Comparison of BTR Measurements

J.E. Janssen
A.N. Pearman

ABSTRACT

Evaluation of the effectiveness of building insulation is a task of growing importance. Five different methods are described for measuring or computing the overall Building Thermal Resistance of a residential structure. Data comparing the methods are presented for a one story, slab-on-grade house located in southern California. Results generally agree within $\pm$ 5% of the ASHRAE calculation procedure.

INTRODUCTION

Determination of the insulation value in a residential structure is a challenge of growing importance. The ASHRAE methods and data for computing heat loss or gain for a building offers a reasonable approach for design purposes. However, these techniques are too laborous for most residential construction, and the quality of workmanship introduces uncertainty of unknown magnitude. Further, evaluation of the insulation in houses already constructed is difficult.

It has been shown previously[1] that a simple transient technique offers a method of measuring the overall Building Thermal Resistance (BTR) value. This technique consisted of determining the thermal time constant for the structure during a cool-down period when the furnace is off and outdoor temperature is relatively constant. The rate of temperature rise during a relatively long (about one hour) on period provided the additional data needed to compute the overall BTR value for the building. It was assumed that the steady state efficiency and firing rate for the furnace gave an accurate measure of the heat input to the building.

Sonderegger[2] has reported on the use of an electric co-heating method for measuring overall heating system efficiency. The electric co-heat method was used in the experiment reported here to determine the net heat input from the furnace to the building. A direct measurement of the BTR value using the electric co-heat method was compared with the first order transient method. Another version of the transient method which does not impose the first order approximation is compared with the other results also.

J. E. Janssen, Principal Engineering Fellow, Honeywell Inc., TSC, Minneapolis, MN.
A. N. Pearman, Senior Development Engineer, Honeywell Inc., TSC, Minneapolis, MN.

