Energy Monitoring Results of a Superinsulated Passive Solar Building

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ABSTRACT

This paper presents results of an investigation of the thermal performance of a super-insulated passive solar house which is heavily equipped with instruments. Three test days were chosen to measure the building thermal losses under specific controlled conditions. The test periods were conducted during cold nights following cold cloudy days. Infiltration was measured. Calibrated heating units were used to maintain a constant temperature in the house during the test periods. The house was operated in three configurations: (1) a base case, in which the windows were uncovered and the furnace was not used, (2) a period in which the furnace fan was run continuously to measure duct losses, and (3) a period in which the windows were covered with insulating panels. The base case building loss rate was .137 Btu (hr ft^2 °F) [.779 W/(m^2 · K)]. With the fan system running, losses increased. The 27 percent greater loss rate was attributed to uninsulated duct losses to the crawl space. The effect of shuttering the window was approximately a 7 percent decrease in building loss rate.

INTRODUCTION

Because of current energy perspectives and the uncertainty about the availability, amount, and price of future energy supplies, energy-efficient buildings are a necessity. In contrast to transportation, process technology, or other energy uses, buildings constructed today will be in use well into the next century, essentially as they were originally constructed. Theoretically, substantial energy savings can be gained by upgrading design and construction techniques. The question to be answered now is how much energy will actually be saved by using the new theoretical design and construction techniques. This investigation, and the project of which it is a small part, was initiated to answer this question.

With this goal established, a project proposed by the Small Homes Council-Building Research Council (SHC-BRC) of the University of Illinois was granted funding by the Illinois Department of Energy and Natural Resources and the U.S. Department of Energy. To determine energy savings, field data are being collected for the thermal performance of two occupied, super-insulated, passive solar light-frame residences in Champaign, IL. The specific objective of the project is to test the energy-saving features incorporated into the design of the "Illinois Lo-Cal House."

To this end, the overall insulating effectiveness of the Lo-Cal design concept must be determined under different controlled operating modes (e.g., fan system running, windows shuttered). The term building thermal loss rate, BTL (U-value times surface area normalized to the building floor area) will be used to describe the building's overall resistance to heat loss. The lower the BTL value, the more energy-efficient the building. Having experimentally established the BTL for the Lo-Cal House, evaluations of the Lo-Cal approach can be

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made more accurately. Also, actual houses and computer-simulated models can be compared. The design concept employed the Building Loads Analysis and Systems Thermodynamics (BLAST) program developed by the U.S. Army Construction Engineering Research Laboratory to predict thermal loads.

This investigation will concentrate on establishing the experimental methodology and on isolating the contributing effects of factors such as window area, uninsulated duct work in the crawl space, and infiltration on energy consumption during specific controlled periods. Subsequently, recommendations will be made about the relative effectiveness of specific design improvements and areas that need further research.

ILLINOIS LO-CAL HOUSE DESIGN FEATURES[1,2]

The Lo-Cal design incorporates two basic concepts:

1. A heavily insulated envelope that allows only a low rate of infiltration and features a double-staggered stud-wall configuration, triple glazing on all windows, and a polyethylene vapor and infiltration barrier. (See specification sheet, Tab. 1.)

2. Solar orientation, in which a majority of the glass is facing south, the major axis of the house is oriented east-west, and the roof overhang is designed to optimize solar input. (See floor plans and elevations, Fig. 1 through 3).

DATA ACQUISITION[3,4]

The test residence is heavily equipped with instruments to monitor the thermal performance of the building envelope, the interior comfort conditions, and the energy use in response to exterior climatic conditions.

Weather data are collected from a tower on the roof of the structure. Sensors are also located in the attic, living area, and crawl space to measure ambient temperatures, interior and exterior wall temperatures, heat fluxes through walls, relative humidity, etc. The furnace, air conditioning, and electrical power are also monitored.

The data acquisition system is a data acquisition/control unit and a desktop computer. The system features interrupt capabilities, a small CRT display, graphics capabilities that can generate quick data summaries in graphic form, a printer, and cassette-tape storage.

All sensors are scanned sequentially at five-minute intervals, and the data are averaged every fifteen minutes. These average values are stored locally on cassette tape and transferred to the University's main computer regularly.

PROJECT TIMETABLE

August 1981 - September 1982: Instrument Setup

After the instrumentation equipment was acquired and installed, the computer program and the instruments were tested, calibrated, and debugged.

December 1981 - September 1982: Data Collection

During this period, data were collected from the sensors in the method described earlier. The data were tabulated and analyzed, using the main computer at the University of Illinois. Days were selected and set aside for the testing of the furnace equipment and structure and for calibrating the instruments.

March 1982: Thermal Performance Experiments

To test the energy-saving features incorporated in the "Lo-Cal" design, the overall insulating effectiveness of the building had to be determined under various controlled operating modes. The building thermal performance (UA-value divided by the floor area) is a measure of overall resistance to heat loss. The lower the performance value, the more energy-efficient the building.

For the experiment, space heaters were used in each room to keep the interior temperature constant during the test period. An energy balance determination was performed to calculate the UA-value for different operating modes. For the base house when the furnace fan was off, the performance was 3.3 Btu/($ft^2 \cdot DD$) [0.779 W/($m^2 \cdot K$)], and approximately 77 percent of the heat loss was through the building envelope and 23% by infiltration. When the fan was on, the losses increased by 27% to 4.18 Btu/($ft^2 \cdot DD$) [0.987 W/($m^2 \cdot K$)], and 61% of the heat loss was via the building envelope. Shuttering the windows decreased the losses by 7% to 3.1 Btu/($ft^2 \cdot DD$) [0.722 W/($m^2 \cdot K$)].

BUILDING THERMAL LOSS RATE (BTL)

The intention of this specific work was to determine the sources and rate of heat loss from the structure under specific controls such as internal loads and known weather conditions. Basic divisions were assumed regarding the sources of heat loss from the structure, and operating conditions were modified in an attempt to identify and quantify major sources of heat loss. The sources of heat loss were divided into three primary areas: (1) heat loss via building components, (2) heat loss caused by air changes, and (3) radiation losses through transparent portions of the envelope. The heat-loss rate under each operating condition was determined as an overall average heat-loss rate normalized to square footage at the structure and temperature difference between the exterior and interior conditioned environment. The method used in this investigation to calculate the BTL is based on several requirements and assumptions. A major part of this paper will be a discussion of the development of these requirements and the degree to which the experimental conditions approached these requirements.

