AN INSTRUMENT FOR MEASURING BUILDING-ENVELOPE THERMAL RESISTANCE

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ABSTRACT

The ability to measure the overall heat loss of existing structures is needed by energy auditors, utilities, lending agencies, building owners and operators, and others concerned with evaluating the cost/benefit of energy conservation measures. Conventional techniques of measuring the total heat loss require long periods of near-steady indoor and outdoor conditions which are difficult if not impossible to capture in practice.

Previous research showed that a transient procedure could measure the overall building thermal resistance, or BTR, of a residential structure. This paper summarizes the computer modeling and simulation studies used to define the accuracy of the technique. The algorithms were then programmed into a microprocessor-based meter. This BTR meter has been field tested in one Minneapolis and two Oak Ridge Tennessee homes. The transient method is shown to yield BTR values within 4% of that known from simulation and within 10% of ASHRAE heat loss calculation methods for the field test houses.

INTRODUCTION

There is currently an abundance of fossil fuels in the world market and prices have stabilized over the past two or three years. However, if one agrees with the premise that market control of fossil fuels is certain to return to the sellers, then there remains an opportunity to continue our efforts in energy conservation.

A number of things can be done to conserve energy in the heating and cooling of buildings. The net effectiveness of these modifications, however, must usually be accepted on faith. Thus, there is a need for methods and instruments to quantify the thermal integrity of a building and to measure the effectiveness of modifications intended to reduce building heat loss.

Steady state thermal measurements of the building envelope are generally unsatisfactory. Daily weather variations are too fast to allow steady state heat transfer to occur. Temperature gradients in the walls of a structure are rarely linear, and even if so, this condition would be difficult to capture.

It was shown previously (Janssen 1978; Janssen and Pearman 1981; Janssen 1982) that a transient method using a two-hour cool-down period and a one-hour warm-up period can provide data for calculating the building thermal resistance, or BTR, of a single-family residence. Operation of the heating system for the indicated cycle length during cold weather provides the needed data. When the measurement is made at night over this short time interval, weather effects such as large outdoor temperature changes and solar radiation are minimized.

The method makes some assumptions of previously unknown magnitude. The primary objective of this study was to investigate the limitations imposed by the assumption that the walls of a

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typical single-family residence react to a change in temperature on one side in the same manner as a homogenous wall would react. If this could be established, the secondary objective was to develop an instrument, built around a small personal computer, that could operate a furnace according to the prescribed cycle, could collect the necessary data, and could use these data to calculate the BTR value for the building.

TRANSIENT METHOD

The basic assumption is made that a residential building can be treated as a homogenous, isotropic structure. The outdoor temperature is assumed to be constant and the indoor temperature is assumed to change in response to a constant heat output from the furnace that is either turned on or off. If the furnace has been controlling the house at a relatively constant indoor temperature during the heating season, and the furnace is turned off for an extended period of two or three hours, the indoor temperature will cool according to some exponential function. When the furnace is turned on again, the indoor air temperature will rise according to the same function.

There are at least two obviously different response rates. The air in the building has a small heat capacity and its temperature will respond quickly to operation of the heating system. The walls and furnishings have a much greater heat capacity and will respond more slowly. These effects can be separated if the first part of the temperature transient in the indoor air is ascribed to the air itself and is ignored. After a suitable delay the response of the structure dominates the indoor temperature transient. The time response of the air is largely damped out within 30 minutes after a warm air furnace is turned on. The analysis thus, assumes a simple first order transient with an initial delay for a homogenous, isotropic structure as seen in Figure 1.

The heat balance for a time interval dt is

$$Q_s dT = Q_F dt. \tag{1}$$

The time dependence of the heat storage rate Q_S is reflected in the time rate of change of the internal air temperature dT. The rate of heat loss Q_L is

$$Q_L dT = Q_F dt - Q_L dt. \tag{2}$$

Then

$$dT = (Q_F/Q_s)dt - (UA/Q_s)\ (T-T_o)\ dt. \tag{3}$$

where
U = overall heat transfer coefficient
A = heat transfer area
T = space temperature at time t
T_O = outdoor temperature.

Equation 3 can be integrated and solved for the R value or the time constant under the conditions that $T = T_r$ at time $t = 0$ and that $Q_S/UA = \tau$ (Janssen and Pearman 1981). The thermal resistance R is the reciprocal of the heat transfer coefficient U. The equation can then be solved for R or T.

$$R = 1/U = A/Q_h\ [(T_r - T_o) - (T - T_r)\ (e^{t/\tau} - 1)^{-1}] \tag{4}$$

and

$$\tau = t/\mathrm{Ln}\left[[(RQ_c/A)-(T_r-T_o)]/[RQ_c/A)-(T-T_o)]\right] \tag{5}$$

Note that the heat term Q_h in Equation 4 is the total heat input to the house during the warm-up or furnace on period. The heat term Q_c in Eution 5 is the extraneous heat dissipated in the house during the cool-down period when the furnace is off.

Equations 4 and 5 are different expressions for the same equation solved for each of two unknowns, R and . Two independent sets of values can be found for solving this equation by using the measured temperatures, heat inputs Q_h and Q_c, and the heat transfer area A during an extended furnace off-period and furnace on-period.

Note that Equations 4 and 5 are in parametric form. They can be solved explicitly for R if the time interval t is the same for the heat-up and cool-down periods or if the heat input to the house Q_c is zero during the furnace off period. Extraneous heat such as the fan power in a warm-air furnace, lights, and the heat output of occupants must be included as part of Q_h and Q_c in Equations 4 and 5. Thus, an iterative solution usually is required to solve Equations 4 and 5 simultaneously.

The procedure developed assumes an initial R-value for the structure. The total extraneous heat in the building is used as the furnace output in Equation 5 to obtain an estimate of the time constant during the furnace off-period. This value of , the actual furnace output plus the extraneous heat dissipation in the building and the temperature transient during the warm-up period, is used in Equation 4 to get a corrected value of R. This value of R is then used to improve the estimate of the time constant from Equation 5. Usually three or four iterations provide convergence to the correct values of R and .

SIMULATION STUDY

Any measurement must consider the sources of error and the magnitude of the uncertainty in the measurement. One method is to consider the potential error in each element of the measurement and then add these together to get the total potential error. Another method is to compare the overall measurement to some standard. We chose this latter method. A model was derived to calculate the transient temperatures. These were then compared with temperatures measured under similar operating conditions. The measured BTR values were also compared with calculated values.

Dynamic building, furnace, and control models were derived to investigate effects of the assumptions in the BTR calculation method. The building model used in the simulation required that all of the various parts of the house be described as resistance-capacitance (RC) networks. The split level design of the test house, including the built-in garage and the partial basement (Figure 2) presented a wide variety of construction elements (Table 1). There were additional variations within some of the listed components. The cross-sectional area of each different parallel heat flow path normal to the heat flow was computed and multiplied by the RC networks for each path.

The detailed RC network for one of the exterior walls is shown in Figure 3. Each building material is represented by two resistors and a single capacitor. The network is arranged to model heat flow as a one-dimensional, parallel path process. From the house plans, each different wall, ceiling, floor, window, door, etc. subsystem was described in detail in this fashion. Surface coefficients were treated as combined convection and radiation resistances.