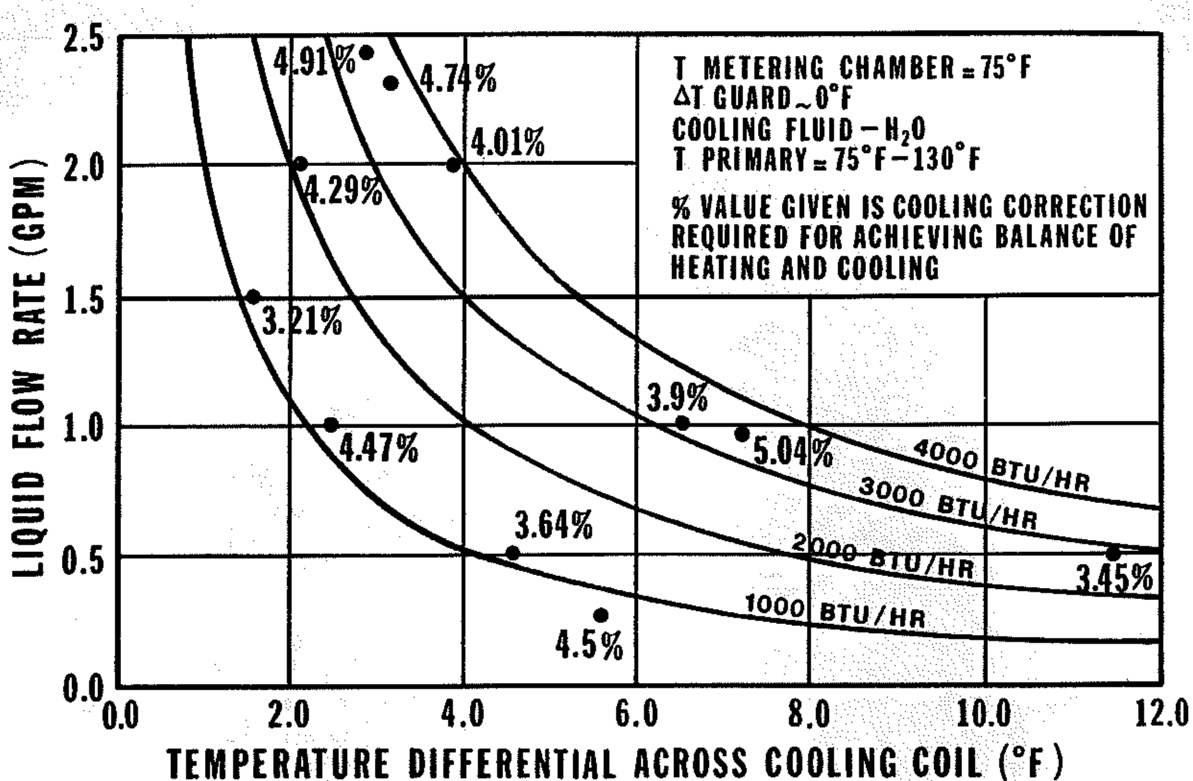


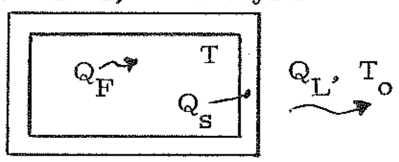
Fig. 7 Cooling system calibration data

The data are for a well insulated house located in southern California. The mild climate and the long time response associated with heavy insulation presents a good challenge for this measurement method. Equal or less insulation in a more severe climate should improve the measurement sensitivity and accuracy.

The house was unoccupied and measurements were made at night. This eliminated both solar effects and internal heat gains of unknown magnitude. The object of this paper is to present a comparison of measurement techniques.

ANALYSIS

First Order Approximation. The various heat transfer paths through the walls, windows, ceiling, and floor act in parallel. It is assumed that the indoor and outdoor dry-bulb air temperatures average and describe the heat transfer potential for each of the parallel heat transfer paths. Thus, for analysis the house is described as an isotropic structure.



The instantaneous heat balance is given by:

$$Q_S dT = Q_F dt - Q_L \ dt \tag{1}$$

Since the temperature, T, is a function of time, the heat storage rate, $Q_S dT$, is also time dependent.

The heat loss rate is given by:

$$Q_L = UA \ (T - T_o) \tag{2}$$

Then:

$$dT = \frac{Q_F}{Q_S} dt - \frac{UA}{Q_S} (T - T_o) \ dt \tag{3}$$

Integration of equation 3 gives:

$$\frac{Q_F}{UA} - (T - T_o) = Ce^{-t/\tau} \tag{4}$$

$$\text{where} \quad = Q_S/UA = RQ_S/A \tag{5}$$

If $T = T_r$ at time $t = 0$ (see reference[1]),

$$R = \frac{A}{Q_F} \quad \frac{(T - T_o) - (T_r - T_o) \ e^{-t/\tau}}{(1 - e^{-t/\tau})} \tag{6}$$

Note that during the cool-down period

$$Q_F = 0 \tag{7}$$

Then:

$$\tau = \frac{t}{\ln\left[\dfrac{T_r - T_o}{T_c - T_o}\right]} \tag{8}$$

Thus, Eq. 8 can be used to determine the thermal constant for the structure. The assumption of a single order transient is a substantial approximation. It is obvious that the air temperature in a building heated by a warm air system will respond much faster than the walls. A second order transient is described by:

$$\frac{T_c - T_o}{T_r - T_o} = BE^{-(t/\tau_1)} + (1 - B)\, e^{-(t/\tau_2)} \tag{9}$$

The constant, B, is a weighing factor less than unity. The time constant, τ_1, describes the time response for the temperature of the air in the house. It can be approximated by:

$$\tau_1 = V_h/\dot{V}_F \tag{10}$$

The second time constant, τ_2, describes the thermal response of the envelope of the house. Since $\tau_2 >> {}_1$, τ_1 can be ignored if the first part of a transient is ignored. It was found that the effects of τ_1 generally disappear if the first 30 minutes of a transient are ignored. This was the technique used here.

The first order approximation assumes that the thermal time response of the envelope of the house is the same regardless of whether heat is flowing into the walls (heating period) or out of the walls (cooling period). This should be a good assumption since thermal conduction is independent of direction of heat flow. Convection at the surface of the walls, floor, and ceiling is somewhat dependent on the direction of heat flow, but the resistance of the air film is small compared to the resistance of the insulated walls and ceiling. The time response for the air in the heating or cooling period may be somewhat different since the characteristics of the furnace are involved. However, ignoring the first part of the transient should reduce the effect of this uncertainty.