Two measurement methods were available to determine the BTL: steady-state and transient. Because the residence is heavily equipped with instruments, a transient approach would probably be possible. J. E. Janssen[5] has developed a transient approach that measures both the BTL and the heat storage of building components. This approach requires two measurements under different conditions so that the thermal loss and heat storage components can be uncoupled. Janssen recommends that measurements be taken during a continuous heating cycle and during the cooling period in which the furnace remains off. There is one major drawback at the test house: furnace efficiencies are readily measurable, but the fraction of heat delivered to the conditioned space is not. The ducts in the test house run through the crawl space; temperature differences of 27-36°F [15-20°C] are observed between the furnace mixing box and far delivery registers approximately 50 ft [15.2 m] away.

The error associated with a transient measurement procedure under conditions of high duct loss is more significant than that associated with departure from steady-state conditions.[6] Therefore, a study of methods that would allow the structure to be tested under steady-state conditions was initiated.

A steady-state measurement requires that the interior and exterior temperatures of the structure be kept constant while the structure and contents come to thermal equilibrium. The study must be made under as constant an exterior environment as possible with minimal solar gain. Thus, a cloudy night after a number of cloudy days was determined to be the best test period. The temperature of the interior of the building and its components must also be maintained as constant as possible. Normal cycling of the natural-gas heating system will cause interior temperature fluctuations of up to 5.4°F [3°C] (see Fig. 5 and 6); therefore, a more constant interior ambient temperature was maintained with an auxiliary electric heating system. (The electric system was chosen because its overall efficiency is known.) The system was configured so that a very small interior temperature variation can be maintained (see Fig. 5 and 6); therefore, the effect of thermal storage inside the structure can be assumed to be small. The exterior ambient temperature must also remain nearly constant, or change slowly enough to approach a steady-state condition.

Under these prescribed conditions, the energy balance on the house is

$$\int \dot{Q}_{Stor}\, dt + \int \dot{Q}_{Input}\, dt = \int \dot{Q}_{Loss}\, dt \qquad (1)$$

where

$\dot{Q}_{Stor}$ = The heat retained in the building components and contents that is released or absorbed during the time period.

$\dot{Q}_{Input}$ = The heat input into the house per time period.

$\dot{Q}_{Loss}$ = The heat lost from the structure to the exterior during the time period.

The common form of this normalized heat loss in the United States is $Btu/(h \cdot f^2 \cdot {}^oF)$, or, for yearly approximations, $Btu/(f^2 \cdot DD)$.

To assure uniform distribution of heat and temperatures, eight separate electric heating sources were used. These electric heaters were loaned by a national laboratory and are the equipment used to test national solar data network structures. Each heating source included a calibrated electric heater, a remote thermostat on a stand, and a clock.

The use of the electric heaters made calculation of energy input easier. The power input for the heaters is equal to the delivered heat. The heat input was calculated relative to a reference voltage measured during heater calibration and multiplied by a correction factor determined by the measured operating voltage. The time each heater ran during each hour was recorded. The heat input from all heaters during each hour was calculated using the equation

$$\dot{Q}_{Input} = C^* \sum_{I=1}^{8} P_{Calibrated}{}^* t_I \qquad (2)$$

<u>where</u>

$\dot{Q}_{Input}$ = heat input to the house per time period per heater

C = correction factor for voltage variation:[7]

$$C = \frac{V^2_{Recorded}}{V^2_{Calibrated}}$$

V = voltage

$P_{Calibrated}$ = power measured during heater calibration testing

t_I = elapsed heater on-time

If the rate of change of the internal temperature can be assumed to be zero, the $\dot{Q}_{Stor}$ term can be dropped out, and the energy balance is

$$\int \dot{Q}_{Input}\, dt = \int \dot{Q}_{Loss}\, dt \qquad (3)$$

or more simply

$$\dot{Q}_{Input} = \dot{Q}_{Loss} \qquad (4)$$

If the heat losses are normalized for the area of building and the temperature differential, the BTL can be obtained from

$$\dot{Q}_{Input} = (BTL)^* A^* (T_{Int} - T_{Ext}) \qquad (5)$$

<u>where</u>

A = floor area ($ft^2[m^2]$)

$(T_{Int} - T_{Ext})$ = internal-external temperature difference (°F[°C])

Calibration of Equipment

The eight heaters were calibrated to an arbitrary reference voltage (120.8 V), using a sensitive watt-hour meter. The actual operating voltage was read hourly during the testing and used to establish the output correction factor.

To maintain a uniform constant temperature throughout the house, the individual unit heaters were calibrated. If a thermostat varied significantly from the others, either in rising or falling temperature, it was not used. The temperature data recorded during the test period verified the consistency of temperature throughout the house (Fig. 4, 5, and 6).

Experimental Conditions

Three different operating conditions were chosen in an attempt to separate and quantify the major components of the building heat loss.

1. Base Condition. In the base condition, the residence was operated with a minimum internal load. No cooking, use of appliances, cleaning, or bathing was done. The house was heated with the portable electric units only; the furnace and fan were not operated, and the windows were unshuttered. This base test condition was used to quantify the heat loss and infiltration of the structure with window losses but without duct system and burner-induced stack losses.

2. Base House With Furnace Fan Running. The same conditions applied as in No. 1, except that the furnace supply-fan was run continuously for the entire test period. The house was heated solely by the electric heaters and by minimal measured internal loads; the furnace blower was not operated. This test condition was used to quantify the impact on heat-loss rate and infiltration of the uninsulated duct system in the crawl space and the attic.

3. Base House With Windows Shuttered. All windows in the base house were covered with 1-in. [0.0254-m] foil backed polyisocyanurate with an in-place R-value of 10 ($ft^2 \cdot hr^o \cdot {}^oF$)/Btu [1.76 ($m^2K$)/W]. This test condition was used to quantify the impact of reduced window losses on the overall BTL.

Each of the three data collection periods started at approximately 8:00 AM. The heaters were turned on, and the time displays were zeroed. To minimize the solar input into the residence and to operate under conditions that would minimize temperature fluctuations of the building envelope, the test periods were chosen for maximum cloud cover during the daylight portion of the test. The heaters were allowed to operate for 10 to 12 hours to bring the house to thermal equilibrium. Starting at 7:00 to 8:00 PM, the hourly on-time of each heater was tabulated. It was expected that the most accurate data could be collected during the period of 11:00 PM to 6:00 AM.

Infiltration Effects

An important component of the heating load on any structure is that associated with infiltration. The infiltration component can so dominate the heating load that a calculated BTL value, using only ASHRAE-established building-component resistance values, can have significant error.

For example, using a temperature differential of 72°F [22°C], an infiltration rate of 0.5 ach and standard property values for air, the infiltration load alone is 16.2×10^3 Btu/h [4.75 kW]. The steady-state approach used for this investigation measures both the heat transfer losses and the infiltration load. Both these terms appear as $\dot{Q}_{Loss}$ in the energy balance equation. To better understand the magnitude of the effect of infiltration on BTL, infiltration studies were conducted on the test residence. Simultaneous infiltration data corresponding to test periods 1 and 2 were not available, but infiltration data for the test residence under similar weather conditions were.