Networks were combined on an area weighted basis to reduce complexity. This resulted in one network for each building component (exterior wall, floor, ceiling, roof, windows, interior walls). For example, 14 types of the exterior wall construction were combined into one, such that the overall R-value equaled the area weighed sum of R-values for the 14 types. This is allowable since the elements are all linear and the principle of superposition applies. The same procedure was used to determine a total capacitance per unit area, which was equaled in the final exterior wall configuration. The final exterior wall RC network is shown in Figure 4. The most important criteria to satisfy was the final temperature distribution through the wall section and proper placement of component mass. Since the brick veneer over frame construction constituted the major mass of exterior walls found in the test house, the final composite network was similar to the brick network. Parallel heat flow through the insulation and studs was maintained. This procedure was followed for all other building components where more than one type of construction existed. The final model was a 34th-order model composed of a network for an exterior wall, interior walls, roof and ceiling, floor to basement, interior furnishings, interior air masses, and windows.

Once networks were generated for each component, an automatic modeling program was exercised to create an overall system model. The program, called BLDCON, selects the individual component networks from the library and interconnects them based on the user's specification.(MacArthur et al. 1981.) Internal surfaces were interconnected with radiation resistors, automatically calculated based on the room size and generated shape factors. Two interior zones were established, an interior living zone and the basement zone, but there was no air coupling established between zones in the base model.

The output of the modeling procedures is a matrix of coefficients which describes the overall linear system. The house in block diagram form is shown in Figure 5. Infiltration, the heating plant, weather inputs, basement heat loss, thermostat, and internal loads are all modeled in nonlinear routines that are interconnected prior to simulation.

Other Models

Since testing of the BTR algorithm requires step changes in the heating system to drive the air response, the most important characteristics of the heating plant to be included in the model are the heat-up and cool-down time constants, and the steady state output. The model therefore predicted the furnace output as a first order exponential rise and decay with an on and off time constant of three minutes. The steady state heat output was set at 95 thousand Btu/h, equal to the output of the test house furnace. Five percent of the output (4750 Btu/h at steady state) was lost to the basement air as jacket losses.

The infiltration rate was specified in air changes per hour permitting a direct calculation of load based on the indoor-outdoor temperature difference. Except for times where infiltration was specifically studied, the air exchange rate was set to 0.5 air changes per hour. Internal loads were held constant at 850 W (2816 Btu/h), representing a continuous fan of 550W and three adults at rest of 100 W each.

Except for cases when the effects of varying outdoor temperature were studied, the outdoor temperature was held constant at 30F(-1°C). Solar inputs to the exterior surfaces of the building were set to zero; hence no solar effects were included.

Basement Model

A two-dimensional basement heat flow model was used to determine the effects of ground coupling on system response. This was interconnected to the house model through the basement air node. This more detailed basement/earth model permitted study of the effects of basement size, insulation, and coupling of basement air to living zone air. Test simulations were run to prove the BTR algorithm's ability to detect changes in basement R-values and interzonal coupling. The basement model did not affect the design heat loss or gross BTR value because the resistances used for the basement walls and floor slab yielded a heat loss at design conditions (-20F outside, 75F inside) equal to the values used for the simplified steady state calculation. Figure 6 presents the equations that are solved to calculate the temperature field as a function of location and time. The nodes are concentrated near the basement surfaces where a more accurate temperature profile is desirable.

The deep ground temperature at location D is assumed to be constant, while the ground and basement surface temperatures (F, A and B) are convectively coupled to the constant air temperatures T and T_b respectively. Surfaces C and E are considered adiabatic with the ground in the x direction. The boundary conditions are specified as shown in the figure. Here T_G is constant and equal to the deep ground temperature of 46F (7.8°C) for Minneapolis. The inside coefficient, h_i, is also taken as constant, and the ground surface coefficient is a combined convective and radiative coefficient that is actually a function of weather conditions. For this analysis, however, the ground surface coefficient was assumed to be constant.

The simulation was validated in two ways. The steady state heat loss was computed using the standard ASHRAE method and thermal property data. This gave a steady state heat loss of 49,997 Btu/h (14,649 W) under design conditions of 75°F (24°C) inside and -20F (-29°C) outside. The building load line of 526 Btu/h-F (277 W/°C) was linearly related to the outdoor temperature.

Most of the experimental data were gathered when the outdoor temperature was about 30F (-1°C). This is close to the average winter temperature in the United States. The computer simulation was carried out at this same outdoor temperature. In addition, it contained a thermostat to cycle the furnace input of 95 thousand Btu/h (27.8 kW) in order to maintain a constant 75F (24°C) indoor temperature. Under these conditions the simulation computed a heat loss at 30F (-1°C) outdoors and 75F (24°C) indoors of 24,064 Btu/h (7.05 kW) versus 23,682 Btu/h (6.94 kW) obtained from the steady state calculated load line. The 1.5% discrepency was due to an assumption of a constant basement temperature of 73.6F (23.1°C). This was the calculated basement temperature at a design load of 95F (52.8°C) indoor-outdoor temperature difference. At 45F (25°C) temperature difference the basement temperature would be 74.3F (23.5°C) and the heat loss from the basement would be slightly increased, bringing the simulated and calculated heat in very close agreement.

The overall thermal resistance calculated from the simulation compared exactly with the measured value, 13.30 $ft^2 \cdot {}^oF \cdot h/Btu$ ($2.33 m^2 \cdot {}^oC/kW$), with about half the storm windows on the house in each case.

The computer model was also validated for its ability to predict the indoor air temperature transient. The measured and simulated return air temperatures are shown in Figures 7 and 8.

The simulation was then used to examine the assumption that a first order exponential with a delay could adequately describe the thermal response of the structure. Figure 9 shows this result. This assumption implies that the slope of the log function in Equation 4 or 5 is a constant. Figure 10 shows that this slope does in fact become a constant after about one hour. A time window of 60 - 90 minutes after the start of a transient provides conditions which comply with the assumptions made.

This time window was tested with models of similar structures with R values that ranged from 8 to 16 ft^2-F-h/Btu. This corresponds to a range of no insulation in the walls or ceilings to 6 inches in the walls and 12 inches in the ceilings. Increasing or decreasing infiltration or reducing the heat capacity of the plasterboard by one half had little effect on the time window.

BTR METER

A portable briefcase computer was modified to measure automatically the BTR. An analog-to-digital (A/D) board was installed to permit automatic input of two temperatures, the outdoor temperature and the indoor temperature (usually the return air temperature is used with warm-air systems). Resistance-type temperature sensors were used. The A/D board converts the analog signals to digital format and supplies the readings to the computer when it interrogates the sensors.

The keyboard was removed except for the numeric keys. The function keys were programmed and relabeled to accommodate the desired functions. The computer has a built in tape drive unit, printer, and battery backup power. The program can be retained in ROM for several days by the battery. However, when the program in random access memory (ROM) is eventually lost, it can be reloaded from the tape. A final printed record of the input data and computed BTR value is presented on command. The recorded temperature histories may also be printed at the conclusion of a test. Photographs of the BTR meter and the layout of the keyboard are shown in Figures 10 and 11.