<u>Fixed Time Interval Transient.</u> If it can be assumed that the heating and cooling transients are described by the same time dependent function, another method exists for estimating the steady state limit of the heating transient from the cooling transient. Consider Fig. 1.

If f(t) describes the shape of the curves, the cooling curve is described by,

$$T_c - T_{oc} = (T_{rc} - T_{oc})\,(f(t)) \tag{11}$$

and the heating curve by:

$$T_h - T_{rh} = (T_b - T_{rh})\,(1 - f(t)) \tag{12}$$

The thermal resistance of the structure at steady state is:

$$R = \frac{A}{Q_F}\,(T_b - T_{oh}) \tag{13}$$

Therefore,
$$R = \frac{A}{Q_F} \left[(T_h - T_{rh}) \frac{(T_{rc} - T_{oc})}{(T_{rc} - T_c)} + (T_{rh} - T_{oh}) \right] \tag{14}$$

Eq. 14 implies that if the temperature rise $(T_h - T_{rh})$ and the temperature fall $(T_{rc} - T_c)$ are measured for the same time interval, t, it should be possible to compute the BTR value, R.

Electric Co-Heat. One of the uncertainities in the measurement of the BTR value is the net output of heat from the heating system. The use of a relatively long on period reduces uncertainty about cyclic efficiency. If the flue oxygen and flue temperature are measured and the hydrogen carbon ratio of the fuel is known, combustion efficiency can be computed. However, this calculation does not account for any losses from the furnace jacket or distribution system.

Sonderegger[2] has reported on an electric co-heat method which accounts for all losses. An electric heater with a measured output is used to offset part of the furnace load. With the heating system operating at some steady cycling rate, the electric heater is turned on. Care must be taken to distribute the electric co-heat uniformly. Ideally, the co-heat should be introduced into the furnace distribution system.

With the room thermostat controlling the room air temperature, the addition of the electric co-heat reduces the load on the furnace. The combined output of the furnace and electric heater are then equal to the output of the furnace alone before the electric heater was energized. The heat output of the furnace is,

$$Q_F = \eta_s (L_1)(F) \tag{15}$$

The combined output of the furnace and electric heater is,

$$Q_F = \eta_s (L_2)(F) + Q_e \tag{16}$$

Thus, the heating system efficiency, η_s is,

$$\eta_s = \frac{Q_e}{F(L_1 - L_2)} \tag{17}$$

If the co-heat is only 5% to 10% of the firing rate, the change in heating system efficiency associated with the reduced load on the furnace will be small. Thus, Eq. 17 gives a direct measurement of the heating system efficiency at a given load. If the inside and outside temperatures have been constant for a few hours (two or more), a steady state conduction equation can be used to estimate the BTR value.

$$R = \frac{A(T_i - T_o)}{\eta_s LF} \tag{18}$$

Or, if the thermal time constant has been determined from an extended cooling period and an electric heater is used with the furnace off but the fan on (to distribute the electric heat), Eq. 6 can be used. In this case, the electric heater output is substituted for the furnace output, Q_f, in Eq. 6. This is valid even if the electric heat is too small to produce a rising temperature in the house. The rate of cooling with some heat input will be less than with no heat input and Eq. 6 will apply.

ASHRAE Calculation Method. The BTR value for a house can be computed with the ASHRAE heat loss calculation procedure[3] also. The calculated value is given by,

$$R = \frac{A \quad T}{Q_L} = \frac{A(T_i - T_o)}{A_w U_w = A_c U_c = A_g U_g + A_d U_d + Q_f} \tag{19}$$

The heat transfer area, A, includes the area of all surfaces through which heat is lost.

$$A = A_w + A_c + A_g + A_d + A_f \tag{20}$$

The floor area, A_f, does not appear in Eq. 19 because the ASHRAE method for computing heat loss from a slab-on-grade is based on the perimeter. However, during a transient, it is assumed that the floor heat loss, Q_f, is spread over the entire floor. This seems valid since the entire floor surface participates in the heat storage effect associated with the transient.

Five methods have been described for determining the BTR value of a structure:

1. First order transient
2. Fixed time interval transient
3. Electric co-heat transient
4. Steady state
5. ASHRAE calculation

It was the objective of this test to make a comparison among these methods.

