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Thermal Performance of the Blouin Superinsulated House

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ABSTRACT

An evaluation of the design and thermal performance of a superinsulated residence in South Royalton, VT, is made. Data were acquired by a Solar Energy Research Instiute (SERI) Class B monitoring system during 60 days of March, April, and May of 1982. In addition, air infiltration is measured using the fan pressurization technique, and effectiveness of the air-to-air heat exchanger is analyzed.

The house design is a copy of the colonial "saltbox". Included are R-40 (RSI-7.2) walls, R-57 (RSI-10.0) ceiling, R-25 (RSI-4.5) pressure-treated wood basement walls, R-9 (RSI-1.5) sliding window shutters, a caulked polyethylene vapor barrier, and a site-built air-to-air heat exchanger.

Reported on are the data acquired and an analysis of the thermal performance based on these results. Several possible modifications to the building design are suggested. It is concluded that the measured building thermal parameters are within acceptable error bounds of the calculated values.

INTRODUCTION

Since 1973 energy costs have become a major factor in many people's budgets. During this same time, the government and the private sector have increased efforts to find new ways of conserving energy. Investigation and validation of new ideas have become necessary in the changing energy environment. In residential heating, private individuals and state and local governments have taken on the task of monitoring many of the new energy-conserving systems. Considerable data are now available on passive and active solar heating systems. On the other hand, superinsulated buildings in this country have rarely been monitored in detail by objective third parties. Brookhaven National Laboratory, as a part of its Residential Field Validation Studies funded by DOE's Office of Building Energy Research and Development is working on a study of superinsulated building technology. This study includes the Small Homes Council, Building Research Council "LoCal" superinsulated residence in Illinois and the comparative thermal performance of residences being recorded by several state agencies. The Blouin house described in this paper is also part of this study, and the results reported represent observations from the first segment of this work.

BUILDING DESCRIPTION

The Blouin residence was completed in November of 1981 in South Royalton, Vermont (near Woodstock, Vermont, and Hanover, New Hampshire), latitude about 43°50' north. The Hanover weather station usually experiences 7800 °F days (4333 °C days). The building is on a highland mass at an elevation of about 1400 ft (425 m), about 900 ft (275 m) above the nearby White River. The front of the house is oriented within 2° of south.

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The house is a copy of the colonial saltbox design (Fig. 1), but with several major changes to reduce heating energy consumption. The 1557 ft^2 (114.6 m^2) of living space is on two floors (Fig. 2). A kitchen, livingroom, diningroom, bathroom, and a bedroom are downstairs; three bedrooms and a bath are upstairs. The full basement is unheated. The house is two stories tall at the south; the roof line drops to the first floor ceiling on the north side (Fig. 3).

All walls consist of two parallel 2 by 4 in (38 x 89 mm) stud walls separated by 5-1/2 in. (140 mm), allowing installation of 12-1/2 in. (318 mm) of fiber glass batts. The ceiling contains 16-1/2 in. (420 mm) of fiber glass batts. The first floor joists contain 5-1/2 in. (140 mm) of fiber glass batts, and the basement is framed of treated 2 by 8 in. (38 x 184 mm) wood with 7-1/2 in. (191 mm) fiber glass batts (Fig. 4). The basement slab is not insulated. Sliding site-built 1-1/4in. (32 mm) thick urethane window insulation with magnetic refrigerator door seals (Figs. 5 and 6) is installed on all the double-glazed double-hung windows. A six mil (150 μm) polyethylene vapor/infiltration barrier is carefully installed and caulked with butyl tape at all joints in an attempt to make the house airtight. The attic is ventilated by louvered gable vents and continuous eve vents. Total window area is about 152 ft^2 (14.1 m^2), or 10% of floor area; the south glass area is 56 ft^2 (5.2 m^2), or 3.6% of floor area, not including glass covered by the snap-in muntins. The snap-in muntins reduce the south transparent glazing area by 17%.

The original heating system consisted of individual electric baseboard units with integral thermostats in each room. The owner was displeased with the temperature control provided by this system and subsequently turned off all heaters with the exception of two 6 ft. (1.83M) units downstairs, one each in the living and dining areas. These two units were controlled by a common wall thermostat set at 65°F (18.3°C) for the duration of this study. No other heaters were used during the monitoring period.

Ventilation air is introduced into the house through a site-built counterflow air-to-air heat exchanger (Fig. 7) in the basement. The exchanger is fabricated of 1/2 in. (13 mm) plywood and thin aluminum sheets, and is provided with a condensate drain.[1] Insulated flexible supply and exhaust ducts, diameter 8 in. (203 mm), connect to the heat exchanger and penetrate the west basement wall. Air is distributed from the heat exchanger to three centrally located points and is exhausted from the bathrooms and kitchen to the exchanger by an uninsulated flexible duct system. Supply and exhaust fans are switched on by a humidistat when the humidity in the living room exceeds about 40% RH.

The electric domestic hot water heater is located in the basement. This unit is better insulated than the standard type, utilizing about 2 in. (51 mm) of high-density fiber glass insulation. The manufacturer's published standby loss for a 50.0°F (32.2 °C) temperature difference is 514 btu/hr (151 watt) for a total heat transfer coefficient of 5.71 Btu/hr·°F (4.68 watt/°C). The heating elements are also controlled by timer so that less expensive off-peak electricity may be used.

CALCULATED PARAMETERS

Before the building site was visited, an ASHRAE-type steady-state heat-loss calculation was performed.[2] The calculated R-values for the various components are:

1.	Walls	R-41	(RSI- 7.2)
2.	Flat Ceiling	R-57	(RSI-10.0)
3.	Sloped Ceiling	R-55	(RSI- 9.7)
4.	Floor	R-21	(RSI- 3.7)
5.	Windows (uninsulated)	R- 2.0	(RSI- .35)
6.	Windows (insulated)	R-10.7	(RSI- 1.88)
7.	Door	R- 2.5	(RSI- .44)

Table 1 summarizes the house's statistics, including heat loss. Natural infiltration was neglected in the calculation. One-half air change per hour of forced ventilation was assumed, but the actual air-handling capability of the fans was unknown. Heat-recovery effectiveness was assumed to be 0.7, based upon test reports from similar units.[3] Note that ventilation, even with heat recovery, increases the calculated heat-loss by 37% (window insulation in place) or 19% (window insulation removed). Removing all of the window insulation increases the building heat-loss by 67%. The basement temperature was assumed to be a constant 50°F (10°C), providing a constant heat loss of 921 Btu/h (270 Watt). This loss is 6% to 10% of the building design heat loss, depending upon window shutter position.

The nominal building heat transfer coefficient (UA) is obtained by dividing the heat loss of the building at design conditions by the design inside-outside temperature difference. This yields a UA for this building of 116 Btu/h·°F (61.2 W/°C) to 194 Btu/h·°F (102.3 W/°C) with ventilation. Even with window shutters removed, this building UA is less than half that of the smallest previously calculated for buildings monitored by Brookhaven National Laboratory. It should be noted that while this calculated building UA is useful for gross comparisons it is not a true heat transfer coefficient since a portion of the heat losses are driven by a different temperature difference (to the basement) as noted above.

The calculated thermal storage capacity of the building is also summarized in Table 1. Handbook values for material properties were used. Included was all sheetrock, flooring, partition framing members, framing members in the inner half of the exterior envelope, indoor air, and furniture and appliances (estimated).