The BTR meter can be operated in the manual or automatic mode. In the manual mode, only the two temperature sensors need to be installed. The operator turns the furnace off by turning the thermostat to the bottom of the scale and commands the computer to record the furnace off period (temperature decay period). After the computer has recorded the off-period indoor and outdoor temperatures, it prompts the operator to turn the thermostat to the top of its scale and record the on period transient. At the end of 90 minutes operation of the burner, the meter can be commanded to compute the BTR value from the stored data and print out the result. At this time the computer also may be commanded to print out the recorded temperatures.

The automatic mode allows the computer to operate the furnace. A switch, operated by the computer, is connected in series with the furnace gas valve or primary control. The operator then starts the measurement cycle by pressing a function switch on the computer. This causes the computer to turn off the furnace. The operator then turns the thermostat to the top of its scale. The computer is instructed to begin the warm-up period at the end of the cool down period or to wait. Since the automatic measurement can be made with the computer unattended, it is often desirable to have the cool down period begin about 10 or 11 p.m. and the warm-up period start at 5 or 6 a.m., which would correspond with a typical night setback schedule.

It is desirable to make the measurements at night so that solar effects do not confuse the result. However, if a measurement made at night is compared to one made under given sunlight conditions, the passive solar input to the structure can be deduced.

INFILTRATION

Infiltration is included as one of the heat loss mechanisms. It is necessary to determine the infiltration so that its effect can be subtracted in order to compare measured and calculated conduction losses. This was done in two different ways.

Ten separate BTR measurements were made on the test house under varying weather conditions. Tracer gas decay measurements (Janssen et al. 1977) of the infiltration were made during six of these BTR measurements. Tracer gas measurements were also made on six previous occasions. These data are shown in Figure 13. The indoor and outdoor temperatures and the wind velocity at an elevation of about 10 ft were also measured. A hot film anemometer was used to measure wind velocity on the windward side of the house. The fireplace damper was open for some measurements and closed for others.

Infiltration involves two kinds of flow, orifice-type flow and diffusion. Orifice-type flow exists through cracks and openings and is proportional to the square root of the pressure difference across the opening. Diffusion flow occurs through porous material and very small cracks. This flow is linearly proportional to pressure difference. Thus, a model for infiltration as a function of outdoor-indoor pressure difference should be

$$I = MP + N\sqrt{P}. \tag{6}$$

This equation is somewhat awkward to work with and a number of investigators have used a simple power equation

$$I = LP^n \tag{7}$$

where n is frequently given a value of 0.65.

ASHRAE (1977, 1981) recommends using Equation 7, with an exponent of 0.5, rather than 0.65, which may reflect the use of plastic vapor barriers in newer construction. This reduces the diffusion component of infiltration. It would seem reasonable to use values of n = 0.5 for buildings with plastic vapor barriers and n = 0.65 for buildings with more porous walls. We used n = 0.5 for the experiments reported here. The infiltration flow is given by

$$I = K\,(P_O - P_I)^n. \tag{8}$$

The outdoor-indoor pressure difference $(P_O - P_I)$ is the sum of the wind pressure effect and the stack or buoyancy effect due to the indoor-outdoor temperature difference. The impact pressure of the wind is

$$P_W - P_S = 0.60\,(V_W)^2 \tag{9}$$

where

P_W=impact pressure, Pa
P_S=static pressure, Pa
V_W=wind velocity, m/s.

A building is exposed to the impact pressure, P_W, of the wind on the windward sides and to the static pressure, P_S, on the leeward sides. The direction of the wind with respect to building shape influences the wind pressure effect. The outdoor-indoor wind pressure on a building is described by (Janssen et al. 1977)

$$(P_O - P_I)_W = \frac{P_W - P_S}{1 + (A_W/A_L)^{1/n}}. \tag{10}$$

The ratio of windward to leeward area, A_W/A_L, on a building depends on wind direction. If the wind is at 45° to one wall, two walls are exposed to the wind and two are in the lee. The wind flowing over the roof tends to create a suction in the attic. Therefore, the ceiling area is considered to be in the lee of the wind also. A cubical building with the wind at an angle to one wall would have two walls exposed to the wind and two walls plus the ceiling in the lee. Thus, A_W/A_L = 2/3. A ranch-type house 48 feet long by 24 feet wide by 8 feet high would have A_W/A_L =[(8x24)+(8x48)]/(8x24)+(8x48)+(24x48)]=0.33 when the wind direction is at an angle to the building. If the wind were to one end of the building A_W/A_L = (8x24)/[(2x8x48)+(8x24)+(24x48)] = 0.09. This would be an unusual condition since there is a much greater probability that the wind is at some angle to the walls of the building.

Values of A_W/A_L for the test house ranged from 0.14 to 0.46 depending on wind direction. This house is surrounded by a number of trees, and turbulence caused by the trees tends to increase the A_W/A_L ratio. Thus, a value of A_W/A_L = 0.5 was used. Equation 10 then became

$$(P_O - P_I)_W = 0.80\,(P_W - P_S). \tag{11}$$

Substituting (9) and (11) gives

$$(P_o - P_i)_w = 0.48\ (V_w)^2. \tag{12}$$

If the wind velocity is in ft/min instead of m/s, the constant in Equation 12 is 1.24 x 10^{-5}. The wind pressure is in Pascals in both cases.

The buoyancy or chimney effect due to the indoor-outdoor temperature difference is given by (Janssen 1981)

$$(P_o - P_i) = 0.0342\ Bh\ (1/T_o - 1/T_i) \tag{13}$$

where

B =barometric pressure, Pa
h =height of neutral pressure level, M
T_o=absolute outdoor temperature, K
T_i=absolute indoor temperature, K.

The height of neutral pressure level is half the building height if there are no large openings and if the small leakage sites are uniformly distributed. The distance from the ground to the ceiling of the building was 3 m (10 ft) for half the building and about 5.5 m (18 ft) for the remainder. A neutral pressure level of 3 m (10 ft) was used. Therefore, Equation 13 becomes

$$(P_o - P_i) = 10{,}363\ (1/T_o - 1/T_i). \tag{14}$$

The total outdoor-indoor pressure difference that determines the infiltration rate is then given by

$$P_o - P_i = (P_o - P_i)_w + (P_o - P_i)_T. \tag{15}$$

The measured infiltration rates versus pressure are shown in Figure 13. Measurements were taken with the fireplace damper open and closed.

Two uncertainties exist in modeling the infiltration - the effective wind velocity V_w to be used in Equation 12 and the effective height of the neutral pressure level h in Equation 13. If the building in question is reasonably tight with windows more or less uniformly distributed, a neutral pressure level equal to half the height of the building is a reasonable estimate. However, if there are major openings, e.g., an open window, the neutral pressure level will be closer to that of opening. An open fireplace damper will bring the neutral pressure level closer to the pressure level of the fireplace. A furnace in the basement with an open draft hood will tend to lower the neutral pressure level, but this may be offset by a vented range hood, a bathroom vent, or a vented clothes dryer.

Determination of effective wind velocity generally creates more uncertainty than the height of the neutral pressure level. The measured wind velocity should be at a height above the ground similar to the neutral pressure level. The presence of trees, other buildings, etc. will affect local turbulence. Thus, the velocity should be measured reasonably close to the building in question. When the indoor-outdoor temperature difference is 40F (25°C) or greater, a wind velocity of 300 ft/min (3.5 mph or 1.52 m/s) has only one-third the pressure effect as the indoor-outdoor temperature difference. Thus, it is desirable to make the BTR measurements under low wind velocity conditions.