EXPERIMENT

The house studied was a one story, three bedroom, 98.1 m^2 (1056 ft^2) slab on grade house located in the Los Angeles, California area. Fig. 2 shows the floor plan. Walls were insulated with 0.089 m (3.5 in.) fiberglass plus 0.025 (1 in.) styrofoam planks, and the outside surface was 0.025 (1 in.) cement stucco. The windows were sliding, single glass in aluminum frames. The ceiling was insulated with 0.152 m (6 in.) of brown cellulose insulation. The floor slab was uninsulated. The front door was of insulated construction with magnetic weather-stripping but the two patio doors were single glass with only moderately tight rubber weather-stripping.

The heating system consisted of a compact boiler located in the laundry closet in the kitchen. This boiler had a sealed combustion system that drew its combustion air from outside. This air intake was a concentric tube around the flue that provided some heat recovery from the flue gas. The boiler water was circulated through a coil in an air handler that in turn distributed warm air to the rooms of the house. Boiler water was used also to heat domestic hot water, solenoid values operated by the room thermostat and hot water aquastat separated the room heating and water heating functions.

Measurements were all made a night with the house unoccupied. This eliminated solar effects and internal sources of unknown magnitude. Experiments were started about 8:00 p.m. after the furnace had established a reasonably constant cycling rate. This cycling rate was recorded for an hour or two along with the room air and outside air temperatures. A 1300 W electric heater was then positioned near the air handler return air register so that this co-heat would be picked up and distributed to the house. The co-heat was allowed to operate for 1.5 to 2 hours during which furnace cycling rate and the inside and outside temperatures were recorded. The current and voltage to the electric heater were measured also to determine the actual power consumption. The gas flow rate to the boiler during the on period was measured by timing the rotation rate of the high speed dial (0.2 ft^3/rev.) of the gas meter.

The electric co-heat was then turned off and the change in boiler cycling rate was again recorded before the night setback thermostat turned the boiler off. The circulating fan operated continuously during the off period to prevent stratification in the house. The decay in room temperature was recorded along with the outside temperature during the long off period. About 4:00 a.m. the thermostat turned the boiler on again and brought the room temperature back up to the comfort level. The thermostat was set high enough, usually 24°C to 27°C (75°F to 80°F) so that the boiler would operate for at least one hour. With this procedure, data need for both the transient and co-heat calculations were recorded essentially simultaneously.

RESULTS

A typical set of temperature transients is shown in Fig. 3 and 4. Fig. 3 is a cool down curve and Fig. 4 is the warmup curve for the following morning. The natural log of the cooling temperature function $\frac{T_{rc} - T_{oc}}{T_c - T_{oc}}$ is plotted as a function of time in Fig. 5.

The effect of the rapid response of the room air is clearly evident. However, after about an hour the longer time response of the walls is evident. The striaght line part of the curve, shifted to pass through the origin, for all of the cooling runs is shown in Fig. 6. An average cooling time constant of 1040 minutes was found. This was the time constant used to evaluate Eq. 6.

The temperatures used in Eq. 6 were taken from the warmup curves. The first 30 minutes of each warmup period was ignored and the temperature rise during the next 30 minutes (from 30 to 60 minutes after the beginning of a warmup period) was used to evaluate Eq. 6. The total heat transfer area was 308 m^2 (3314 ft^2). The boiler firing rate was 19.5 kW (66,560 BTU/hr.). This was multiplied by the per cent on time during the warmup period and the system efficiency as determined from the electric co-heat test.

Data for computing the BTR values by the Fixed Time Interval method were obtained from the individual cooling and warming curves. The same 30 to 60 minute period from each transient was used.

Data from the recordings including the electric co-heat measurements are shown in Table 1. The current and voltage supplied to the electric heater were measured during each run and the power was calculated. Slight variations were noted.

The air handler and the boiler circulation rate were undersized with respect to the boiler capacity. As a result the boiler cycled from the boiler water temperature control during the morning warmup. Thus, the heat input to the house, Q_F, was reduced both by the burner cycling rate and the system efficiency.