Infiltration data were collected using new equipment developed and owned by a national laboratory. The equipment maintains a constant target tracer-gas concentration as a microprocessor controls tracer-gas flow rate and monitors gas concentration. Infiltration data are derived by calculating the tracer-gas flow rate needed to maintain the measured concentration. The sampling rate is once every 5-1/2 minutes, and air change rates are tabulated every thirty minutes (Tab. 2).

DATA ANALYSIS

Energy Inputs

According to Eq 1, the determination of the building's heat loss is based on an energy balance.

The heat input to the building comes from three sources:

1. The existing heating system and any auxiliary heaters, $\dot{Q}_{Heat}$
2. Internal heat sources, such as appliances, lights, people, $\dot{Q}_{Int}$
3. Insolation transmitted or conducted into the house, $\dot{Q}_{Solar}$

The heat loss from the house can also be divided into three categories:

1. The heat conducted, radiated, or convected away from the building, $\dot{Q}_{Con}$
2. Heat lost raising the temperature of the infiltration air, $\dot{Q}_{Infil}$
3. Heat losses from the exfiltration of air at a temperature above the internal ambient air temperature (e.g., dryer and furnace stack losses), $\dot{Q}_{Exfil}$

The detailed form of Eq 1 may be written as

$$\dot{Q}_{Heat} + \dot{Q}_{Int} + \dot{Q}_{Solar} = \dot{Q}_{Stored} + \dot{Q}_{Con} + \dot{Q}_{Infil} + \dot{Q}_{Exfil} \qquad (6)$$

According to the theory behind the experimental approach (see previous section), the thermal storage term can be eliminated if conditions are right. If the criteria are met, the applicable energy balance is

$$\dot{Q}_{Heat} + \dot{Q}_{Int} + \dot{Q}_{Solar} = \dot{Q}_{Con} + \dot{Q}_{Infil} + \dot{Q}_{Exfil} \qquad (7)$$

If the exterior ambient temperature is not steady, a correction factor must be applied to account for the thermal storage in the exterior layers of the building.

Estimation of $\dot{Q}_{Heat}$. The term $\dot{Q}_{Heat}$ actually accounts for two heat sources. The first source is any heat delivered to the house by the existing HVAC system. The gas furnace was not used as a source of heat, but the furnace fan was on for one test mode and must be considered. A one-time measurement of the current going to the furnace fan showed the heat input to be 1310 Btu/h [384 W]. This was included for the test run with the furnace fan on.

The second heat source is the input from the electrical resistance heaters. The total heat delivered to the house by the heaters was determined by recording the fraction of each hour that the heaters were on and by knowing their calibrated heat output.

Estimation of $\dot{Q}_{Internal}$. This term accounts for all internal heat sources other than the heater. There were three sources in this category: electrical loads, interior gas loads, and occupant loads. Interior electrical loads were measured by assuming that all electric power entering the house appears as heat in the house. The watt-transducer measurement taken by the data-acquisition unit was used to provide this term. The average background electrical consumption was calculated to be 0.23 kW/h. The furnace fan was included as a separate source. This electric input appears as heat in the $\dot{Q}_{Int}$ term.

The only gas appliances in the house were the dryer and the hot water heater. The dryer was not used during the test period. The heat delivered by the water heater can be divided into three parts: (1) the heat convected into the interior when the burner is on, (2) the heat conducted through the heater jacket, and (3) the heat transmitted from the hot water to the air during showers, etc. Number 3 was eliminated because no showers or baths were taken in the house during any of the test periods. Number 1 was assumed to be negligible because the burner was not on for any great amount of time, as judged from increases in the flue-gas temperature (less than fifteen minutes total for each test mode). Thus, the only source of heat from gas appliances was that conducted through the water heater jacket. This term was also assumed to be negligible, because the heat output from the hot water heater should be small compared to the total heat input to the living space.

The occupant load was calculated using the rate of heat gain from occupants data presented in the ASHRAE Handbook of Fundamentals.[8] For each male occupant present, 115 W were added as input, and for each female present, 100 W were added.

Estimation of Q_{Solar}. By appropriately choosing the test weather conditions and using only the data collected from 10:00 PM to 6:00 AM, the effects of solar input to the house can be limited. Test periods were chosen when the daylight cloud cover was heavy and the test periods were preceded by predominantly cloudy skies. There were occasional peaks above 47.5 Btu/(ft^2 · h) [150 W/m^2] horizontal. However, because the transmitted insolation was small and any input would have preceded the data collection period by at least seven hours, the heat input from solar effects was assumed to be negligible.

Estimation of $\dot{Q}_{Exfil}$. The exfiltration term consists of energy exhausted by the gas dryer, the water heater and furnace stack losses, the bathroom fan, and the fireplace. By suspending the use of most of these items, their contribution to $\dot{Q}_{Exfil}$ is eliminated. The only losses that cannot be eliminated by this means are stack losses.

Stack losses can be considered in two parts: the heat lost up the stack and the heat necessary to replace that lost. The first part is Q_{Exfil}. The second term is measured by the infiltration equipment and is therefore incorporated in $\dot{Q}_{Infil}$. The gross input to the water heater includes both the exfiltration losses and the net heat going into the water. Because the net heat input is not considered a source of heat to the living space, exfiltration losses from the water heater (gross minus net heat input) can also be neglected. A similar argument applies to the furnace. Because the gross input is not considered, furnace stack losses can also be disregarded. Therefore, $\dot{Q}_{Exfil}$ is equal to zero.

Estimation of $\dot{Q}_{Infil}$. The section on Infiltration Effects gives background information for the infiltration study. Using equipment from a national laboratory, infiltration data were generated for the test residence. It was necessary to try to correlate the infiltration rate to climatic conditions because experimental infiltration rates were available only for the third test period. An attempt was made to correlate the infiltration data collected to wind velocity and interior to exterior temperature difference. This correlation is one recommended in the ASHRAE Handbook of Fundamentals and is based on long-term field measurements.[9] The infiltration data and actual climatic conditions for the applicable period are listed in Tab. 2. Fig. 4 is a plot of this data as well as the infiltration rate measured with the furnace fan on. From the figure, it appears that no correlation exists between the climatic conditions and infiltration. To further investigate the apparent lack of a correlation, a regression analysis was done on the ASHRAE model as well as two other possible models. No acceptable correlation could be established using temperature difference and wind velocity as independent variables.

Further research and data analysis will have to be done to determine the reasons for a lack of correlation in these data. Because of the lack of a satisfactory correlation, the average value of the data was used and was assumed to be constant. (The standard deviation was 0.0313.)

For the furnace fan off condition, the infiltration rate was assumed to be 0.237 ach. This is the mean value of the data presented in Tab. 4. The assumed infiltration rate with the furnace fan running was 0.533 ach. This is the average rate established with the furnace fan running under similar weather and operating conditions.