The effect of infiltration can be estimated if measurements are made under two or more weather conditions. The wind velocity and outdoor temperature must be measured for each BTR measurement. The infiltration driving force, i.e., the total indoor-outdoor pressure difference, is then determined from Equations 12, 14, and 15. The gross BTR values can then be plotted versus the indoor-outdoor pressure difference. When this is done, a line can be fitted to the points and extrapolated to zero pressure difference to find the net BTR value. If the inverse of the gross BTR value (i.e., $1/R_g$) is plotted versus the square root or 0.65 root of the indoor-outdoor pressure difference, the correlation will be a straight line. The choice of exponent, 0.5 or 0.65, depends on whether or not there is a plastic vapor barrier in the walls and ceiling as described earlier.

The steady state calculation does not include infiltration, and this is called the net BTR value. Thus, it is necessary to measure or calculate infiltration in order to compare measured and calculated BTR values.

The tracer decay method was used to measure infiltration (Janssen et al. 1977). The infiltration rate I (in air changes per hour) was then multiplied by the house volume V_h to get the infiltration flow rate V_I.

$$V_I = V_h I = V_h \frac{\ln C_1 - \ln C_2}{t_2 - t_1} . \tag{16}$$

The tracer gas concentrations C_1 and C_2 are measured at times t_1 and t_2 during the decay period.

The infiltration energy loss is given by

$$Q_I = V_I \; C_p \; (T_I - T_o). \tag{17}$$

An equivalent infiltration thermal resistance can be defined from the infiltration heat loss

$$R_I = \frac{A \; (T_I - T_o)}{Q_I} . \tag{18}$$

Then from equation 13 and Equation 14

$$R_I = \frac{A}{(V_h)(I)(\rho)C_p}. \tag{19}$$

The gross and net BTR values are related by

$$\frac{1}{R_g} = \frac{1}{R_h} + \frac{1}{R_I} \tag{19}$$

or

$$R_g = \frac{R_n \; R_I}{R_I + R_n} \tag{21}$$

$$R_n = \frac{R_g \; R_I}{R_I - R_g} \tag{22}$$

The inverse of the infiltration resistance, i.e. the conductance, $1/R_I$ is linearly proportional to the square root (or 0.65 root) of the pressure difference. Thus, from Equation 20, a plot of the inverse of the gross BTR value $1/R_g$ versus the infiltration rate I is a straight line. The data are shown for this plot in Figure 14. The difference between having storm windows and not having storm windows is clearly evident. Extrapolation to zero infiltration gives the net BTR value R_n which can be compared with steady state heat loss calculations.

As in Figure 14, the gross conductance values can be plotted versus the square root of the infiltration pressure. This illustrates a method for deducing infiltration from the BTR measurements. A series of BTR measurements can be made at differing infiltration conditions. The measured wind velocity and indoor and outdoor temperature can be used to calculate the infiltration pressure using the model. A linear correlation of the measured gross conductance $1/R_g$ versus the square root of the infiltration pressure can then be extrapolated to zero to get the net conductance and R_n values (Figure 15).

BTR METER RESULTS

The gross R values presented in Figures 14 and 15 were obtained by recording return air and outdoor temperatures on a strip chart recorder. The R-values were then computed by hand. The BTR meter has been used for one measurement each on the test house and the two houses used by the Department of Energy's Oak Ridge National Laboratory. These houses are of identical floor plan and construction and are located in Karns, TN, a few miles east of Oak Ridge. A typical printout for the measurement on the test house is shown in Figure 16. A comparison of the BTR meter results with calculated values is shown in Table 2.

The Karns test were made under low infiltration conditions. The infiltration rate for the Minnetonka house was much higher. and it was obtained from the calculated outdoor-indoor pressure difference and the previous tracer gas measurements. There were more people than normal in the house during the test. and the estimate of the off-period extraneous heat was somewhat in doubt. This and uncertainty over the infiltration contributed to the 6% difference between the BTR meter results and the calculation.

The Karns houses were unusual in that they had a computer and data-logging system in the master bedroom of each house. This produced a substantial heat input and made the master bedroom unusually warm. House Number 1 was unoccupied during the test, but there were three adults in House Number 2. The measurements were within -4% to +6% even with these unusual conditions.

Experience with the BTR method when using strip chart recorded data and hand calculations has shown that the errors tend to be random in nature. These are probably associated with variability of infiltration. When several measurements are averaged the difference between the measured and calculated BTR values decrease.

CONCLUSION

It has been shown that the envelope conduction of a home can be measured by observing the rate of temperature fall and the rate of temperature rise when the heating system is turned on an off for periods ranging from one to two hours. The method has been shown to be sensitive enough to measure the effectiveness of storm windows. Infiltration can be deduced from multiple measurements under different weather conditions. A meter based on a portable personal computer, capable of automatic measurements with relatively unskilled labor, has been discussed We believe this meter has potential use for measuring the insulation in existing buildings and for measuring the effectiveness of energy conservation measures.

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TABLE 1

Construction Types and Heat Flow Paths

Exterior Wall Construction Types:
- Brick Veneer over Frame
- Cedar Siding over Frame
- Cornice
- Cement block plus insulation and panel

Exterior wall heat flow paths:
- Stairwell to garage
- Reception hall to garage
- Half bath to garage
- Basement to garage
- Family room to closet to garage
- Utility room to closet to garage
- Garage to outdoors
- Basement to outdoors

Floors:
- Bedroom to garage
- Basement to ground
- Family room to ground
- Bedrooms to family room
- Kitchen, dining room, living room to basement
- Bathrooms

Ceilings/Attic/Roof:
- Kitchen, dining room, living room
- Bedrooms

Windows:
- Double pane
- Triple pane

Doors:
- Vestibule, family room to garage
- Front door, utility room to outdoors
- Patriot door

Internal Walls:
- Plaster board
- Wood panel
- Tile
- Plasterboard, cement block, tile chimney
- Brick fireplace
- Hollow core doors

TABLE 2

Comparison of BTR Meter with Calculations

House	BTR Meter R_g (^oF-ft^2-hr/BTU)	BTR Meter I (ach)	BTR Meter R_I	BTR Meter R_n (^oF-ft^2-hr/BTU)	Calculated R_n (^oF-ft^2-hr/BTU)
Minnetonka, MN					
test house	8.7	0.73	26	13.1	13.9
Karns, TN					
House No. 1	10.7	0.20	92	12.1	12.6
House No. 2	11.7	0.20	92	13.4	12.6

