^2 \cdot °C/W$
Walls above grade	5 - 9
Ceilings	9 - 14
Walls below grade	3.5 - 5
Floors over crawlspace	5 - 7
Underbasement floor of concrete	1 - 2
Window shutters	2 - 3

$$1 \frac{m^2 \cdot °C}{W} = 5.68 \frac{ft^2 \cdot °F \cdot hr}{Btu}$$

TABLE 2

Low-Energy House Features

House Code	Date of Completion	Total Floor Area (Based on Outside Dim) Incl. Basement m^2	Number of Occupants During Monitoring Period	Type	Insulation Levels RSI ($m^2 \cdot °C/W$)				Caulked Vapor Barrier	Air-to-Air Heat Exchanger	Insulating Shutters	Auxiliary Heating System		Pressure Test Result
					Wall	Ceiling	Basement wall	Floor				Space Heat	Water Heat	Air Changes/h @ 50 Pa
A1	1980	179	1	Split level wood basement	5.1	10.6	5.1	0	yes	yes	no	Elec. furn.	Elec.	1.7
B1	1979	199	2	2-storey crawlspace	7.8	10.6	-	3.5	yes	yes	partial	Elec. B.B.	Elec.	2.2
B3	1979	300	3	Split level wood basement	7.9	10.6	3.5	0	yes	yes	no	Nat. gas	Elec.	1.5
B5	1979	306	4	2-storey wood basement	7.0	12.3	6.3	1.3	yes	T.B.I.	no	Nat. gas	Nat. gas	0.6
B6	1978	287	4	1½-storey crawlspace	7.0	10.6	-	5.3	yes	yes	no	Elec. B.B.	Elec.	1.0
B7	1980	164	2	Bi-level wood basement	5.3	8.8	4.9	0	yes	yes	partial	Elec. B.B.	Elec.	2.2
D1	1980	284	2	1½-storey concr. basement	6.3	7.0	3.9	0	yes	no	no	Nat. gas	Nat. gas	3.2
F1	1980	297	3	1-storey concr. basement	5.1	7.0	1.3	0	yes	no	no	Nat. gas	Nat. gas	1.6
G2	1979	218	3	Bi-level wood basement	7.8	4.7	3.5	0	no	no	no	Elec.	Elec.	2.4
G3	1979	265	2	2-storey concr. basement	5.3	10.6	2,2	0	yes	no	no	Nat. gas	Nat. gas	1.4
G4	1979	241	2	2-storey crawlspace	7.8	10.6	-	4.9	yes	yes	no	Elec. B.B.	Elec.	1.0
G5	1979	297	2	1-storey wood basement	7.0	10.6	4.2	1.0	yes	yes	no	Elec. furn	Elec.	1.4
H1	1979	225	2	1-storey wood basement	5.3	8.8	4.9	0	yes	yes	partial	Elec. B.B.	Solar & Elec.	1.7

TABLE 2

Low-Energy House Features (Cont'd)

House Code	Date of Completion	Total Floor Area (Based on Outside Dim) Incl. Basement m^2	Number of Occupants During Monitoring Period	Type	Insulation Levels RSI ($m^2 \cdot {}^\circ C/W$)				Caulked Vapor Barrier	Air-to-Air Heat Exchanger	Insulating Shutters	Auxiliary Heating System		Pressure Test Result
					Wall	Ceiling	Basement Wall	Floor				Space Heat	Water Heat	Air Changes/h @ 50 Pa
K3	1980	210	3	1-storey wood basement	5.3	8.8	4.9	0	yes	yes	partial	Elec. B.B.	Elec.	3.2
L2	1978	163	1	split level wood basement and crawlspace	6.3	10.6	3.5	0	yes	yes	no	Elec. Furn.	Elec.	4.0
L6	1980	226	2	1-storey wood basement	5.3	8.8	4.9	0	yes	yes	partial	Nat. gas	Nat. gas	2.5
R1	1979	217	4	2-storey wood basement	4.8	7.0	3.5	0	yes	no	no	Nat. gas	Nat. gas	2.3
S1	1979	167	1	2-storey slab on grade	6.4	10.6	-	3.5	yes	T.B.I.	T.B.I.	Elec. B.B.	Elec.	1.3
S2	1979	328	4	2-storey concr. basement	5.3	8.8	1.8	0	yes	yes	partial	Elec. B.B.	Elec.	
T1	1980	250	1	2-storey crawlspace	10.6	10.6	-	4.9	yes	yes	no	Elec. B.B.	Elec.	0.8
V1	1979	495	2	1-storey concr. basement	5.3	8.8	1.8	0	yes	no	no	Elec. B.B.	Elec.	2.5
W1	1980	212	4	bi-level wood basement	4.2	6.4	3.1	0	no	yes	no	Nat. gas	Nat. gas	
W4	1978	242	5	2-storey wood basement	7.8	10.6	5.6	0	yes	yes	partial	Elec. Furn.	Elec.	1.3
AA2	1980	219	0	split level wood basement	5.3	8.8	4.9	0	yes	yes	partial	Elec. B.B.	Elec.	2.3
AA3	1979	200	0	1½-storey wood basement	5.3	8.8	4.9	0	yes	yes	partial	Elec. B.B.	Elec.	1.6
AA4	1979	204	4	1-storey wood basement	5.3	8.8	4.9	0	yes	yes	partial	Elec. B.B.	Elec.	
AA5	1979	200	2	1½-storey wood basement	5.3	8.8	4.9	0	yes	yes	partial	Elec. B.B.	Elec.	2.8