Estimation of $\dot{Q}_{Con}$. This is the term that incorporates the energy lost through all surfaces of the building and is the only term that is not measured directly. It is obtained by an indirect method and equates the other terms in Eq 7 $\dot{Q}_{Con}$ such that

$$\dot{Q}_{Con} = \dot{Q}_{Int} + \dot{Q}_{Heat} + \dot{Q}_{Solar} - \dot{Q}_{Infil} - \dot{Q}_{Exfil} \tag{8}$$

BTL Calculation Method. When each test was completed, the hourly on-time for each heater was available. The test data were converted to heat input data as described previously.

The total power required to maintain the constant equilibrium internal temperature was tabulated. The BTL value was then obtained by dividing total power input by the temperature difference for each period.

RESULTS

Trends

Generally, the experimental BTL coefficient of the Lo-Cal House was very good compared to estimated BTL values for houses built using other construction approaches (see Tab. 3).

The experimental BTL coefficient for the Lo-Cal design with the furnace fan running was 4.05 Btu/(ft^2 · DD) [0.987 W/(m^2 · K)]. With the fan off, the BTL coefficient dropped to 3.1 Btu/(ft^2 · DD) [0.732 W/(m^2 · K)]; using the average of these two values for comparison purposes gives the Lo-Cal home an average BTL coefficient of 3.58 Btu/(ft^2 · DD) [0.860 W/m^2K)].

An expected value for homes built in the 1950s and 1960s in the Champaign, IL, area would be about 12 Btu/(ft^2 · DD) [2.8 W/(m^2 · K)]. This is an average value for a house with 3.5 in. [0.089 m] of wall insulation and 6 in. [0.152 m] of ceiling insulation. A house built before 1950, typically with no wall insulation, would have an average BTL value of about 18 Btu/(ft^2 · DD) [4.3 W/(m^2 · K)].

Effect of Individual Systems

The magnitude of the overall energy improvement is impressive; however, to complete the evaluation of the Lo-Cal design, one must know the contributing effects of the individual building systems. These results can then be used to gauge the relative effectiveness of future energy-saving modifications. Tab. 4 and 5 summarize the results.

Base House

The base house was used as a reference point from which to gauge the contributions of several individual systems. The criteria associated with interior conditions (i.e., constant temperature of the internal mass and constant interior ambient temperature) were met. Fig. 5 and 6 show the constant internal ambient temperature and the temperature profile of the interior north wall. The requirement of measuring a steady or slightly falling exterior ambient temperature was not satisfied. Fig. 7 shows the magnitude of the exterior ambient temperature drop — approximately 11.8°F [6.6°C] from 11:00 PM to 6:00 AM. This corresponds to an average temperature drop of 1.7°F [0.94°C] per hour. The heat storage effect was therefore considered. Because the exterior ambient temperature was falling, the exterior wall surface temperature was slightly higher than if the exterior ambient temperature were constant. The change in the wall surface temperature lagged behind the change in the exterior ambient temperature. Fig. 8 is the temperature profile of the north wall's exterior surface. Assuming that only the exterior sheathing and siding contributed, an approximate thermal storage term was calculated. Using a control volume around the exterior wall components, sheathing, and siding produced the following energy balance:

$$mC_p \frac{dTs}{dt} + h_o A_o \; (T_s - T_A) = \dot{Q}_{Total} \qquad (9)$$

where

t = time

T = temperature

m = total mass of siding and sheathing

C_p = heat capacity of siding and sheathing wall surface temperature

h_o = convective heat transfer coefficient

A_o = outside surface area

$T_s - T_A$ = temperature difference between wall surface temperature (T_s) and exterior ambient temperature (T_A)

$\dot{Q}_{Total}$ = total heat transfer through wall

From the original discussion on the theory behind the steady-state method,

$$\dot{Q}_{Total} = UA(T_I - T_A) \tag{10}$$

where

T_I = interior ambient temperature

Substituting Eq 10 into Eq 9 and rearranging terms yields

$$mC_p \frac{dTs}{dt} = h_o A_o (T_s - T_A) + (T_I - T_A) \tag{11}$$

Rearranging Eq 11 in terms of UA gives

$$UA = \frac{mC_p \frac{dTs}{dt} + h_o A_o (T_s - T_A)}{T_I - T_A} \tag{12}$$

Assume that

$$h_o A_o (T_s - T_A) = \dot{Q}_{Total} \tag{13}$$

Substituting this into Eq 12 yields

$$UA_{Actual} = \frac{\dot{Q}_{total}}{T_I - T_A} + \frac{mC_p \frac{dT_s}{dt}}{T_I - T_A} \tag{14}$$

The first term in Eq 14 is the steady-state term. The second term accounts for thermal storage effect. If the exterior temperature is constant, the thermal storage term is zero. The average rate of change of the wall surface temperature from Fig. 8, with representative material constants for the wall and Eq 14, gives an approximate thermal storage effect of 18.9 Btu/(h · °F) 10.0 W/K. The steady-state value is 254.4 Btu/(h · °F) [140 W/K]. This thermal storage correction term is a conservative approximation and results in a 7% error from the steady-state value. For the base house test case, this correction was applied to the UA-value. The base house used 284.3 Btu/(h · °F) [150 W/K], corrected for thermal storage effects. Based on the approximated infiltration rate (see section on Estimation of Q_{Infil}) and an average temperature difference of 54°F [30°C], the estimated losses as a result of heat transfer through the building envelope were 77% of the total losses. (See Tab. 6.)

Base House With Furnace Fan Running

This portion of the investigation conformed well to all the requirements. The interior ambient temperatures remained constant and uniform throughout the house. The interior surface temperature of the walls remained constant for the test period. The outside ambient temperature also remained relatively unchanged.

The interesting point is the dramatic increase in the BTL of the house caused by having the fan system running. The BTL value jumped from 0.137 Btu/(h · ft^2 · °F) [0.779 W/(m^2 · K)] to 0.174 Btu/(h · ft^2 · °F) [0.987 W/(m^2 · K)] when the fan was running. This is a 27% increase in the BTL value. Operating in this mode, the estimated infiltration rate more than doubled from the base house rate. Using this infiltration rate, 39% of the heat input is caused by infiltration effects and 61% is related to heat transfer losses. The duct system actually has a double-edged impact on the BTL coefficient, increased infiltration losses, and increased heat transfer losses. The ducts in the crawl space (ambient temperature about 50°F [10°C]) have not been insulated, and the main duct has been caulked only on three sides. As shown by these numbers, improvements in the HVAC delivery system would yield large energy savings.