One advantage claimed for high mass or well insulated houses is that reasonable indoor air temperature can be maintained during short duration heating-equipment failures or power outages. The temperature drop in a well insulated house when the heating equipment is shut off has been assumed to be an exponential decay:[4]

$$\Delta T(t) = \Delta T_i \times \ell^{-t/TC} \tag{1}$$

where

$\Delta T(t)$ = Inside temperature - outside temperature at time t

t = elapsed time since heating equipment shut off, hours

ΔT_i = $\Delta T(t)$ at time $t = 0$

TC = C/UA = time constant of house, hours

UA = building heat loss coefficient = design heat loss/design ΔT

C = building thermal storage capacity[5]

For constant outdoor air temperature, the instantaneous rate of change in indoor air temperature is:

$$\frac{\partial T_{indoor}}{\partial t} = \frac{\partial \Delta T(t)}{\partial t} = -\frac{1}{TC} \times \Delta T_i \times \ell^{-t/Tc} = -\frac{\Delta T(t)}{TC} \tag{2}$$

The calculated time constant for this house is 97 hours (window shutters in place), or 59 hours (window shutters removed). Thus if the outdoor air temperature was -20°F (-28.9°C) and the indoor temperature was (20°C) 68°F when the heating equipment was shut off the instantaneous rate of change of indoor temperature from equation 2 would be:

$$-\frac{\Delta T(t)}{TC} = -\frac{68 - (-20)}{97} = -.9°\mathrm{F/hr} \times (-.5°\mathrm{C/hr}) \tag{3}$$

This means that the indoor air temperature would drop only about .9°F (.5°C) in the first hour, with window shutters in place. Overnight (8 hours) the house temperature would drop 7°F (3.9°C). Outdoor temperatures above -20°F (-28.9°C) or energy gains inside the house would reduce this small temperature drop. This temperature stability may be advantageous for certain applications.

HOUSE OCCUPANCY

The house was occupied by a family of four for the entire monitoring period. On the typical weekday, the house was vacant from 8:00 a.m. to 3:00 p.m., most people were home by 6:00 p.m., and everyone was home from 10:00 p.m. to 8:00 a.m. North, east, and west window shutters were usually applied 24 hours a day, while the south shutters were removed for daylight hours. If a very cloudy day was anticipated, even the south shutters would remain applied during day-light

light hours when the building was vacated. On a day with cloudy morning hours and sunny later hours, much useful sunlight would thus be blocked from entering the house. Since only 2 of the 9 south shutters were monitored for status, the owner was asked to open and close all south shutters simultaneously for the duration of the monitoring period.

DATA COLLECTION

The data acquisition system was assembled from equipment on-hand to allow collection of the data that is required by the S.E.R.I. Class B monitoring system,[6] however no data analysis could occur on-site due to the nature of the equipment.

Hourly data were recorded continuously on three different sets of equipment. The 20 type T thermocouple temperature data channels and two silicon cell pyranometer data channels were recorded hourly on magnetic tape. The temperatures were instantaneous values, but the pyronometers were integrated over the hour. Seven thermocouples were mounted throughout the house to sample indoor air temperature. Two shielded thermocouples were mounted between the window glass and the moveable insulation to detect the insulation status and determine its thermal performance. In the basement, one thermocouple sensed air temperature near the ceiling, and two others measured floor-slab surface temperatures. The temperature between the hot water heater tank and the insulation at midheight was recorded. Five thermocouple rakes were installed in the air-to-air heat-exchanger system to detect its status and effectiveness. Two shielded thermocouples measured outdoor air temperature. Printed 15-minute, hourly, and daily summaries of three pulse-initiated kilowatt-hour meters, supplied by Central Vermont Public Service Company, augmented the data logger system. With these data, energy inputs to the heaters, appliances and domestic hot water heater could be calculated individually. Indoor relative humidity was recorded by a strip-chart hair-type hygrometer.

One-time measurements were made on several building subsystems. A blower door was used to detect flaws in the air-infiltration barrier and to measure the relative airtightness of the house. The air-to-air heat-exchanger and duct system were monitored to determine effectiveness and airflows. Rakes of thermocouples were installed in the four heat exchanger plenums, and temperatures were recorded every minute for 30 min after the system appeared to be in a steady-state condition. This test was performed when the outdoor air temperature was above that which would cause condensation of the indoor air, as indicated on the psychrometric chart. Air flow in the inlet and exhaust ducts was measured by recording crossing eight-point traverses of the ducts with a common HVAC pitot tube type of anemometer.

Several desired tests could not be performed because the house was continuously occupied. A cool-down time constant test was planned, but allowing the temperature of the house to drop and eliminating internal gains to the house was not possible during the season. Electric coheating to determine the building-loss coefficient could not be performed, for the same reason. Domestic hot water heater standby losses also could not be measured during this period. Data manually recorded earlier by the owner, before and after overnight trips, did provide a crude verification of the hot water heater manufacturer's published heat-loss coefficient.

DATA HANDLING

For this report data analysis was done on hourly, daily, and monthly bases. Magnetic tape hourly data were analyzed for the entire period using a microcomputer, whereas printed hourly data were manually entered only for selected periods. Daily printed kilowatt-hour data were entered for the entire period. The hourly data were then converted to daily and monthly summaries for comparisons.

Data were successfully assembled for a total of 60 complete days, divided into two blocks of 33 days (called month 1) and 27 days (called month 2). Month 1 covered March 6 through April 6, and month 2 covered April 14 through May 10.

The two instantaneous temperatures at the beginning and end of each hourly recording interval were averaged to approximate the mean temperature for the hour. The average house temperature was calculated by weighting each indoor air measurement by its calculated percent of the total building heat-loss. This average temperature results in the same total building heat-loss that would occur if each area was at this average temperature.

Metabolic energy was estimated in the study. The owner recorded hourly records of the number of people in the house during a one-week period. These people-hours were averaged for each hour of the day to produce an "average" occupancy schedule. Probable activities were estimated for the various hours, typical metabolic rates were selected for these activities, corrections were made for the average-sized person in the family, and the hourly results were added.[6] At best this is a speculative presumption, but it at least indicates the relative order of magnitude of this energy source.

RESULTS

As expected from the amount of insulation in the building, auxiliary heating requirements were very small. During month 1, with an average dry bulb temperature of 29.9°F (-1.16°C), the building required only 29% of the energy requirement indicated by the steady state heat loss calculation with window insulation. Appliance, metabolic, and solar energy are thus responsible for meeting at least 71% of the very small calculated heat loss for month 1. Figure 8 is a plot of energy into the house for a "typical" day in month 1. Energy use for the warmer month 2 is even smaller (Tables 2 and 3).

Comfort conditions in the house were not extreme. Minimum temperature in any one room for the 60 day period was 60.5°F (15.8°C). Maximum temperature in any room was 76.0°F (24.4°C). The largest diurnal temperature swing in any room was 9.9°F (5.5°C), and the largest instantaneous temperature difference between any two rooms was 8.8°F (5.8°C). These are extremity indicators of the comfort levels in the building. They may be much more severe than normal values and could have been caused by unconventional activities in the house. Daily average house temperatures ranged between 62.8°F (17.1°C) and 72.1°F (22.3°C). The diurnal temperature changes in the rooms with the maximum ΔT for each day averaged 5.5°F (3.1°C). Indoor relative humidity was always between 37% and 52%. The outdoor air temperature varied from 0.2°F (-17.7°C) to 78.7°F (25.9°C), presenting a wide range of operating conditions.

The monthly summaries, Tables 2 and 3, include the environmental data needed to perform most of the simplified energy analysis procedures.(7,8,9,10)

The window insulation performance was analyzed using a linear regression technique. Eighty four data points from two weeks for the hours of 1:00 through 6:00 a.m. were utilized.

The following model was used:

$$T_{spa} = a_0 + a_1 \times T_{out} + a_2 \times T_{in} \qquad (4)$$

where

T_{spa} = air temperature between glass and insulation

T_{out} = temperature outdoors

T_{in} = temperature indoors

a_0 = 0 = least squares coefficient

a_1 = $U_{glass}/(U_{glass} + U_{ins})$ = least squares coefficient

a_2 = $U_{ins}/(U_{glass} + U_{ins})$ = least squares coefficient

$a_1 + a_2$ = 1

U = thermal conductivity

The results follow:

R = 0.9991

S.E.E. = 1.3071

a_1 = .765

a_2 = .235

Therefore:

U_{ins} = .307 x U_{glass}

If U_{glass} = .5 Btu/hr·°F·ft^2 (2.8W/°C·cm^2) then U_{ins} = .15 Btu/hr·°F·ft^2 (.85 W/°C·cm^2) giving a total of R-8.7 (RSI-1.53) for the insulated window. The same analysis for the other monitored window data resulted in R-8.3 (RSI-1.46). The measured average R value of R-8.5 (RSI-1.50) is 79% of the calculated value, a higher percentage than found in the field by others.[11] Possible reasons for reduced performance from the calculated value are:

1. Air may be leaking around the shutters even though they appear to be well-sealed by the magnetic strip.
2. The foamed-on-site urethane may have a higher thermal conductivity than expected.
3. The assumed U value of the glazing 0.5 Btu/hr·°F·ft^2 (2.83 W/°C·cm^2) may be wrong.