TABLE 3

Weather Data for Monitoring Period, Saskatoon, Sask., 52°N, May 1980 to April 1981

	Average Outside Air Temp. (°C)	Monthly Degree-Days (Ref 18°C) (°C-days)	Solar Radiation Monthly Average (Horizontal Surface) MJ/(m²-day)
1980 May	14.5	150.3	22.1
June	16.1	77.7	23.2
July	18.8	23.3	22.8
Aug	15.7	81.4	15.4
Sept	11.3	211.3	12.1
Oct	6.1	370.7	7.9
Nov	-2.2	606.3	3.8
Dec	-16.4	1066.1	3.0
1981 Jan	-10.0	867.4	4.0
Feb	-10.3	791.5	7.9
Mar	-1.1	589.4	12.4
Apr	5.3	380.6	16.9
		5216.0	

TABLE 4

Measured Energy-Consumption and Inside-Temperature Values
May 1980 - April 1981

House Code	Total Energy Consumption (MJ/m²)	Space Heating Energy Consump. (MJ/m²)	Summertime Energy Consump. Rate (W)	Inside Temperature (°C)
A1	273	210	355	21.7
B1	372	209	1021	24.6
B3	444	293	1416	25.3
B5	397	177	2121	19.9
B6	257	128	1171	22.3
B7	264	160	532	21.2
D1	458	262	1744	22.0
F1	606	388	1810	22.9
G2	307	171	931	19.9
G3	502	388	957	23.0
G4	266	153	863	18.1
G5	237	152	795	21.8
H1	244	148	684	20.5
K3	355	199	916	21.9
L2	655	455	1080	24.0
L6	415	203	1535	
R1	757	427	2238	19.7
S1	317	263	283	24.2
S2	318	210	1118	19.9
T1	218	159	461	21.1
V1	186	154	498	20.1
W1	575	285	1964	22.7
W4	317	189	967	22.1
AA2*	227	219	48*	
AA3*	224	201	141*	
AA4	347	173	1127	23.3
AA5	318	190	871	23.3
	Avg = 365 MJ/m²	228 MJ/m²	1098.3 W	21.9°C
	S.D. = 146	89.9	543.7	1.8

*UNOCCUPIED

TABLE 5

Measured Balance Point Temperature and Slope Values for 27 Low-Energy Houses

House Code	Balance Point Temperature (°C)	Measured Slope of Power Consumption versus Degree-Day/Day (W/°C)
A1	15	91.2
B1	10	143
B3	15	222
B5	11	183
B5	10.5	127
B7	6	117
D1	15	219
F1	15	282
G2	13	105
G3	15	262
G4	10	156
G5	16	112
H1	15	89.4
K3	14	120
L2	9	281
L6	16	129
R1	18	238
S1	15	108
S2	10.5	248
T1	10	142
V1	15	202
W1	16	247
W4	8	137
AA2	18	79.5
AA3	15	86.6
AA4	15	101
AA5	13	117
	Avg. = 13.3 S.D. = 3.1	Avg. = 161 S.D. = 65.8

TABLE 6

Comparison of Low-Energy House Sample with Non-Low-Energy House Sample

	Low-Energy Houses	Non-Low-Energy Houses	Ratio
Year of construction	1978-1980	1970-1973	
Degree-days of monitoring period (°C-Days)	5216	5764	1.11
Annual total energy consumption (MJ/m^2)	365	1192	3.27
Annual space-heating energy consumption (MJ/m^2)	228	764	3.35
Annual space-heating energy consumption per degree-day ($kJ/m^2 \cdot D.D.$)	43.7	133	3.03
Annual space-heating energy consumption per degree-day ($kJ/m^2 \cdot D.D.$) Natural-gas-heated houses only	60.8	133	2.19