Base House With Windows Shuttered

This portion of the investigation also showed good conformity to the requirements for steady-state operation. The main observation from this test is the limited improvement in BTL gained from the installation of window shutters. The experimental BTL coefficient with the windows shuttered was .128 Btu/(h · ft^2 · °F) [0.722 W/(m^2 · K)]. This is only a 7% improvement over the base house. Using the experimental infiltration rate determined in the section on Estimation of Q_{Infil}, 28% of the load is caused by infiltration and 72% by heat transfer losses.

Because the 7% improvement over the base house is of the same magnitude as the correction for thermal storage and the infiltration data have even larger fluctuations, it is difficult to isolate the effect of window shutters in the current study.

SEPTEMBER 1982 - AUGUST 1984: FUTURE PLANS

From the performance experiments, a substantial amount of heat loss was found to result from infiltration and losses to the crawl space from the furnace and duct system. Therefore, in the winter of 1982, the ducts in the crawl space will be insulated and the furnace closet will be sealed off. A fresh-air inlet from the attic to the furnace closet will be installed. Data will then continue to be collected and the effect of these changes will be analyzed.

Further research includes field validation of the BLAST energy use predictive program. Under a cooperative agreement with the U.S. Army Construction Engineering Research Laboratory, the Small Homes Council-Building Research Council has entered into an agreement with Brookhaven National Laboratory to analyze the data and develop a joint publication concerning the project. This phase will be completed in December 1983. Data will continue to be collected through the summer of 1984.

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The authors are also grateful to Mrs. Jane McCulley, without whose cooperation this investigation and the overall project would not have been possible.

TABLE 1
Structure Information

Location	West house
Exposure	Semirural, very west and south edge of town
Constructed	1977
Date occupied	January 1979
House type	One-story ranch with crawl space
Approximate dimensions	34 x 58 ft [10.36 x 20.72 m]
Floor area	2077 ft^2 [193 m^2]
Attic	Ventilated south continuous soffit and clerestory louvers
Foundation	Crawl space (vented in summer)
Window type	Triple-glazed casement windows and sliding glass doors
Window area	South 214.5 ft^2 [19.13 m^2] East North 45.0 ft^2 [4.18 m^2] West
Equivalent of window to floor area, %	South glazing 10%; all glazing 12.5%
Glazing to the south, %	82%
Ceiling insulation (overall U)	0.0218 Btu/($ft^2 \cdot h \cdot {}^oF$) [U = 0.124 W/($m^2 \cdot {}^oC$)]
Wall insulation (overall U)	
North, east, and west	U = 0.0329 Btu/($ft^2 \cdot h \cdot {}^oF$) [0.188 W/($m^2 \cdot {}^oC$)]
South	U = 0.0798 Btu/($ft^2 \cdot h \cdot {}^oF$) [0.453 W/($m^2 \cdot {}^oC$)]
Floor insulation (insulation U)	U = 0.0519 Btu/($ft^2 \cdot h \cdot {}^oF$) [0.295 W/($m^2 \cdot {}^oC$)]
Crawl space wall insulation (insulation U)	U = 0.0998 Btu/($ft^2 \cdot h \cdot {}^oF$) [0.567 W/($m^2 \cdot {}^oC$)]
Triple glazing	0.3082 Btu/($ft^2 \cdot h \cdot {}^oF$) [U = 1.75 W/$m^2 \cdot {}^oC$)]
Continuous vapor retarder	Polyethylene on wall, ceiling, and crawl space floor
Heating system	1706 Btu/min [30 k/W] forced air-natural gas; central air conditioning
Domestic hot-water heat	Natural gas
Appliances	Dishwasher, gas dryer, refrigerator/freezer

TABLE 2
Collected Infiltration Data[a] for March 21, 1982[b]
(Furnace Fan Off)

Time	Infiltration rate[c]	Δ Temp °F	[°C]	Velocity ft/s	[m/s]
17:24	0.25	64.8	18.20	18.6	5.67
18:24	0.32	65.0	18.35	16.6	5.05
19:24	0.23	65.7	18.70	12.3	3.75
20:24	0.23	66.0	18.90	13.6	4.16
21:24	0.21	66.7	19.25	11.9	3.63
22:24	0.22	67.4	19.65	11.5	3.52
23:24	0.23	67.9	19.95	10.6	3.23
0:24	0.22	68.3	20.15	10.3	3.15
1:24	0.23	68.6	20.35	9.1	2.77
2:24	0.24	68.8	20.45	6.9	2.12
3:24	0.25	68.8	20.45	8.5	2.58
4:24	0.24	68.6	20.35	12.9	3.95
5:24	0.23	69.2	20.65	5.9	1.80
6:24	0.22	68.7	20.40	2.9	0.90
7:24	0.24	67.4	19.65	6.3	1.93
8:24	0.20	66.1	18.95	8.0	2.45
9:24	0.18	63.9	17.70	11.2	3.41
10:24	0.27	62.2	16.75	11.9	3.64
11:24	0.28	62.2	16.75	9.9	3.01

a These values are average values for the preceding hour.
b Wind direction: 240° to 323° (N = 360, W= 270).
c ach.

TABLE 3
Representative BTL Values

	Average BTL Values	
	English	SI
Lo-Cal House[a] (experimental)	3.58 Btu/(h · ft^2 · DD)	0.860 W/(m^2 · K)
Computer predicted[1,2]	2.7 Btu/(h · ft^2 · DD)	0.650 W/(m^2 · K)
1950 - 1960 house	12.0 Btu/(h · ft^2 · DD)	2.8 W/(m^2 · K)
Pre-1950 house	18.0 Btu/(h · ft^2 · DD)	4.3 W/(m^2 · K)

a Average of the BTL coefficient with the furnace fan on and off.

TABLE 4
Experimental BTL Coefficients

		Base House[a] Fan Off	Furnace Fan On	Fan Off, Windows Shuttered
UA-value	Btu/(h · °F)	284.3	360.2	259.6
	W/K	150	190	140
BTL[b]	Btu/(h · ft^2 · °F)	0.137	0.174	0.128
	W/(m^2 · K)	.779	0.987	0.722
BTL[c]	Btu/(ft^2 · DD)	3.3	4.18	3.1

a Corrected for thermal storage effects present during this test.

b The BTL is defined as the UA-Value divided by the total floor area 2072 ft^2 [192.5 m^2].

c This value is obtained by multiplying the English BTL value by 24 h/day.