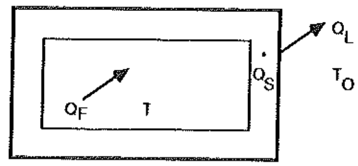


Figure 1. Isotropic model of a house

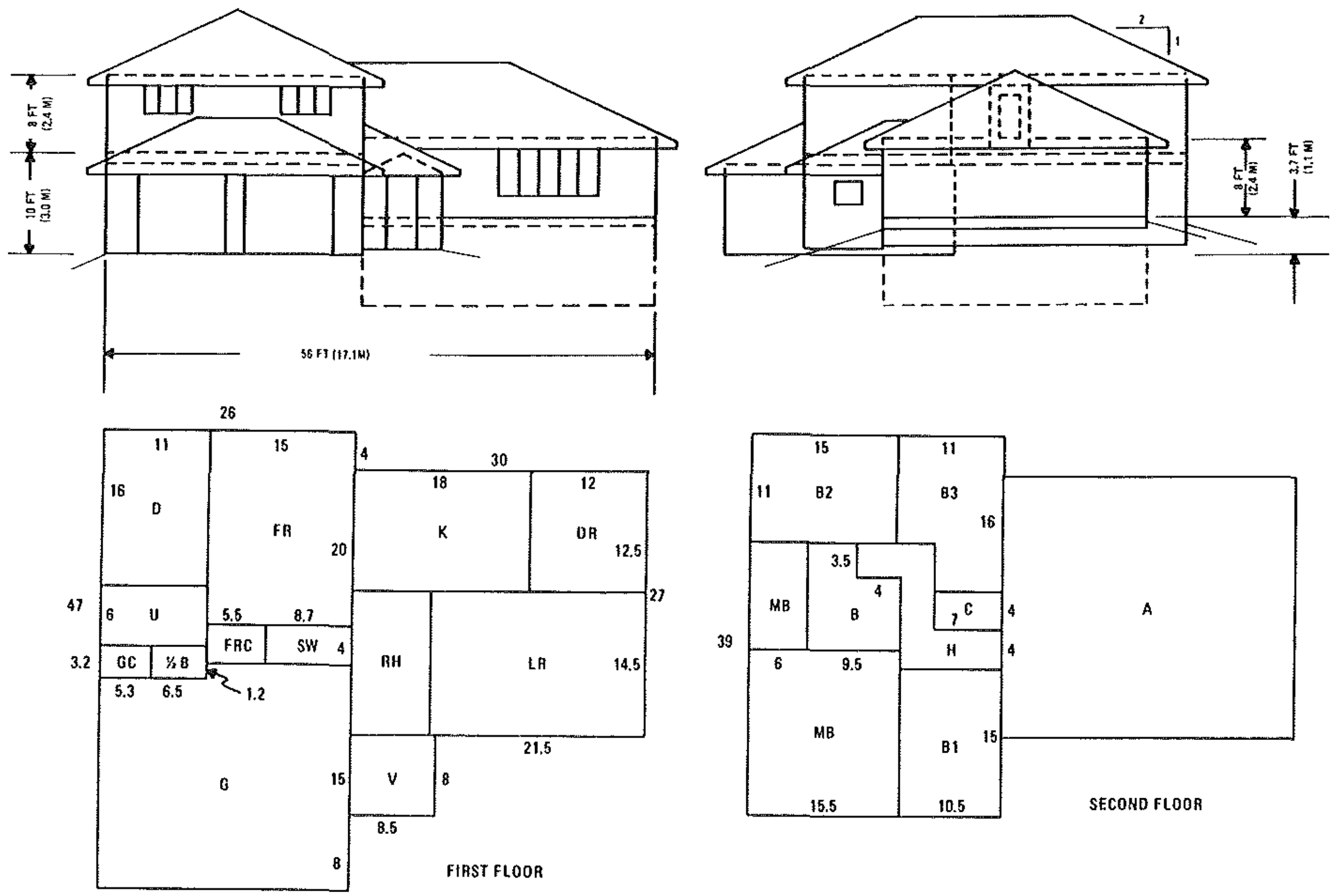


Figure 2. Test house

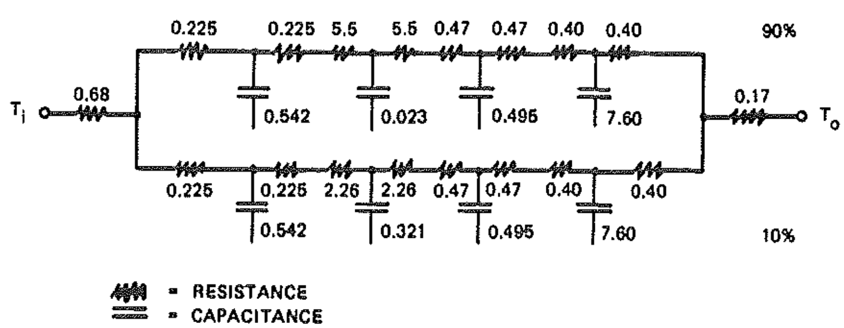


Figure 3. Typical exterior wall network

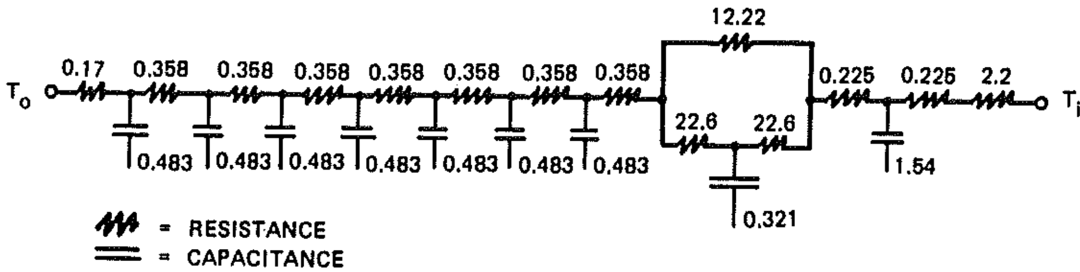


Figure 4. Reduced order wall network

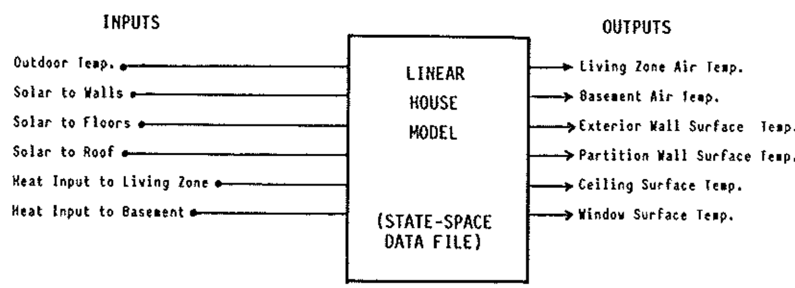


Figure 5. House model with inputs and outputs

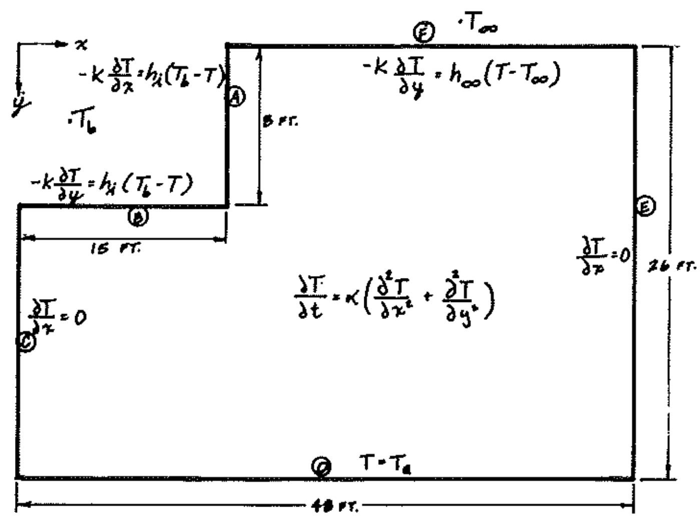


Figure 6. Basement model boundary conditions

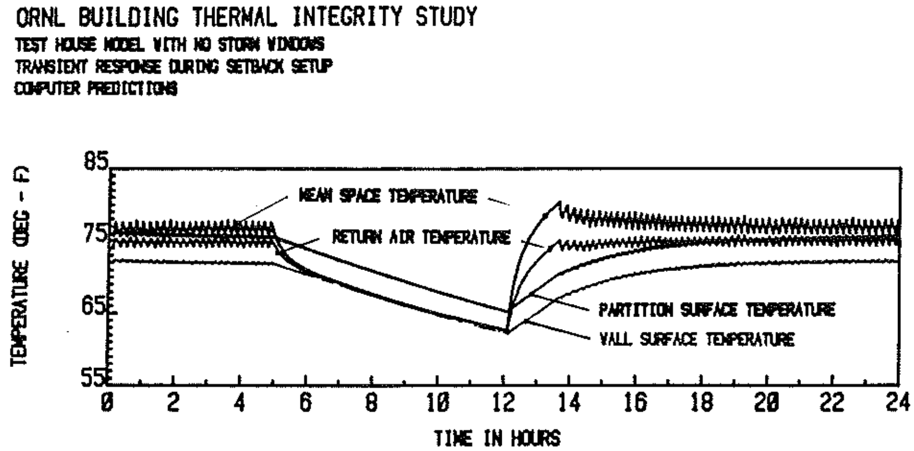


Figure 7. Computer model transient temperature response

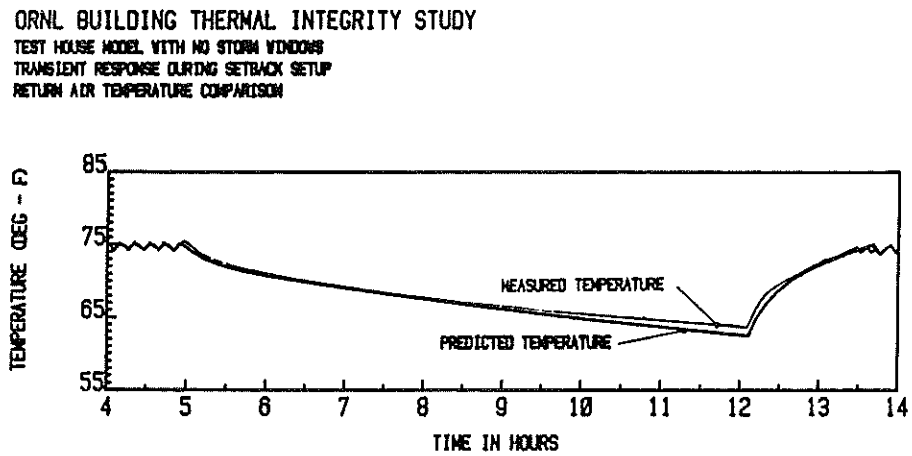


Figure 8. Transient response comparison--
model vs. measurement

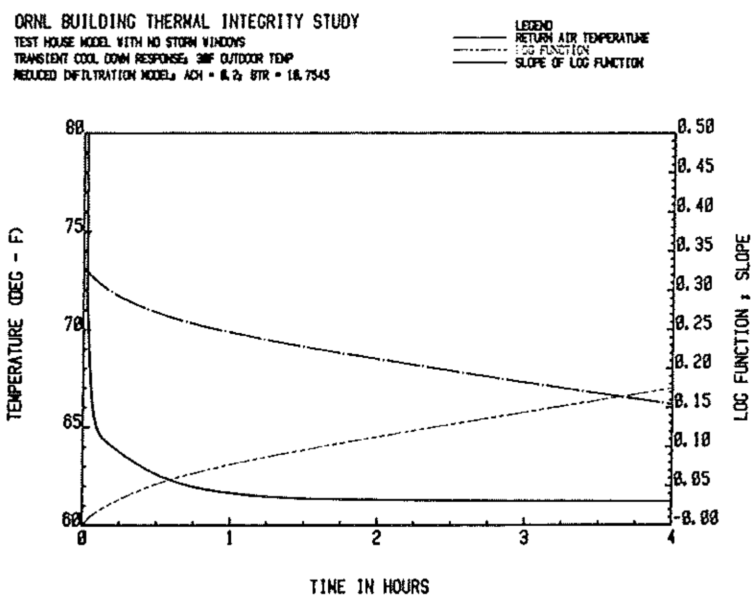


Figure 9. Transient air and log function response

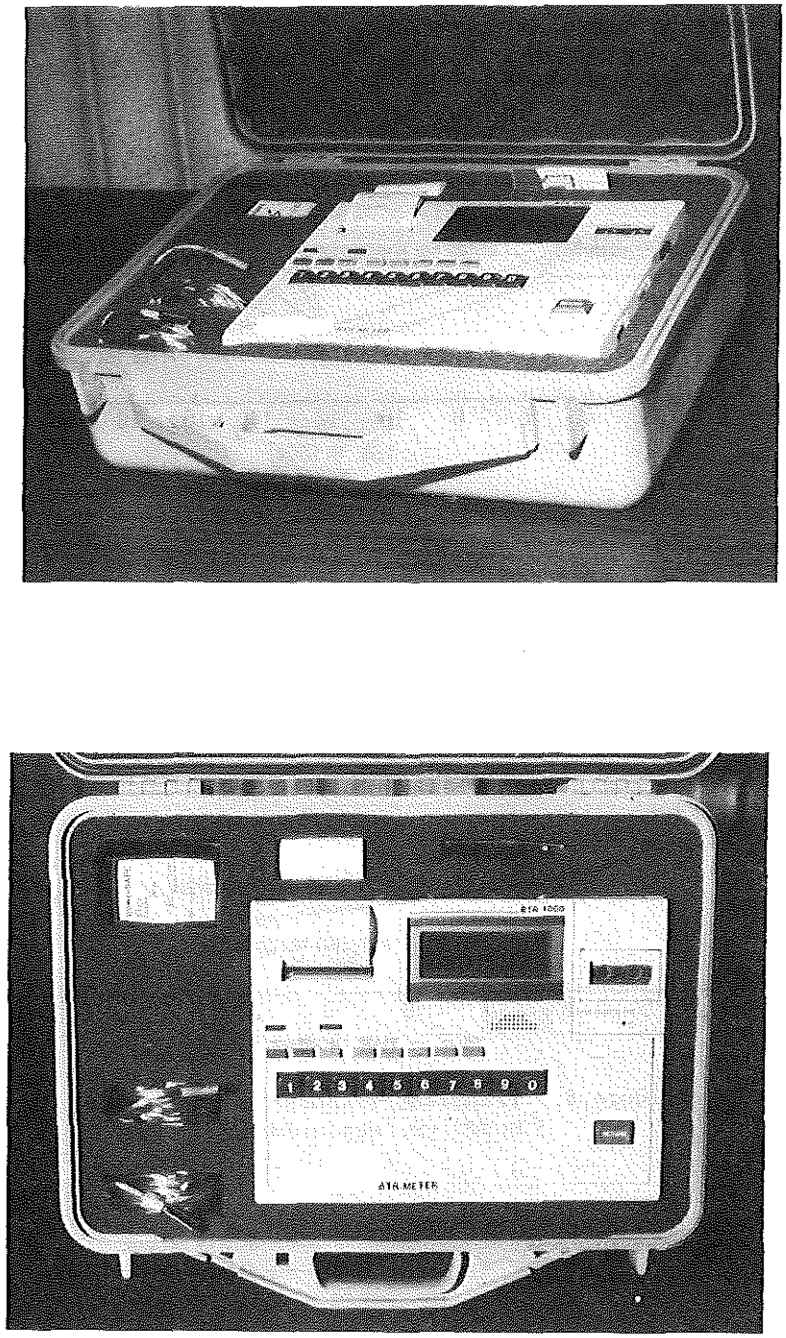


Figure 10. BTR meter

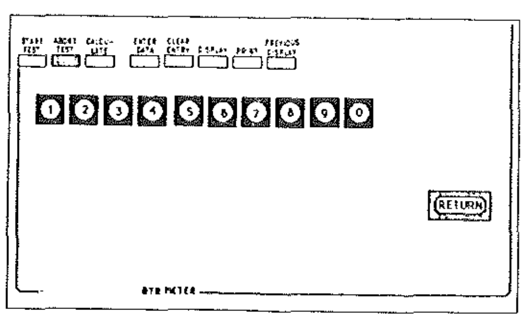
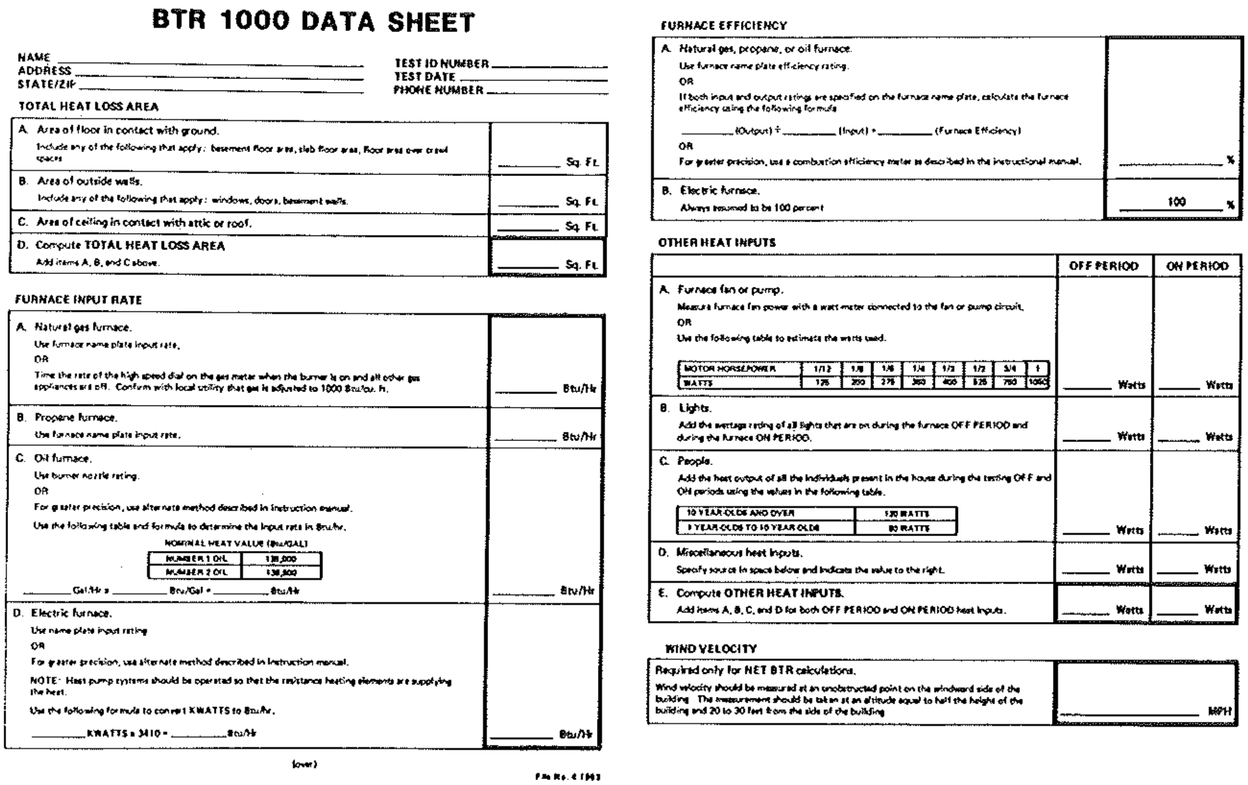


Figure 11. Meter keyboard



BTR 1000 DATA SHEET

NAME ____________________
ADDRESS ____________________