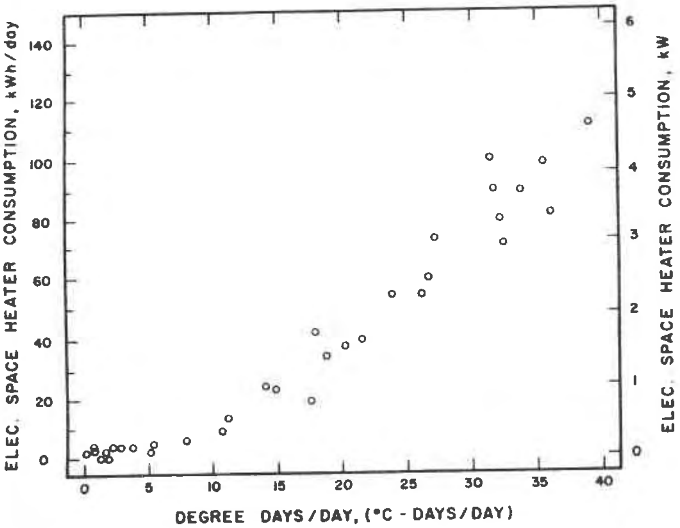

Figure 1. Measured furnace energy consumption - Residence W4

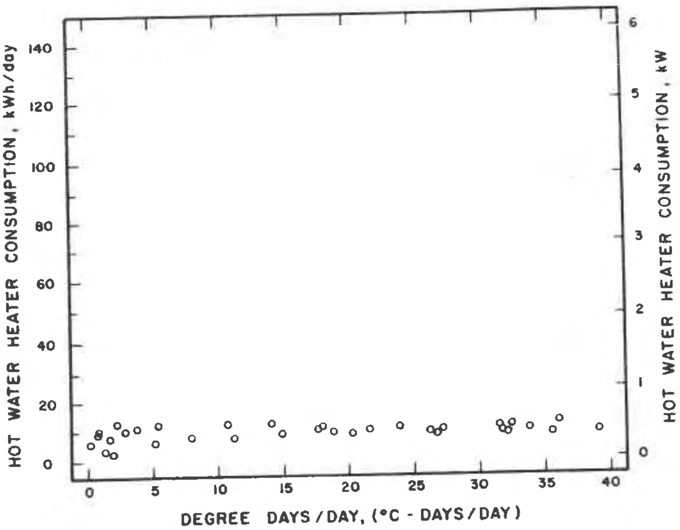

Figure 2. Measured water heater energy consumption - Residence W4

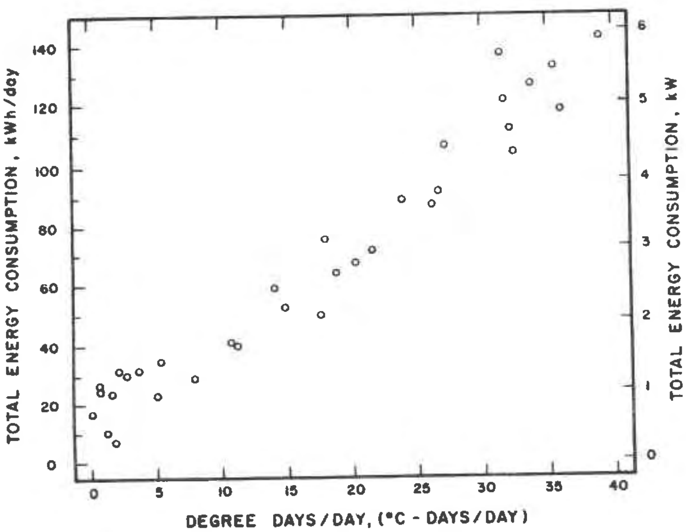

Figure 3. Measured total energy consumption - Residence W4

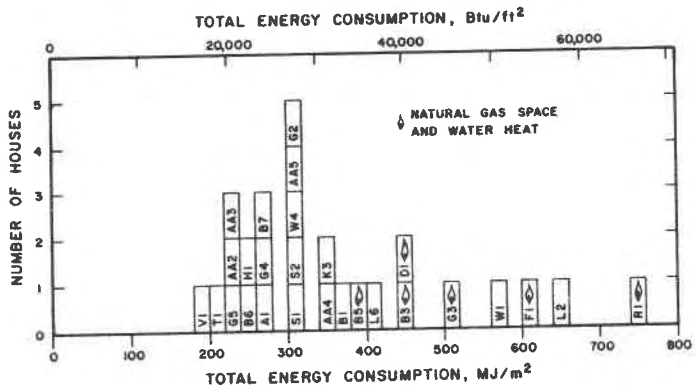

Figure 4. Measured total energy consumption for low-energy house sample

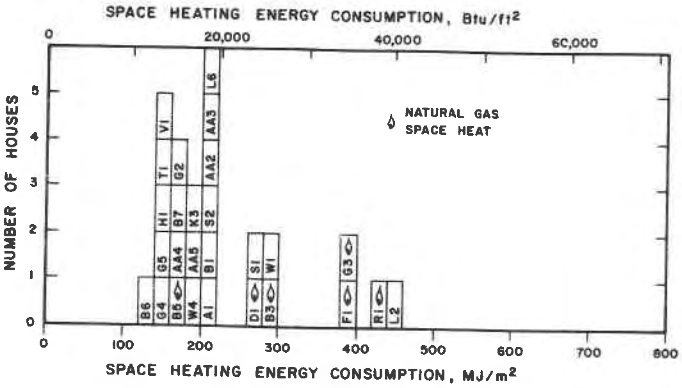