TABLE 5
Fractional Contribution to $\dot{Q}_{Loss}$ Term

	Base House, Fan Off	Furnace Fan On	Fan Off, Windows Shuttered
Infiltration[a]	$\frac{0.937\ kW}{4.07 kw} = 23\%$	$\frac{1.87\ kW}{4.76\ kW} = 39\%$	$\frac{0.590\ kW}{2.12\ kW} = 28\%$
Heat transfer through building component[b]	$\frac{3.13\ kW}{4.07\ kW} = 77\%$	$\frac{2.89\ kW}{4.76\ kW} = 61\%$	$\frac{1.53\ kW}{2.12\ kW} = 72\%$
Total[c]	$\frac{4.07\ kW}{4.07\ kW} = 100\%$	$\frac{4.76\ kW}{4.76\ kW} = 100\%$	$\frac{2.12\ kW}{2.12\ kW} = 100\%$

a The fraction of the load contributed by infiltration is calculated using the average temperature difference for that test period, the experimental infiltration rate, and typical thermodynamic constants for air.

b The portion of the load attributable to heat transfer effects is assumed to be the total heat input less the infiltration fraction.

c The total heat input into the house is the sum of the calculated input of all the electric heaters for the 7-hr period.

TABLE 6
Corrected BTL Coefficient for Base House

Units	Values
UA-W/K	150
UA-Btu/(h · °F)	284.3
BTL-W/(m^2 · K)	.779
BTL-Btu/(h · ft^2 · °F)	.137
BTL-Btu/(ft^2 · DD)	3.3