Several attempts have been made to evaluate the building heat transfer coefficient in lieu of the electric coheating test. In one scheme hourly data from the hours ending at one through six for 21 days was analyzed according to the equation:

$$UA = (Q_{Heating} + Q_{Appliance} + Q_{Storage} + Q_{Metabolic}) / \Delta T \qquad (5)$$

where

UA = conduction and natural infiltration building heat transfer coefficient

$Q_{Heating}$ = heating equipment energy (measured)

$Q_{Appliance}$ = appliance energy (measured)

$Q_{Storage}$ = $C \times \Delta T_2$ = storage energy released

$Q_{Metabolic}$ = metabolic energy (estimated)

C = fraction of building thermal storage capacity (estimated)

ΔT_2 = temperature change in building (measured)

ΔT = indoor - outdoor temperature difference

This 6 hour time period was selected because (1) metabolic rates are relatively constant, (2) solar transients are minimized, (3) window insulation is installed, (4) ΔT is maximized and, (5) the ventilation system does not operate at this time on these days. This hourly heat balance method is difficult to stabilize, and a satisfactory error analysis has not been developed. Difficulties in estimating $Q_{Storage}$ and $Q_{Metabolic}$ are assumed to be responsible for these problems. Refined estimating methods may improve confidence levels for this evaluation.

Another technique employed to verify the building UA has been multiple linear regression on the daily building envelope heat balance, following the S.E.R.I. Class B technique:[12]

$$Q_{(Heat)} + Q_{(App)} = b_0 + b_1 \times (T_I - T_0) + b_2 \times (H_r t) \qquad (6)$$

where

$Q_{(Heat)}$ = heating equipment energy, daily total

$Q_{(App)}$ = appliance energy, daily total

b_0 = nonmeasured constant losses - constant gains = least squares coefficient

b_1 = 24 x UA = least squares coefficient

UA = total building heat transfer coefficient

T_I = indoor air temperature, average daily

T_0 = outdoor air temperature, average daily

b_2 = solar radiation multiplier = least squares coefficient

$H_r t$ = south vertical solar radiation, daily total

Limiting the analysis to the 33 days when over 1 kilowatt-hour of heating equipment energy was actually needed gives the following results:

$R = .66$

$C_0 = 27720$

$C_1 = 1530.80$, SEE = 345.62

$C_2 = -12.06$, SEE = 4.06

The correlation coefficient of 0.66 indicates that this is a poor model. Several nonlinearities exist in Equation 6 above which decrease the accuracy and meaningfullness of the correlation results:

1. South window shutters were applied and removed on a diurnal basis, thus changing the actual building UA. On some days, the south window insulation was not removed.
2. The ventilation system ran different amounts of time on different days, thus changing the actual building UA.

We would expect to get more meaningful results by removing these non-linearities from the regression equation as follows:

$$Q_{Heat} + Q_{App} - Q_{Vent} - Q_{South} = c_0 + c_1 \times (T_I - T_O) + c_2 \times H_{rO} \qquad (7)$$

where

Q_{Heat} = heating equipment energy, daily total, measured

Q_{App} = appliance energy, daily total, measured

Q_{Vent} = forced ventilation air heating energy, daily total, measured

Q_{South} = energy lost through variable R-value south windows, calculated from measured ΔT's and window system R-values

c_0 = non measured constant losses - constant gains = least squares coefficient

c_1 = $UA_{Partial} \times 24$ = Least Squares Coefficient

$UA_{Partial}$ = constant component of building conduction and natural infiltration heat transfer coefficient, (walls, ceiling and N, E, W windows with insulation to ambient temperature)

T_I = indoor air temperature, average daily

T_O = outdoor air temperature, average daily

c_2 = solar radiation multiplier = least squares coefficient

H_{rO} = vertical solar radiation with south shutters removed, daily total

The regression results are:

$R = .7982$

$c_0 = -10810.84$

$c_1 = 1878.40$ SEE = 318.32

$c_2 = -14.89$ SEE = 3.33

This analysis results in a better fit than that for equation 6. The 95% confidence level for the UA_p value is:

$$UA_{pMeasured} = c_1/24 = (1878 \pm 1.96 \times 318)/24 = 78 \pm 26 \text{ Btu/hr}\cdot{}^\circ\text{F } (41 \pm 14 \text{ W/}^\circ\text{C}) \qquad (8)$$

The calculated value of UA_P, is obtained by subtracting the calculated ventilation, and basement losses from the design values in Table 1; and dividing by the design ΔT,

$$UA_{P_{Calculated}} = (9034 - 2643 - 92)/84 = 65 \text{ Btu/hr}\cdot{}^\circ\text{F } (34 \text{ W/}^\circ\text{C}) \tag{9}$$

The mean UA_P obtained by the regression technique is thus within 20% of the calculated value. Only .06 air change/hour natural infiltration (not included in the calculated value) would account for this difference. From this analysis it appears that the ASHRAE-Type heat loss calculated for this level of insulation is about as accurate as that obtained for more conventional conservation measures.[13]

c_0 is thought to be composed of daily first floor losses to basement minus daily metabolic gains. The calculated first floor loss is 921 Btu/hr (270 W) at a 15°F (8.3°C) temperature difference. When this is corrected for the measured 16.5°F (9.2°C) ΔT and multiplied by 24, the result is a 24,314 Btu/day (25.653 MJ/day) calculated loss through the first floor. Daily metabolic gains, calculated as described earlier, total 16,600 Btu/Day (17.515 MJ/day). c_0 calculated is thus +7714 Btu/day, (8.139 MJ/day) compared to c_0 measured of -10,811 Btu/day (11.40 MJ/day).

The difference is a large number, about equal to the total metabolic gain estimate. Identification of the cause of this large difference could lead to a much better linear curve fit. Several possiblities are suggested:

1. The losses to the basement may be overestimated.
2. The metabolic gains may be underestimated.
3. A previously unidentified energy gain to the building may exist. One possibility is that domestic hot water usage, ignored in the S.E.R.I. Class B data analysis, contributes an important amount of energy.

c_2 can be thought of as the area of south facing glass times the monthly transmission-absorption product for the glazing-building system. With a south glass area of 56 ft^2 (5.2 M^2) and an expected transmission-absorption ($\tau\alpha$) product of about .6, c_2 would equal -33.6. The results from the regression analysis indicate c_2' to be only -14.89, less than half the expected value. Further analysis is needed to resolve this difference.

The house envelope was tested by the fan pressurization, or "blower door" method for air leaks.[14] The heat-exchanger ducts, which are the only intentional wall penetrations, were sealed with polyethylene and tape before the test. At 125 CFM (59 L/S) for ΔP = .04"H_2O (10 Pa) depressurized, this house is near the mean of a group of 40 "airtight" houses recently studied in Canada.[15] Depressurized to .2" H_2 (50 Pa) this house experienced 1.5 air changes per hour (including basement volumes), compared to 1.49 for the Canadian sample. The blower door unit used for the test was calibrated for use in a wide range of buildings, but this house is tight enough to allow air flow only in the lower extreme of the calibration range. Therefore maximum experimental error for the air flow calculation is quite large, perhaps + 100%, - 50%, although close inspection of the data indicates that more confidence may be justified.

Table 4 shows test results for several pressures. Note that increasing ΔP causes a smaller increase in air flow in the pressurized mode than in the depressurized mode. In fact these two flow rates, when plotted as a function of $|\Delta P|$ cross at about .1"H_2O (25 pascal). This is apparently caused by the indicated changes in the calculated effective leakage areas for different ΔP's, calculated by:

$$A_0 = q/\sqrt{2\cdot \Delta P/\rho} \tag{10}$$

where

q = air flow rate (m^3/sec)

ΔP = Pressure Difference (Pascals)

ρ = 1.3 Kg/m^3

A_0 = effective leakage area, (m^2)

Increasing the ΔP when depressurized causes the effective leakage area to increase, but increasing the ΔP when pressurized helps some of the leakage paths to self-seal. Further investigation may indicate whether this phenomenon is real or merely a result of experiment or calculation procedures.