Figure 5. Measured space-heating energy consumption for low-energy house sample

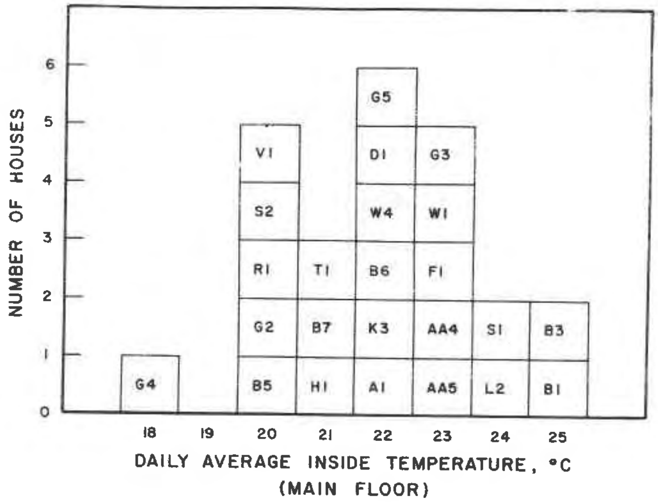

Figure 6. Average inside temperatures for low-energy house sample

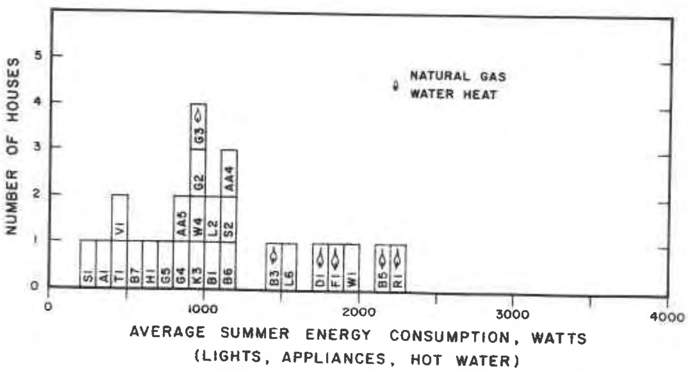

Figure 7. Average summer energy consumption rate for low-energy house sample

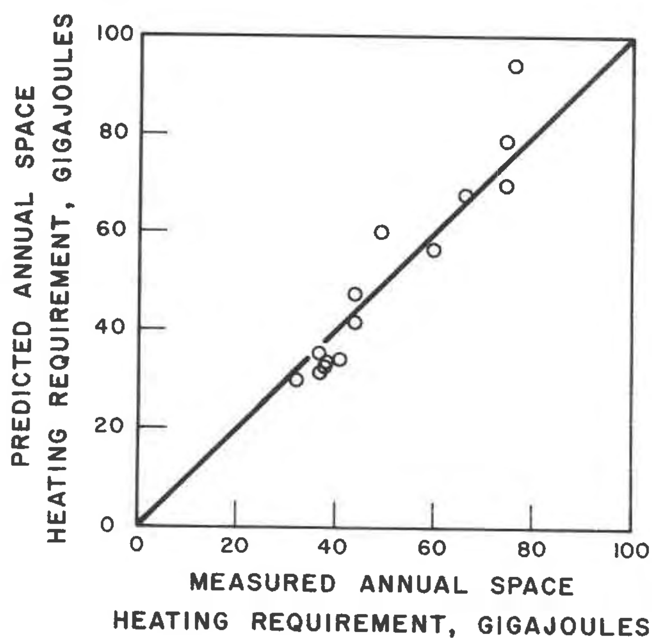

Figure 8. Comparison of predicted and measured space heating energy comsumption for a group of low energy houses