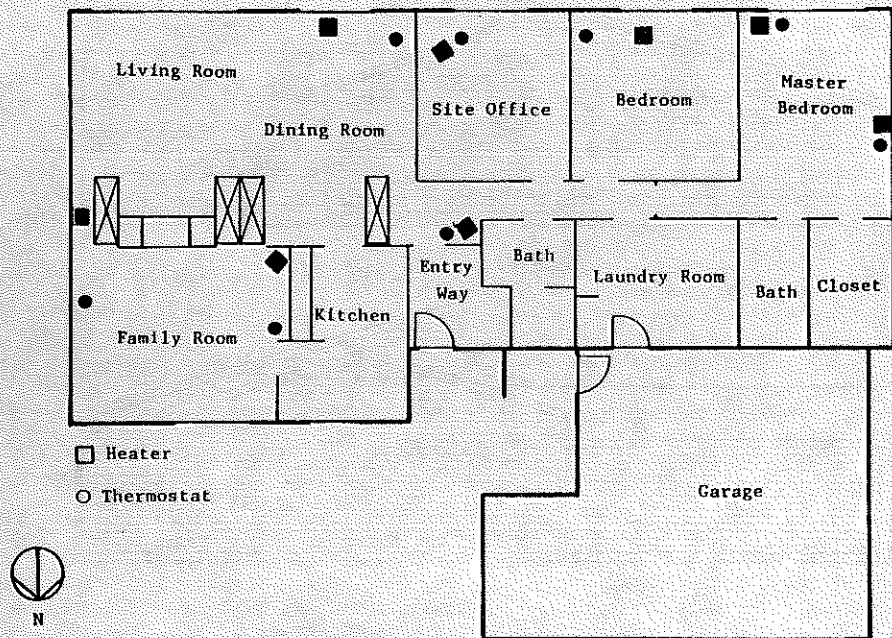

Figure 1. Resistance heater positions

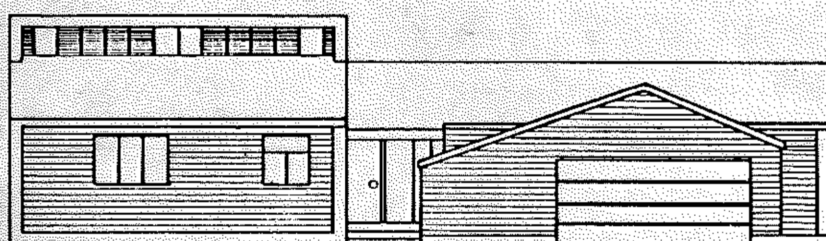

Figure 2a. North side elevation drawing

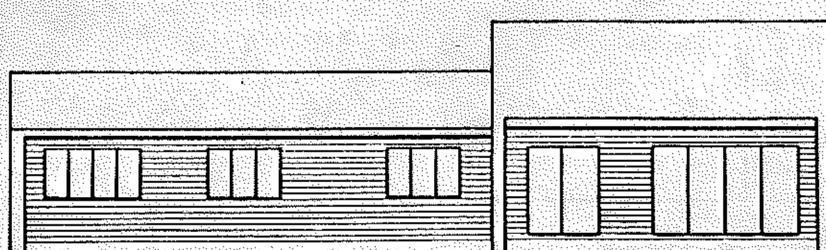

Figure 2b. South side elevation drawing

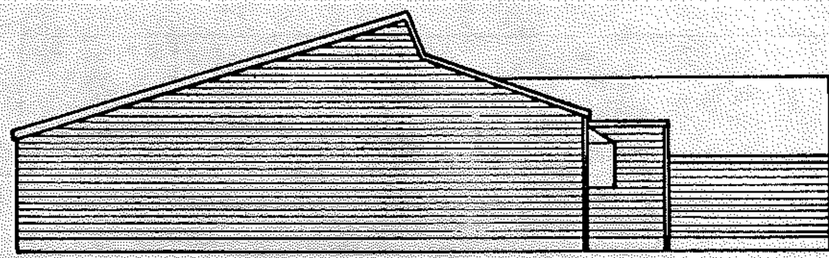

Figure 3a. East side elevation drawing

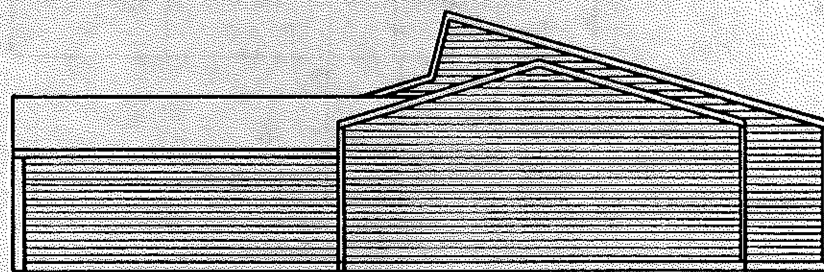

Figure 3b. West side elevation drawing

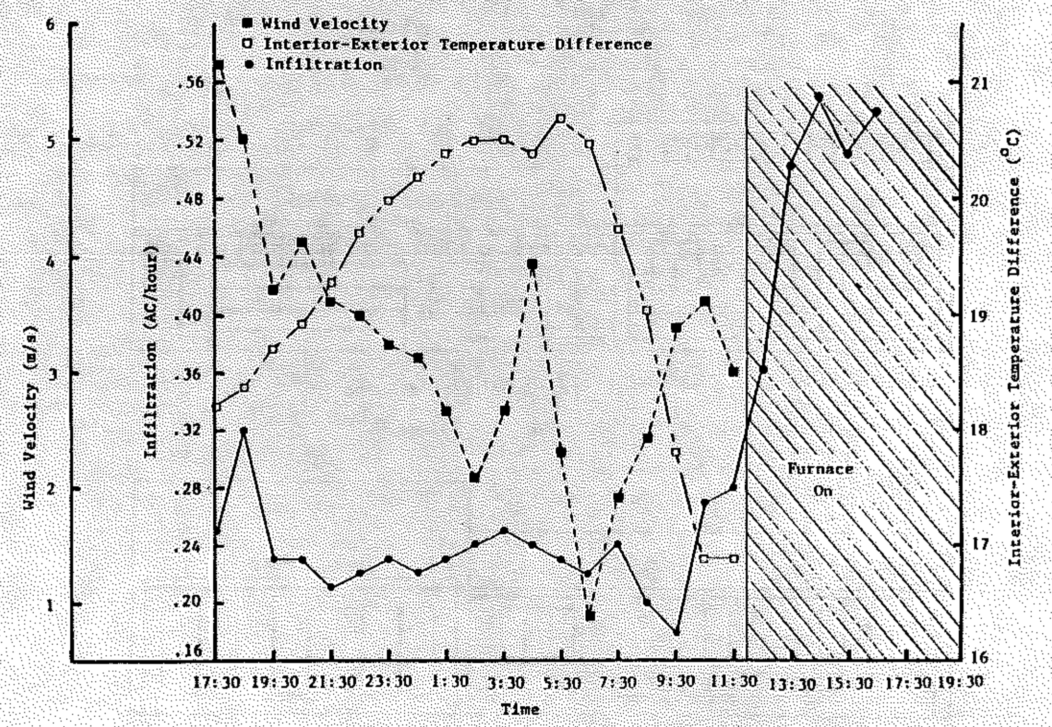

Figure 4. Infiltration correlation data

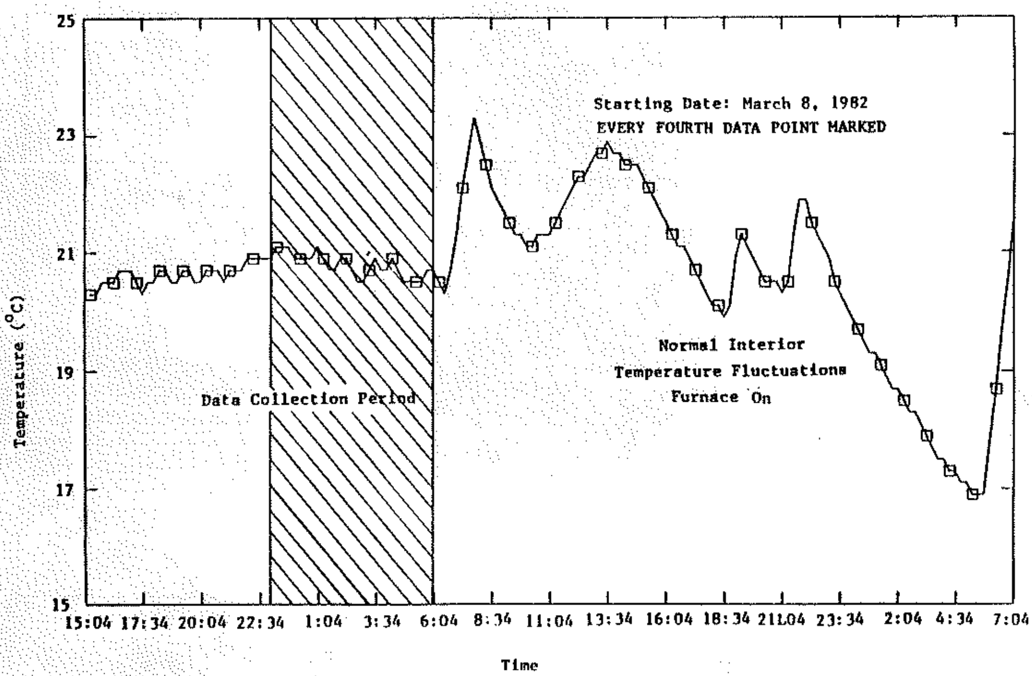

Figure 5. Kitchen ambient temperature with furnace fan off

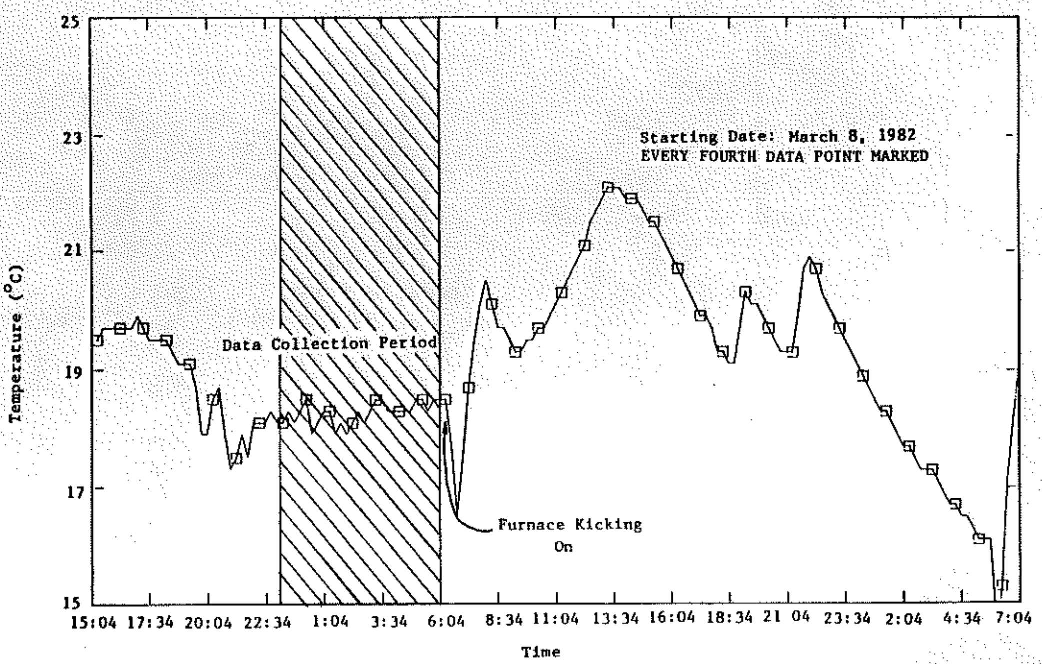

Figure 6. North wall interior temperature with furnace fan off

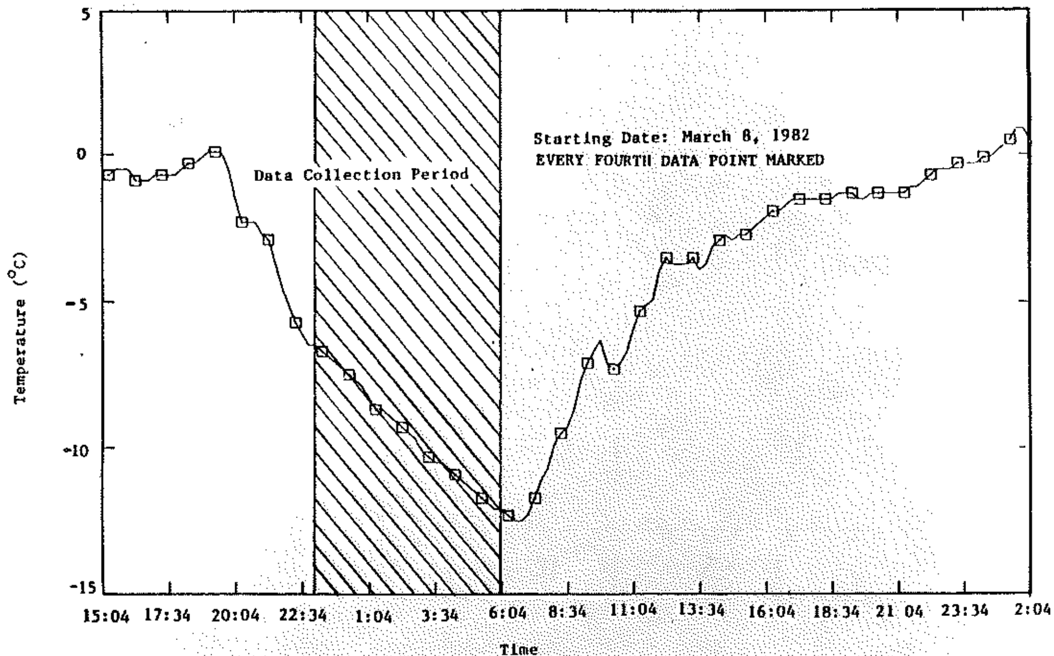

Figure 7. Exterior temperature with furnace fan off

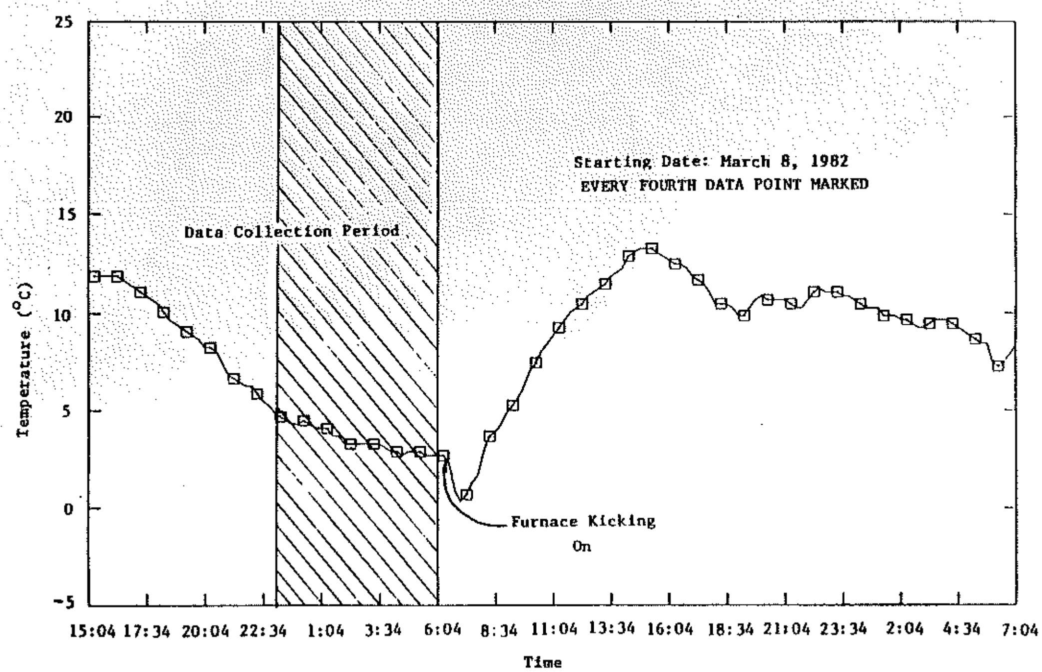

Figure 8. North wall exterior temperature profile with furnace fan off

Discussion

R.J. Berg, Veteran's Administration, Washington, DC: Did you have combustion air intake?

M.T. McCulley: In the first year no, now yes. (Comparison testing is the intention of this project).

R.J. Berg: Did you have make-up air intake?

M.T. McCulley: There was no make-up air. The natural infiltration rate is .2 to .6 air changes per hour.

R.J. Berg: Why R-11 on south wall only--why not total insulation the same on all walls?

M.T. McCulley: It was thought at the time that solar gains would balance losses, but they haven't.

R.J. Berg: Why weren't ducts put in insulated space to start with? (This is a bad design error, from my viewpoint, as is the lack of vapor air barrier).

M.T. McCulley: As was explained in the presentation, this house was built to be cost effective. At the time of construction (1977) losses to a sealed and insulated crawl space were not considered to be significant enough to warrant the expense of special construction. The system was intended to be conventional.