Inspection of the house during depressurization revealed the following main leaks, small though they were:

1. Double hung window weather stripping.

2. Faulty infiltration barrier detail at electric main exterior wall penetration.

3. Basement door compression-type weather stripping.

Most manufacturer literature indicates that awning or casement-type windows with compression weather stripping are more air-tight than the sliding seals found on the double-hung windows. The effect on the blower door test of using the tighter windows would be difficult to predict.

The test of the air-to-air heat exchanger indicated an effectiveness of 0.62 in a noncondensing mode, better than lab tests indicated for a similar unit made with plastic rather than aluminum sheets.[16] Aluminum certainly has a higher thermal conductivity than plastic, and this change may account for the higher effectiveness. Measuring air flow in the supply and exhaust ducts was difficult and time consuming. Even on a calm day, small changes in wind velocity pressure, or the closing of a door upstairs would send the system into long transients. During the approximate steady state, flow into the house from the exchanger was 96 CFM (45 L/S) and flow from the house to exchanger was 102 CFM (48 L/S). The average of these two is the equivalent of about half an air change per hour, which is coincidentally the number recommended by a number of sources.[17]

During the monitoring period the ventilation system kept relative humidity under control. During cold weather the system would immediately reverse a sharp increase in the relative humidity curve, reducing the level to near 40% from 52% in an hour. On warmer days, the system would run for many hours with no apparent humidity change from around 40%. The maximum running time for any single day was about 10 hours, while the longest inoperative span was 5.5 days. In warmer weather the system could possibly run 24 hours a day, or in a cold dry season it could possibly not run for several weeks.

Data recorded manually during two short periods of no hot water draw-down indicate that jacket losses are 12,132 Btu/day (12.800 MJ/Day), or 33% of all energy expended for heating water in month one. The average temperature on the tank side of the tank insulation was 129°F (54°C), while the basement temperature during the monitoring period averaged 49°F (9.4°C). Dividing losses by the temperature difference gives a tank loss coefficient of 7.11 Btu/hr·°F (3.75 Watt/°C) compared to the manufacturer's 5.71 Btu/hr·°F (3.01 Watt/°C). The manufacturer's number is probably within the experimental error of this crude measurement.

Assuming that 12,132 Btu/Day (12.800 MJ/Day) is the correct jacket loss to the 49°F (9.4°C) basement, then it follows that if the water heater were upstairs where the air is at 65.5°F (18.6°C), the jacket losses would be reduced by 20%. In addition, during a cold month like month 1, a large part of the remaining jacket losses could directly replace heating equipment energy. Thus moving the heater upstairs could save up to the total 12,132 Btu/day (12.800 MJ/day) basement jacket losses, equivalent to 45% of the heating equipment energy for month 1. Lowering the average water temperature below 129°F (54°C), if acceptable with time-of-day billing, would give additional savings on an annual basis. The basement temperature would drop some small amount if the water heater jacket losses were removed, causing additonal heat losses from the conditioned space, but this effect should be small due to the large amount of insulation between the two spaces.

CONCLUSIONS

The results of this project demonstrate that superinsulated buildings can conserve large amounts of energy while maintaining reasonable comfort conditions within the living space. The energy use of this building is the lowest of any of the buildings yet monitored by the Brookhaven Laboratory field validation group.

Several conclusions may be drawn from this study:

1. Thermal Envelope: The wall, ceiling, and window insulating systems display slightly poorer performance than predicted, but are within expected error bounds for such predictions.

2. Heat Exchanger: Humidistats should not be the only control for the ventilation system. The heat exchanger and cold ducts within the house must be well protected from condensation.

3. Hot Water Heater: If the heater were installed within the envelope, standby jacket losses would be 20% lower and some heating equipment energy would be displaced.

4. Windows: Snap-in window muntins can reduce the glazing area available for solar gains by surprisingly large amount, 17% in this case. Windows with compression-type weather stripping would reduce air infiltration compared to the double-hung units.

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Scott Blouin and his family are acknowledged for allowing the inconveniences of monitoring to take place in their home. Tony Whitehair at Central Vermont Public Service made the project possible by providing the printed kilowatt-hour data. Sharon Zuhoski's efforts in typing this manuscript are also acknowledged.

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TABLE 1
Building Statistics

R-value, Calculated		
Walls	(R-41)	(RSI- 7.2)
Flat Ceiling	(R-57)	(RSI-10.0)
Sloped Ceiling	(R-55)	(RSI- 9.7)
Floor	(R-21)	(RSI- 3.7)
Windows (Uninsulated)	(R- 2.0)	(RSI- 0.35)
Windows (Insulated)	(R-10.7)	(RSI- 1.88)
Door	(R- 2.5)	(RSI- 0.44)
Heat Loss, Calculated at 84°F (47°C) T[1]		
Without Window Insulation	16324 Btu/hr	(4782.9 Watts)
With N, E, W Window Insulation	12986 Btu/hr	(3804.9 Watts)
With N, S, E, W Window Insulation	9750 Btu/hr	(2856.8 Watts)
With N, E, W Insulation Excluding South Window Area	9034 Btu/hr	(2647.0 Watts)
Heat Storage Capacity, Calculated[2]	1124 Btu/°F	(21.325 MJ/°C)
Areas and Volumes, Measured		
Floor Area, Conditioned Space, Inside Exterior Walls	1557 ft^2	(144.6m^2)
Floor Area, Including Basement	2428 ft^2	(225.6m^2)
Volume, Conditioned Space, Excluding Floor Joint Volumes	11128 ft^3	(315.1m^3)
Volume Including Basement	17397 ft^3	(492.6m^3)
Glass Area, Total	152 ft^2	(14.1m^2)
Glass Area, Total South Facing	68 ft^2	(6.3m^2)
Glass Area, South Facing with Muntins	56 ft^2	(5.2m^2)
Envelope Area, Conditioned space, Without Floor	2519 ft^2	(234.0m^2)

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[1] Includes forced ventilation loss of 2643 Btu/hr (774 Watt) and first floor to basement conduction loss of 921 Btu/hr (270 Watt) at 15°F (8.3°C)ΔT. Forced ventilation assumed 1/2 air change/hr @ .70 heat recovery effectiveness. Loss to basement assumed constant at 15 °F (8.3 °C) T.

[2] Includes sheetrock, flooring, partition framing, framing members in inner half of exterior envelope, air, and furniture and appliances (estimated). Handbook material properties used.

TABLE 2
Monthly Bin Data - Month 1 Summary

Temperature Range		OBSN Hour Group			Total OBSN
Deg F	Deg C	01 to 08	09 to 16	17 to 14	
55/59	12.8/ 15.0	0	3	0	3
50/54	10.0/ 12.2	0	14	4	18
45/49	7.2/ 9.4	0	35	8	43
40/44	4.4/ 6.7	10	36	29	75
35/39	1.7/ 3.9	31	70	44	145
30/34	-1.1/ 1.1	52	45	60	157
25/29	-3.9/ -1.7	54	17	46	117
20/24	-6.7/ -4.4	39	19	24	82
15/19	-9.4/ -7.2	29	21	23	73
10/14	-12.2/-10.0	28	4	18	50
5/ 9	-15.0/-12.8	15	0	6	21
0/ 4	-17.8/-15.6	6	0	2	8

Energy Data

Heating Equip. Energy, Avg. Daily	26,735 Btu	28.208 MJ
Appliance Energy, Avg. Daily	39,404 Btu	41.575 MJ
DHW Energy, Avg. Daily[1]	37,284 Btu	39.33 MJ
Metabolic Energy, Avg. Daily[2]	16,636 Btu	17.553 MJ
Outdoor Temperature, Monthly Avg.	29.9°F	-0.2°C
Indoor Temperature, Monthly Avg.	65.5°F	18.6°C
Degree Days, Monthly Total	1157°F·Day	643°C·Day
Vertical Solar Rad., Avg. Daily Total	1278 Btu/ft^2	14.51 MJ/m^2
Horizontal Solar Rad.,Avg. Daily Total	967 Btu/ft^2	10.98 MJ/m^2

Mid Month Solar Declination 0 Deg.
So. Shutters Open Day, Closed Night
N,E,W Shutters Usually Closed

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[1] In Basement.