STATE/ZIP ____________________

TEST ID NUMBER ____________
TEST DATE ____________
PHONE NUMBER ____________

TOTAL HEAT LOSS AREA

A. Area of floor in contact with ground. Include any of the following that apply: basement floor area, slab floor area, floor area over crawl spaces	________ Sq. Ft.
B. Area of outside walls. Include any of the following that apply: windows, doors, basement walls.	________ Sq. Ft.
C. Area of ceiling in contact with attic or roof.	________ Sq. Ft.
D. Compute **TOTAL HEAT LOSS AREA**. Add items A, B, and C above.	________ Sq. Ft.

FURNACE INPUT RATE

A. Natural gas furnace. Use furnace name plate input rate, OR Time the rate of the high speed dial on the gas meter when the burner is on and all other gas appliances are off. Confirm with local utility that gas is adjusted to 1000 Btu/cu. ft.	________ Btu/Hr
B. Propane furnace. Use furnace name plate input rate.	________ Btu/Hr
C. Oil furnace. Use burner nozzle rating. OR For greater precision, use alternate method described in instruction manual. Use the following table and formula to determine the input rate in Btu/hr.	________ Btu/Hr
D. Electric furnace. Use name plate input rating OR For greater precision, use alternate method described in instruction manual. NOTE: Heat pump systems should be operated so that the resistance heating elements are supplying the heat. Use the following formula to convert KWATTS to Btu/hr. ________ KWATTS x 3410 = ________ Btu/Hr	________ Btu/Hr

NOMINAL HEAT VALUE (Btu/GAL)

NUMBER 1 OIL	[illegible]
NUMBER 2 OIL	[illegible]

________ Gal/Hr x ________ Btu/Gal = ________ Btu/Hr

(over)

File No. 4 1983

FURNACE EFFICIENCY

A. Natural gas, propane, or oil furnace. Use furnace name plate efficiency rating. OR If both input and output ratings are specified on the furnace name plate, calculate the furnace efficiency using the following formula ________ (Output) ÷ ________ (Input) = ________ (Furnace Efficiency) OR For greater precision, use a combustion efficiency meter as described in the instructional manual.	________ %
B. Electric furnace. Always assumed to be 100 percent	100 %