Infiltration was measured separately using a methane tracer technique[4]. The infiltration rate varied slightly from 0.031 m^3/s (66 cfm) to 0.035 m^3/s (75 cfm) as a function of wind velocity and inside-outside temperature difference. The variation in infiltration flow rate and the variation in inside-outside temperature difference produced the infiltration heat loss rates shown in Table 1.

The data in Table 1 were then used to compute the BTR values shown in Table 2. The gross thermal resistance values, BTR_g, were based on the heat input rate to the house. The net values BTR_n, were based on the heat input rate minus the infiltration heat loss rate, $Q_F - Q_i$. Thus, the net BTR values exclude the effect of infiltration and are comparable to the value calculated by the ASHRAE heat loss methods.

Run 7 presents a run using electric heat as a source. Two electric heaters were set up in different parts of the house and operated continuously all night. This was not enough heat to maintain a constant room temperature. It was possible, however, to treat this as another transient case with 100% heating system efficiency. Thus, the data for this run were used to evaluate Eq. 6.

Run 8 was evaluated from data taken at the same time as run 4. During this electric co-heat test used to determine heating system efficiency, the inside and outside temperatures were essentially constant for about 3 hours. The steady state heat loss equation was used to evaluate this case.

DISCUSSION

Five different methods for measuring or computing the overall thermal resistance of a building have been presented and compared. The heating system efficiencies were quite consistent, with an average value of 73%. Run No. 8 used the same data as No. 4 so was excluded from the average. Run No. 1 also was excluded from the average because it was made without the benefit of an electric co-heat measurement. An average efficiency of 73% was assumed.

This high heating system efficiency for a cycling burner was possible because the burner was a power burner with a sealed combustion system that recovered some heat from the flue gases. Combustion air was drawn in through an annular passage around the flue pipe. The flue pipe also was horizontal rather than vertical. During the off period the burner blower was off and there was virtually no air circulation through the combustion chamber. This essentially eliminated the off period losses.

The operating time of the burner was measured by connecting a relay in parallel with the burner gas valve. The relay contacts then operated an event pen on the strip chart recorder. This particular gas valve was designed for use with an intermittent pilot. There was a delay of between 36 and 40 seconds between the signal to the gas valve which ignited the pilot and the ignition of the main flame. The delay was longest for a cold start and stabilized at 36 seconds after two or three cycles. Thus 36 seconds was subtracted from the length of each on period.

A further complication arose from the interactor of the room thermostat and the boiler aquastat. The room thermostat had an anticipator designed to make it cycle the burner at about 5 cycles per hour at 50% load. During a long on period, however, the boiler cycled from its aquastat because the air handler heat exchanger was not big enough to handle the full boiler output without exceeding maximum permissible boiler water temperature. Thus, interaction between the room thermostat and the boiler aquastat produced very short cycles or apparent cycles under some load conditions. It was observed that occasionally the gas valve would be energized but the room thermostat would stop the cycle before the burner ignited or a few seconds after the burner ignited. Uncertainty of the actual burner operating time was the main cause of data spread and the low BTR values for run No. 4.

The steady state efficiency was measured by measuring the flue temperature rise and the excess oxygen in the flue gases. Thus, this is a combustion efficiency rather than a system efficiency. Since the boiler was located in the laundry closet off the kitchen and the air handler and ducts were all in the conditioned space, system losses were small. The main losses were from the insulated boiler water pipes in the attic. Thus, steady state system and combustion efficiencies should be within 2 or 3%.

The results of run No. 4 appear inconsistent with the other results. The burner cycling pattern for this run was more erratic than the others. It appears that this may have introduced additional error in both the BTR and efficiency calculations. Since run No. 8 was calculated from the same data it also was questionable.