[2] Estimated.

TABLE 3
Monthly Bin Data - Month 2 Summary

Temperature Range		OBSN Hour Group			Total OBSN
Deg F	Deg C	01 to 08	09 to 16	17 to 14	
75/79	23.9/26.1	0	6	0	6
70/74	21.1/23.3	0	14	7	21
65/69	18.3/20.6	0	28	13	41
60/64	15.6/17.8	4	49	19	72
55/59	12.8/15.0	16	46	31	93
50/54	10.0/12.2	39	33	47	119
45/49	7.2/ 9.4	46	16	37	99
40/44	4.4/ 6.7	31	13	23	67
35/39	1.7/ 3.9	38	9	24	71
30/34	-1.1/ 1.1	23	2	11	36
25/29	3.9/-1.7	17	0	4	21
20/24	-6.7/-4.4	2	0	0	2

Energy Data

Heating Equip. Energy, Avg. Daily	1,112 Btu	1.173 MJ
Appliance Energy, Avg. Daily	34,977 Btu	36.904 MJ
DHW Energy, Avg. Daily[1]	38,719 Btu	40.852 MJ
Metabolic Energy, Avg. Daily[2]	16,636 Btu	17.553 MJ
Outdoor Temperature, Monthly Avg.	50.2°F	10.1°C
Indoor Temperature, Monthly Avg.	67.6°F	19.8°C
Degree Days, Monthly Total	399°F·Day	222°C·Day
Vertical Solar Rad., Avg. Daily Total	886 Btu/ft^2	10.06 MJ/m^2
Horizontal Solar Rad.,Avg. Daily Total	N/A	N/A
Mid Month Solar Declination	13.6 Deg.	

So. Shutters Open Day, Closed Night
N,E,W Shutters Usually Closed

---

[1] In Basement.
[2] Estimated.

Table 4
Blower Door Tests Results for Several Pressures

Pressure		Depressurize			Pressurize		
			Effective Leakage Area[2]			Effective Leakage Area[2]	
"H_2O	Pa	Air Change/Hour[1]	ft^2	m^2	Air Change/Hour[1]	ft^2	m^2
.2	50	1.5	(.26)	.024	1.3	(.22)	.020
.1	25	1.0	(.23)	.021	1.0	(.24)	.022
.04	10	.5	(.16)	.015	0.8	(.31)	.029
.016	4	.1[3]	(.14)[3]	.013[3]	0.3[3]	(.33)[3]	.031[3]

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[1] Includes both 11128 ft^3 (315 m^3) living area and 6110 ft^3 (173 m^3) basement.
[2] Calculated from equation 10.
[3] Extrapolated from experimental data.

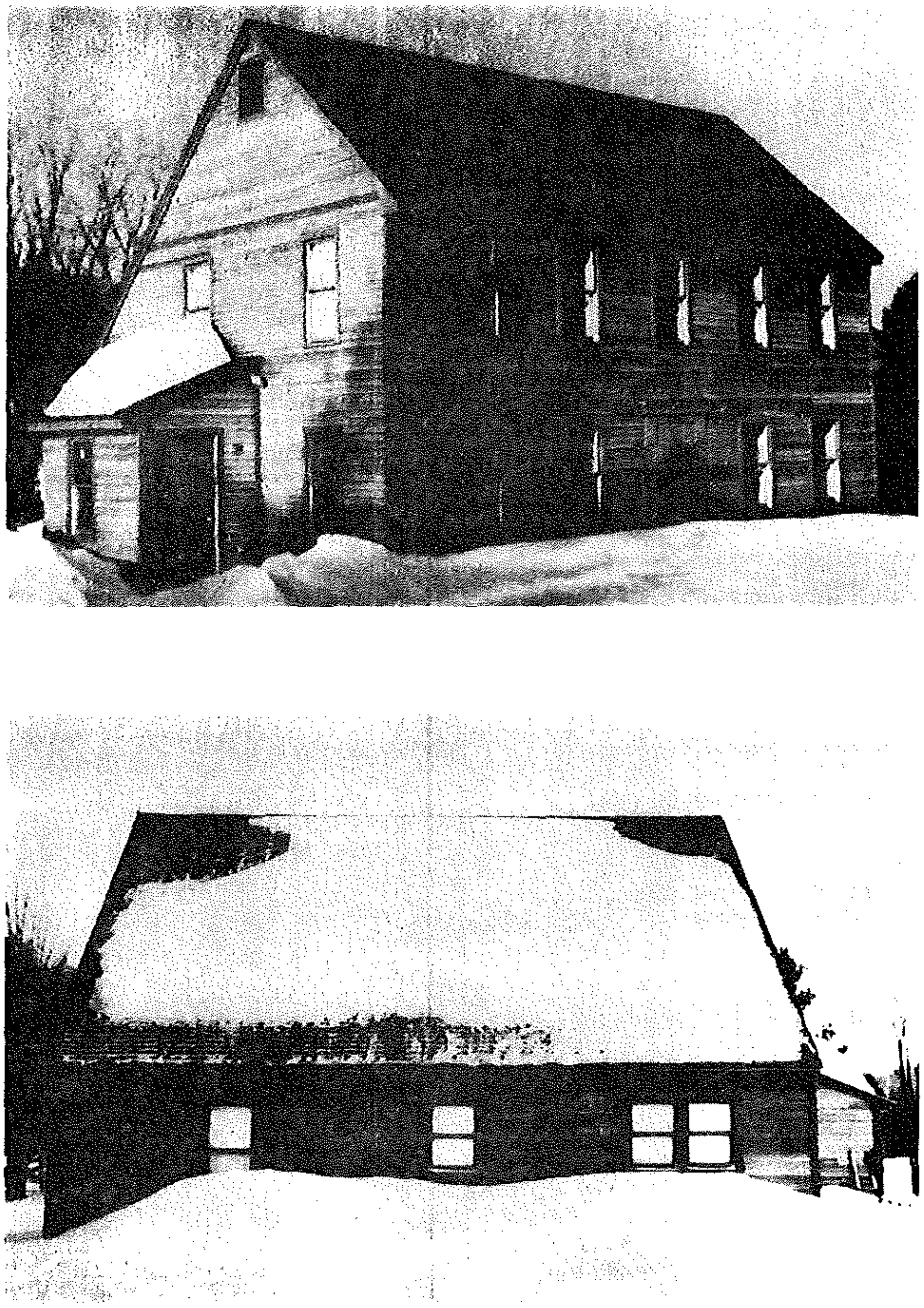
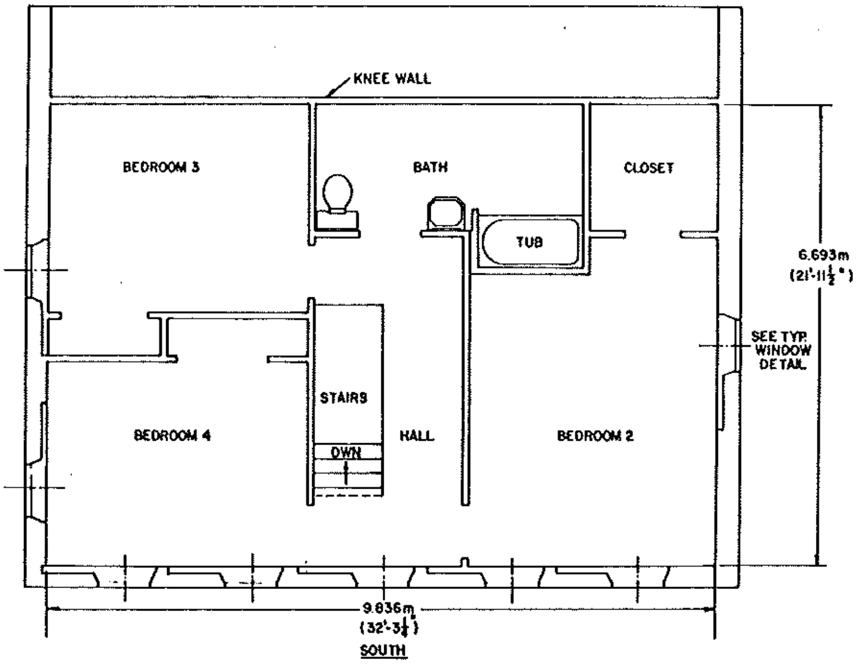
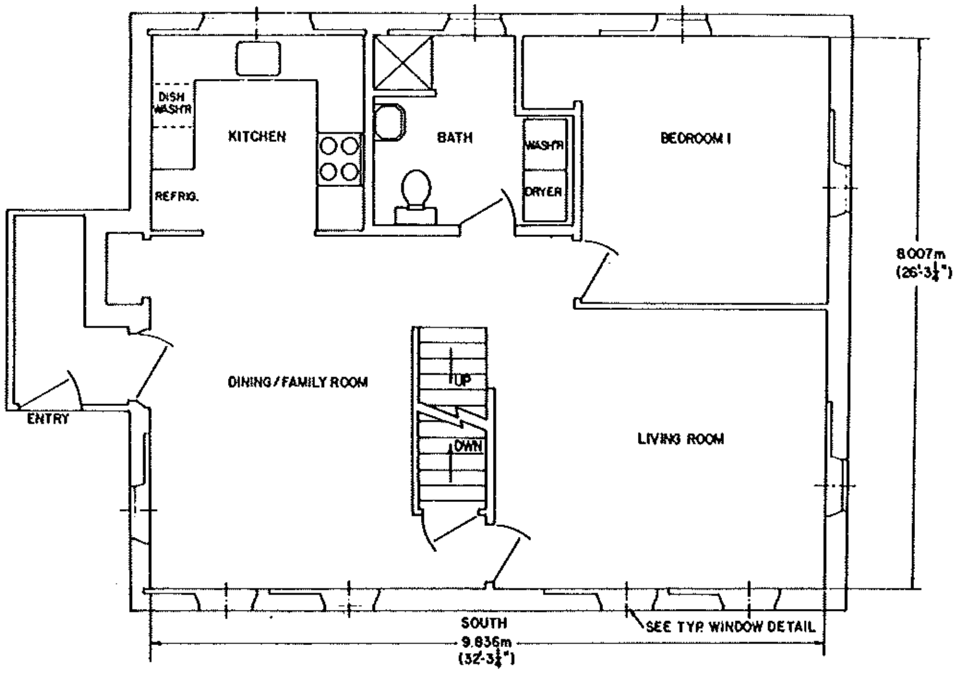