OTHER HEAT INPUTS

	OFF PERIOD	ON PERIOD
A. Furnace fan or pump. Measure furnace fan power with a watt meter connected to the fan or pump circuit, OR Use the following table to estimate the watts used.	____ Watts	____ Watts
B. Lights. Add the wattage rating of all lights that are on during the furnace OFF PERIOD and during the furnace ON PERIOD.	____ Watts	____ Watts
C. People. Add the heat output of all the individuals present in the house during the testing OFF and ON periods using the values in the following table.	____ Watts	____ Watts
D. Miscellaneous heat inputs. Specify source in space below and indicate the value to the right.	____ Watts	____ Watts
E. Compute **OTHER HEAT INPUTS**. Add items A, B, C, and D for both OFF PERIOD and ON PERIOD heat inputs.	____ Watts	____ Watts

MOTOR HORSEPOWER	1/12	1/8	1/6	1/4	1/3	1/2	3/4	1
WATTS	125	200	275	350	400	525	750	1050

10 YEAR OLDS AND OVER	120 WATTS
1 YEAR OLDS TO 10 YEAR OLDS	80 WATTS

WIND VELOCITY

Required only for NET BTR calculations. Wind velocity should be measured at an unobstructed point on the windward side of the building. The measurement should be taken at an altitude equal to half the height of the building and 20 to 30 feet from the side of the building	________ MPH

Figure 12. Data input worksheet

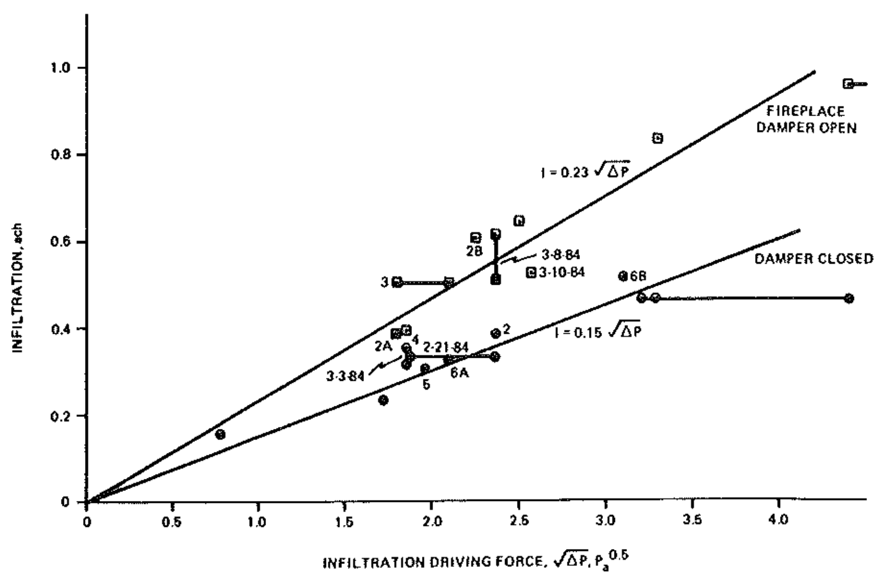


Figure 13. Infiltration measurements

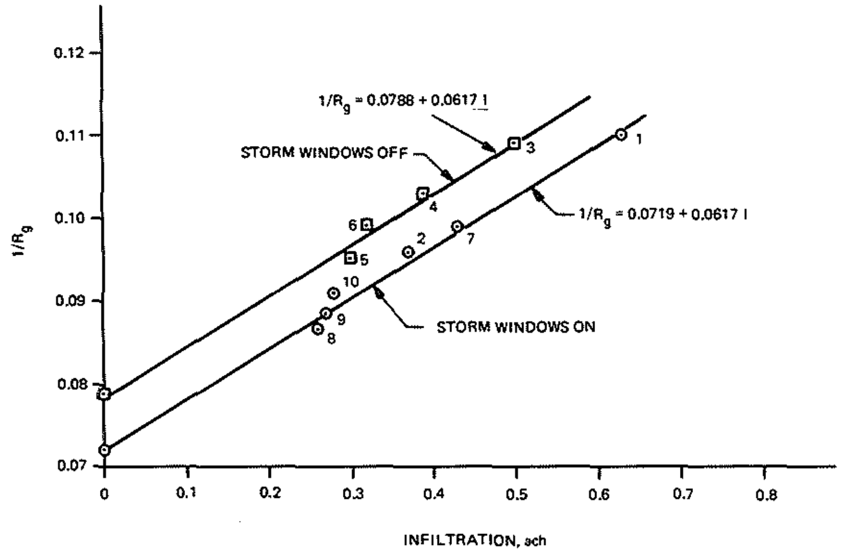


Figure 14. Conductance vs. infiltration

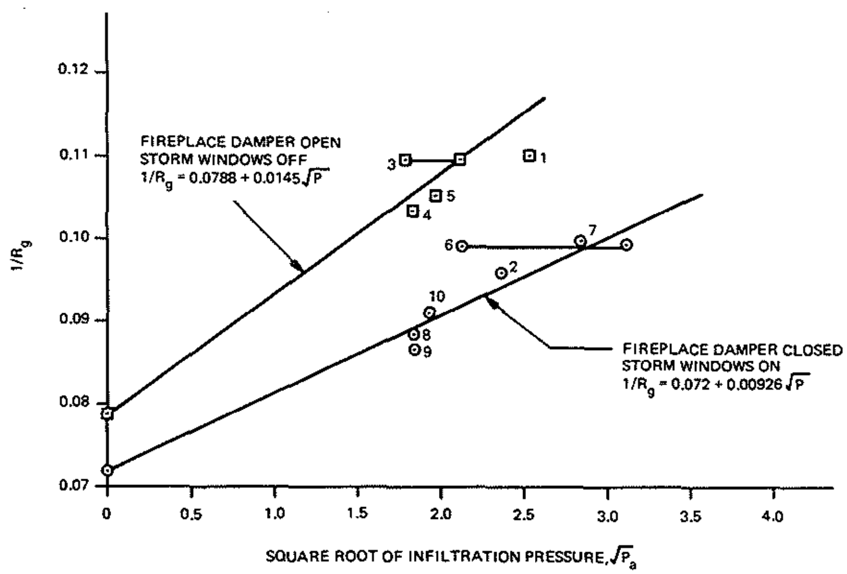


Figure 15. Conductance vs. infiltration pressure

BTR METER

TEST ID NUMBER 1

DATE 02/15/85
TIME 00:15:29

INDOOR TEMP 78.6°F
OUTDOOR TEMP 24.7°F
TEMP DIFFERENCE 53.9°F

TOTAL HEAT LOSS AREA
7000 SQFT

FURNACE INPUT RATE
125000 BTU/HR

FURNACE EFFICIENCY
76 %

OFF PERIOD HEAT INPUT
1140 WATTS

ON PERIOD HEAT INPUT
1140 WATTS

WIND VELOCITY 15 MPH

GROSS BTR VALUE
8.7 (HR)(SQFT)(°F) / BTU

NAME Test House
STREET
CITY Minnetonka
STATE/ZIP MN
PHONE

Figure 16. Sample printout