The average of the net BTR values determined by the transient method, excluding run No. 8, was 2.03 $m^2 \cdot K/W$ (11.55 $ft^2 \cdot F \cdot h/BTU$). This compared to the ASHRAE Calculation of 1.95 $m^2 \cdot K/W$ (11.10 $ft^2 \cdot {}^oF \cdot h/BTU$). This calculation assumed an uninsulated floor with a perimeter heat loss coefficient of 1.40 W/m·K (0.81 BTU/h·ft·F). The Handbook also gives a value of 0.95 W/m·K(0.55 BTU/h·ft·F) for floors with edge insulation 2.5 cm (1 in.) thick that extends 0.6m (2 ft) down along and around the edge of the floor slab or 0.6m (2 ft) in from the edge under the floor slab. This particular house had 2.5cm (1 in.) poly styrene insulation that extended 20 cm (8 in.) down from the top surface of the slab around its edge. A heat loss coefficient of 1.21 W/m·K (0.70 BTU/h·ft·F) would raise the calculated BTR value to 2.03 $m^2 \cdot K/W$ (11.55 $ft^2 \cdot F \cdot h/BTU$). A heat loss coefficient of 1.21 W/m·K(0.70 BTU/h·ft·F)is consistent with reduced length of the slab insulation used. It also appeared that the measurement technique was sensitive enough to detect this difference.

The BTR values computed by the fixed time technique were consistently lower than those calculated by the transient method. A truly first order transient would have to give the same result by both methods since the fixed time method is merely a mathematical manipulation. Fig. 5 shows that it takes about an hour to damp out the short time response of the air. Thus, determination of the wall time response over a period of several hours as shown in Fig. 6 eliminated the short term response of the air. Using a fixed time interval of from 30 to 60 minutes after the start of a cycle was insufficient to eliminate this effect. The transient method gave superior results.

The electric heat transient, Run No. 7 also was lower than the other transient measurements. This is believed to be due to inferior heat distribution. The two electric heaters were set up in rooms on opposite sides of the house. The fan system was used to circulate heat, but the distribution probably was inferior to the heat distribution achieved when the heat was introduced in the fan coil unit. The two rooms where the heaters were located were somewhat warmer than the rest of the house.

Although the temperature recordings for Run No. 8 appeared to indicate steady state, the low BTR value indicates that steady state probably was not achieved.

The electric co-heat method of measuring heating system efficiency and the transient method of measuring overall building thermal resistance appear to be useful techniques for measuring the thermal performance of the exterior envelope of a building.

NOMENCLATURE

A = Total heat transfer area
Q = Heat flow rate
R = Thermal resistance
T = Temperature
t = Time
U = Overall heat transfer coefficient
V = Volume
$\dot{V}$ = Volumetric flow rate
τ = Time constant
η = Efficiency
L = Load, i.e., percent on time
F = Furnace firing rate

Subscripts

b = Balance point
c = Cooling or ceiling
d = Doors
e = Electric co-heat
F = Furnace
f = Floor
g = Glass
h = House
I = Infiltration
i = indoor
L = Loss
o = Outdoor
r = Reference state during a transient
S = Storage
s = System
w = Wall
1 = Furnace % on time without co-heat
2 = Furnace % on time with co-heat

REFERENCES

1. Janssen, J. E., "Building Thermal Resistance Measurement", Energy Conservation in Building Heating and Air Conditioning, P. 77, ASME Symp. Bulletin, December 1978.

2. Sonderegger, R. C., and Modera, M. P., "Electric Co-heating: A Method For Evaluating Seasonal Heating Efficiencies and Heat Loss Rates in Dwellings", Proc. of 2nd Int. CID Symp. on Energy Conservation in the Built Environment, Copenhagen, June 1979.

3. ASHRAE Handbook, Fundamentals Volume, 1977 Ed., Chapter 22, American Society of Heating Refrigeration and Air-Conditioning Engineers.

4. Janssen, J. E., Glatzel, J. J., Torborg, R. H., and Bonne, U., "Infiltration in Residential Structures", Heat Transfer in Energy Conservation, P. 33, ASME Symposium Bulletin, December 1977.