Figure 1. Blouin House southwest and north view

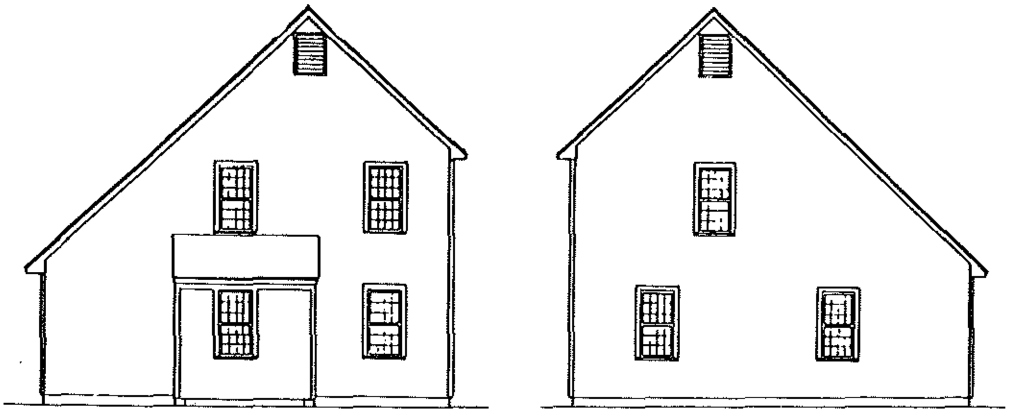


SECOND FLOOR PLAN



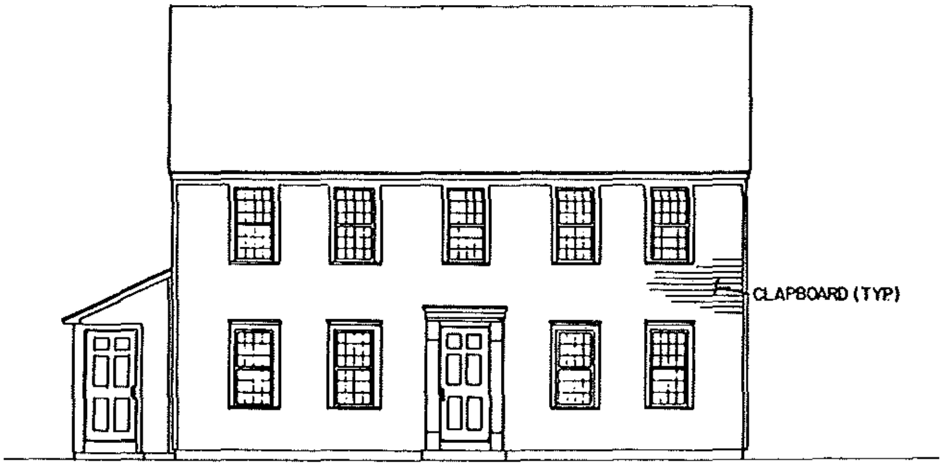
FIRST FLOOR PLAN

Figure 2. Blouin House, first- and second- floor plans



WEST ELEVATION

EAST ELEVATION



SOUTH ELEVATION

Figure 3. Blouin House elevations

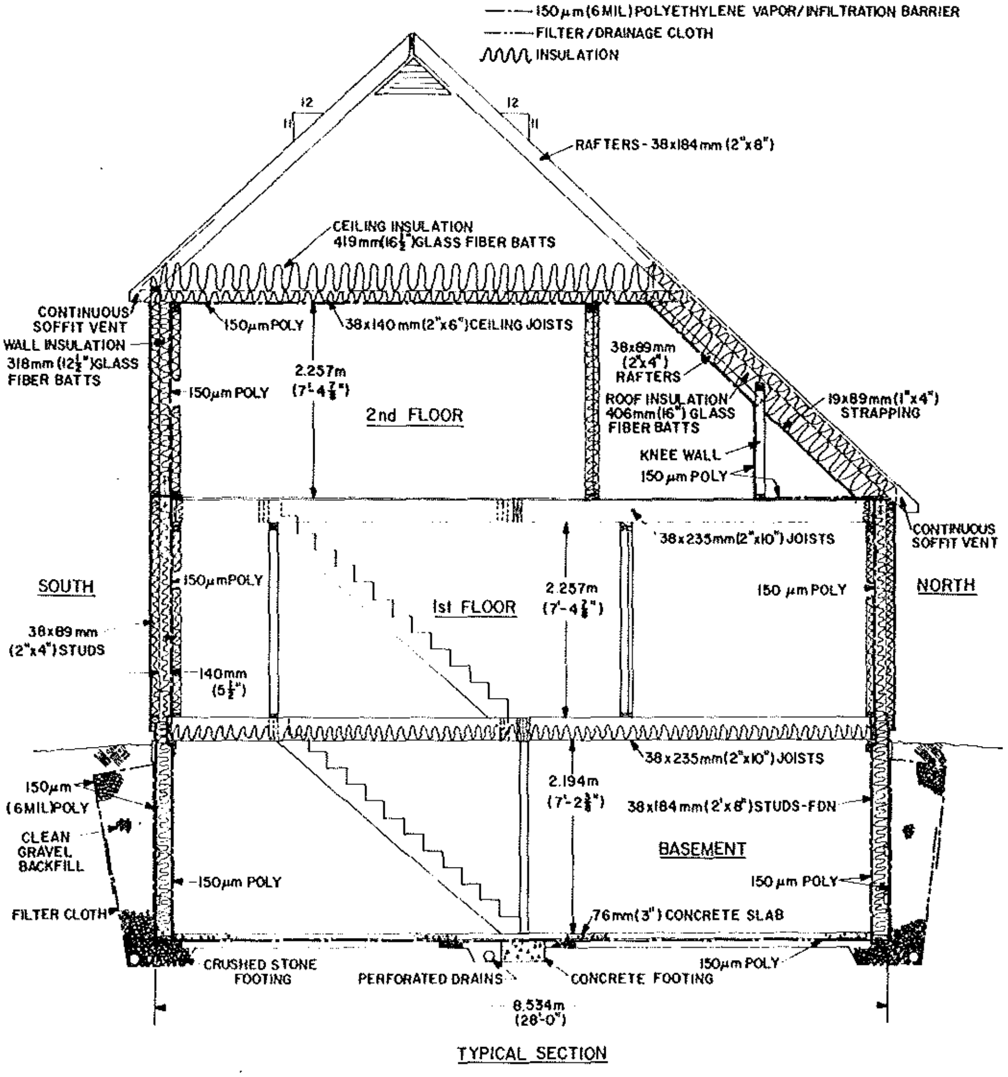


Figure 4. Blovin House framing section

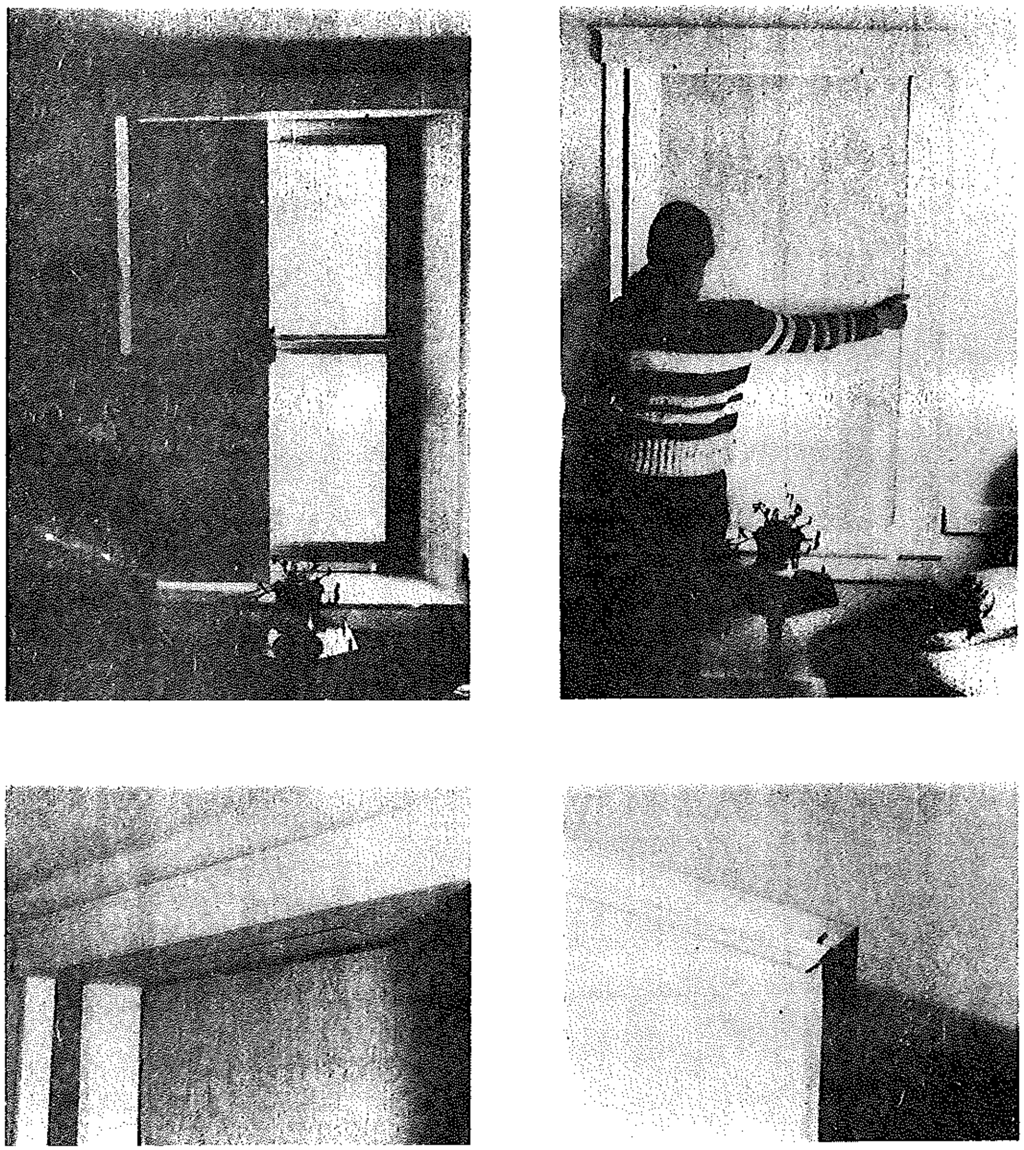