The #2 instrumental house next door has a crawl space insulated differently for comparison. Insulation of the ducts in the crawl space (not a difficult job) has greatly improved performance, but it is still not at optimum conditions. The intention of this testing, as I emphasized, is to measure the performance of standard practice approaches to heavy insulation and passive solar. If and when problems are discovered, ways are explored to improve the situation, and the benefit of each approach is measured. We are not out to set records or promote concepts, but to generate information that will be of value to those interested in cost-effective solutions. The quantification of the impacts of commonly repeated construction practice is one of our major goals.

R.J. Berg: What were the humidity problems?

M.T. McCulley: There have been no humidity problems. Exhaust vents are used and the natural rate of infiltration is between .2 and .6 A/C per hour.

R.J. Berg: Was there any effect from moisture expansion and contraction of framing between summer and winter conditions?

M.T. McCulley: There was none observed in these houses. Truss lifting has been observed on other buildings. It appears to be seasonal. (See University of Illinois SHC-BRC publications on this topic by Donald Percival)

R.J. Berg: Was the house cooled in summer?

M.T. McCulley: Yes, the house was cooled during the summer months.

R.J. Berg: Did solar buildup in summer give any problems?

M.T. McCulley: Not usually, since the house has overhangs. Big groups do tax the air-conditioning system.

R.J. Berg: Did solar buildup occuring in the spring and fall cause any problems?

M.T. McCulley: Because of the lag of the seasons in relation to the solar cycle, the problem occures in the fall, but seldom in the spring.

R. Crenshaw, Lawrence Berkeley Lab., Berkeley, CA: What difference have you noticed between weather stations, especially with respect to wind speed and direction?

M.T. McCulley: We have not yet done any studies concerning weather data variations. It is an interesting question with many possibilities, because of the differences in the location of the stations in relation to the residences.