TABLE 1. DATA USED TO COMPUTE BTR VALUES

Run No.	Cooling Period T_{rc} °C (°F)	Cooling Period T_c °C (°F)	Cooling Period T_{oc} °C (°F)	Heat Period T_{rn} °C (°F)	Heat Period T_n °C (°F)	Heat Period T_{oh} °C (°F)	Co-Heat On-Time %	Syst. Eff. %	Q_F K_w (BTU/h)	Q_I K_w (BTU/h)
1	21.3 (70.3)	20.6 (69.1)	11.0 (51.8)	19.8 (67.6)	20.2 (68.4)	11.0 (51.8)		73	4.27 (14,577)	.34 (1,155)
2	21.8 (71.2)	21.3 (70.3)	8.3 (47.0)	22.2 (72.0)	23.1 (73.5)	8.0 (46.4)	10.0	71	6.82 (23,269)	.55 (1,878)
3	20.1 (68.1)	19.6 (67.2)	8.5 (47.3)	22.4 (72.4)	23.0 (73.4)	8.6 (47.5)	9.5	76	6.62 (22,580)	.56 (1,920)
4	21.3 (70.4)	14.4 (69.6)	9.3 (48.7)	19.8 (67.7)	20.5 (68.9)	8.6 (47.5)	11.5	70	5.19 (17,705)	.46 (1,572)
5	20.2 (70.2)	20.8 (69.5)	11.0 (51.8)	20.5 (68.9)	21.1 (70.0)	10.1 (50.2)	11.8	73	5.27 (17,970)	.40 (1,372)
6	19.6 (67.2)	19.4 (66.9)	13.0 (55.4)	19.6 (67.2)	20.3 (68.6)	12.9 (55.3)		73	5.57 (18,998)	.26 (898)
7				19.3 (66.8)	19.1 (66.3)	6.9 (44.5)		100	2.30 (7,870)	.47 (1,616)
8				21.4 (70.5)	21.4 (70.5)	9.1 (48.4)		70	3.69 (12,580)	.46 (1,572)

TABLE 2. COMPARISON OF BTR VALUES

Run No.	Method	BTR_g M^2-K/W	BTR_g (ft^2-°F-hr/BTU)	BTR_n M^2-K/W	BTR_n (ft^2-°F-hr/BTU)
	ASHRAE Calc.			1.95	(11.10)
1	Transient	1.76	(10.00)	1.91	(10.86)
	Fixed Time	1.13	(6.41)	1.23	(6.96)
2	Transient	1.97	(11.19)	2.14	(12.17)
	Fixed Time	1.56	(8.88)	1.70	(9.66)
3	Transient	1.94	(11.01)	2.12	(12.03)
	Fixed Time	1.71	(9.69)	1.87	(10.65)
4	Transient	1.42	(8.11)	1.57	(8.90)
	Fixed Time	1.22	(6.91)	1.33	(7.58)
5	Transient	1.74	(9.91)	2.02	(11.48)
	Fixed Time	1.55	(8.78)	1.68	(9.51)
6	Transient	1.88	(10.69)	1.97	(11.22)
	Fixed Time	1.91	(10.83)	2.00	(11.37)
7	Elec. Heat Trans.	1.49	(8.47)	1.87	(10.65)
8	Steady State	1.04	(5.95)	1.20	(6.80)