Figure 5. Blouin House thermal window shutters

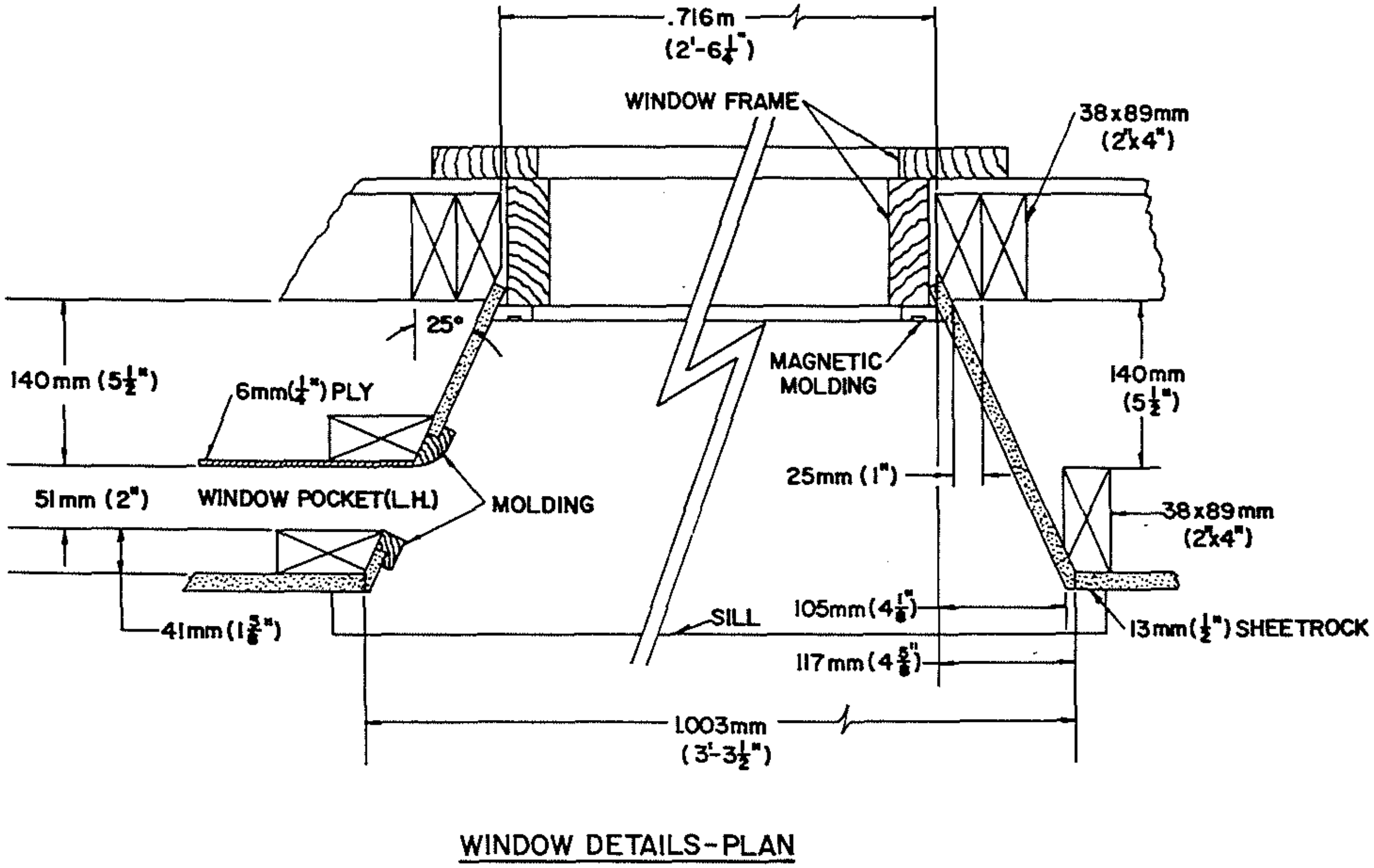


Figure 6. Blouin House window detail plan

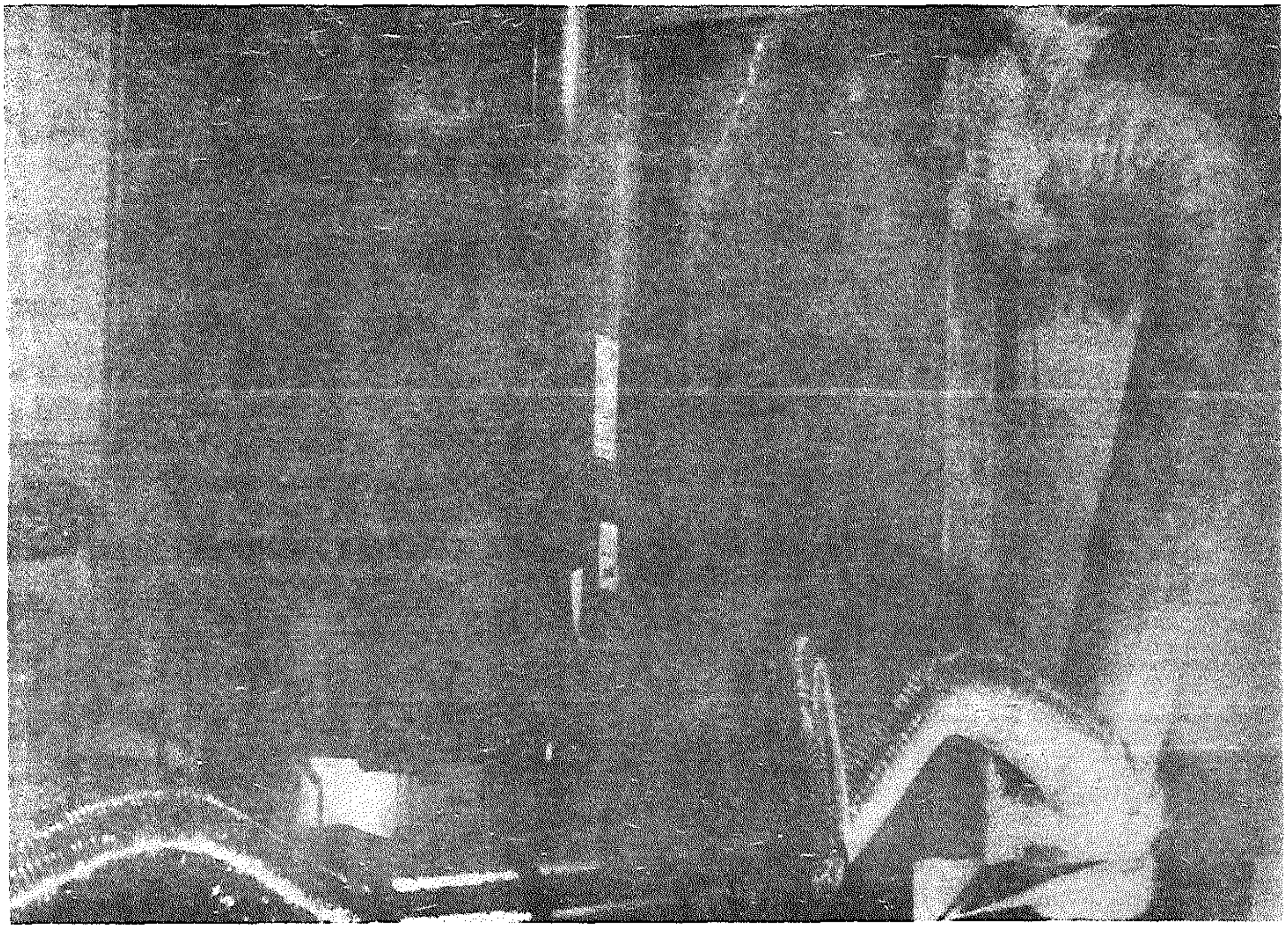


Figure 7. Air-to-air heat exchanger system

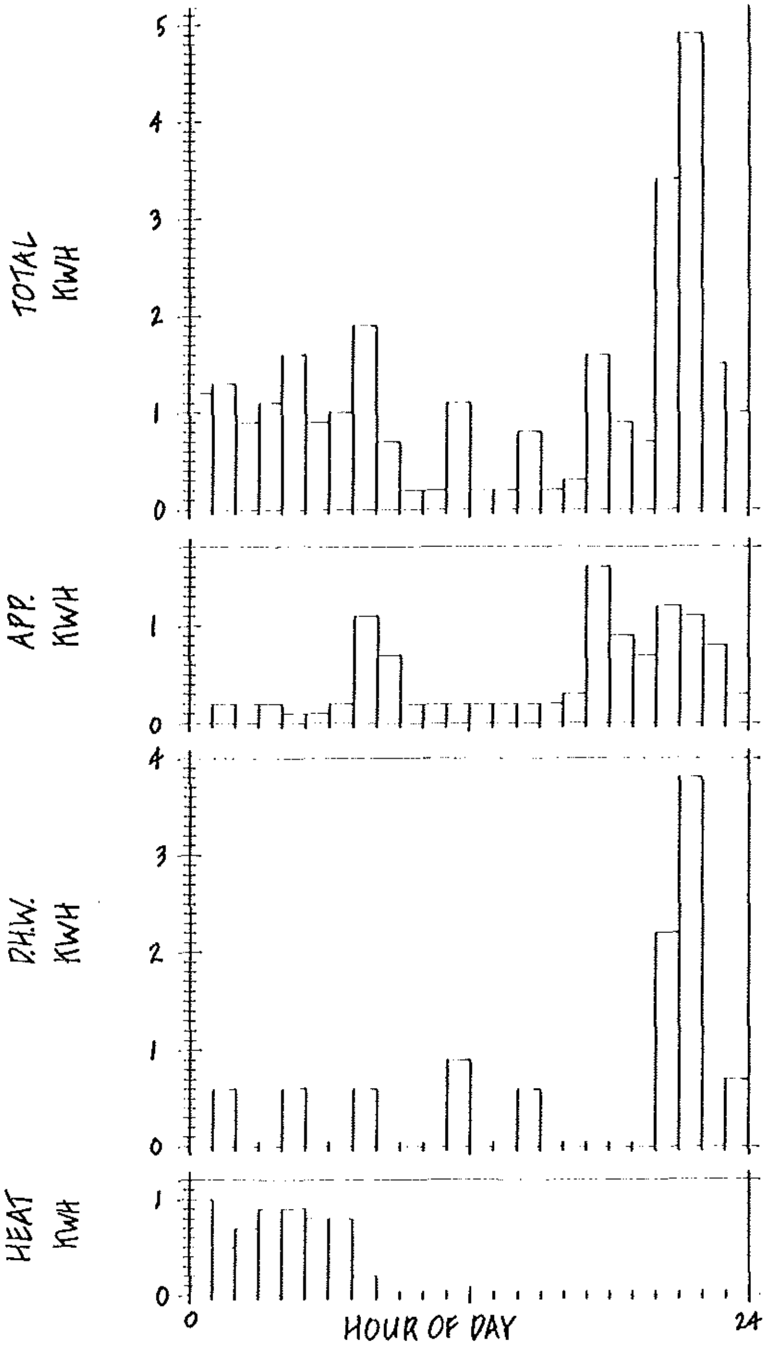


Figure 8. Hourly electricity use for one day (3/18/82) in a "typical" month

Discussion

A. Lannus, EPRI, Palo Alto, CA: What was the heating season electricity use for electricity?

R.F. Jones: The homeowners' electricity bills indicate that 4251 kWh were used for heating and other uses, excluding hot water heating, and 1690 kWh were used for domestic hot water heating for the period November 20, 1981 through April 28, 1982. The house was not occupied before November 20, 1981. The window insulation system was installed between January 5 and 17, 1982.