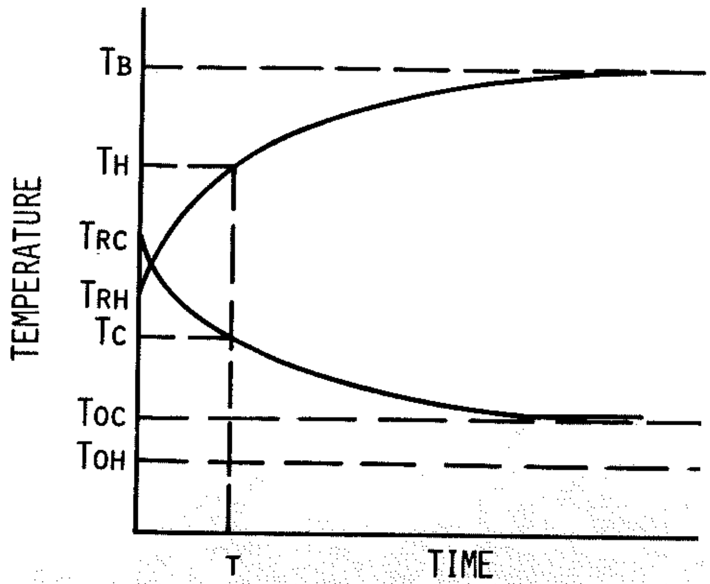


Fig. 1 Building Temperature Transients

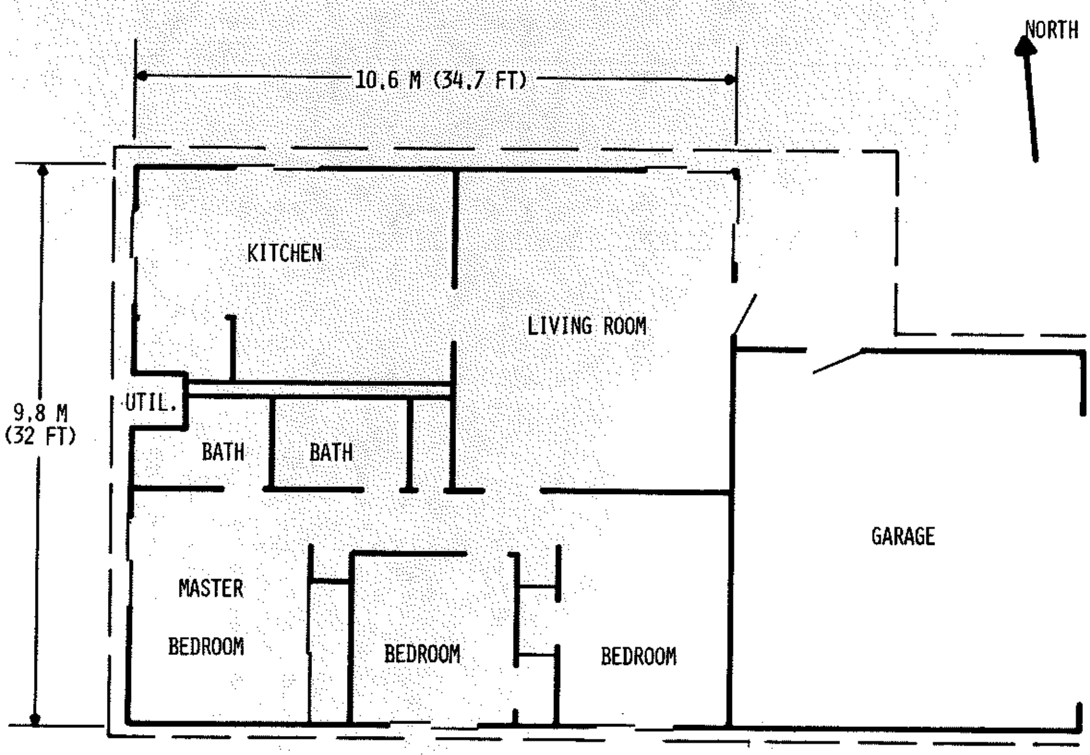


Fig. 2 Test House Floor Plan

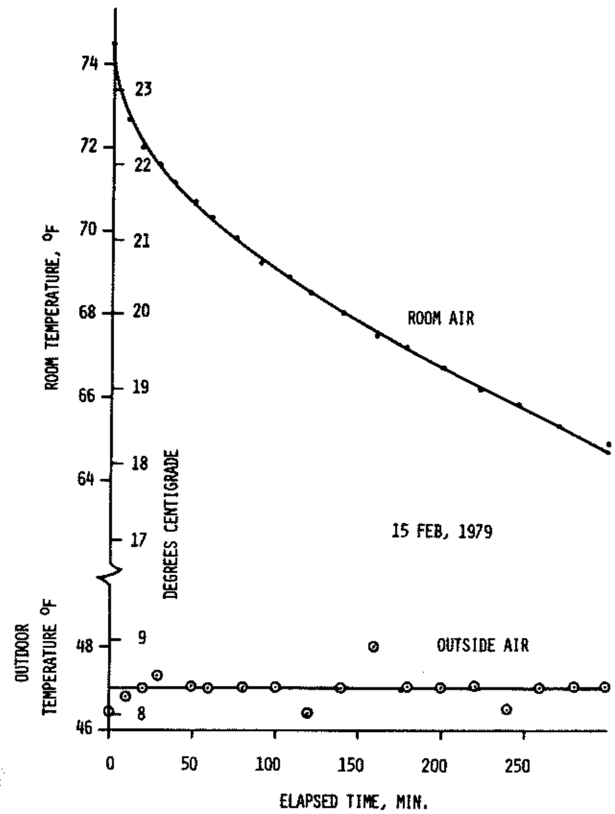


Fig. 3 Evening Cool Down

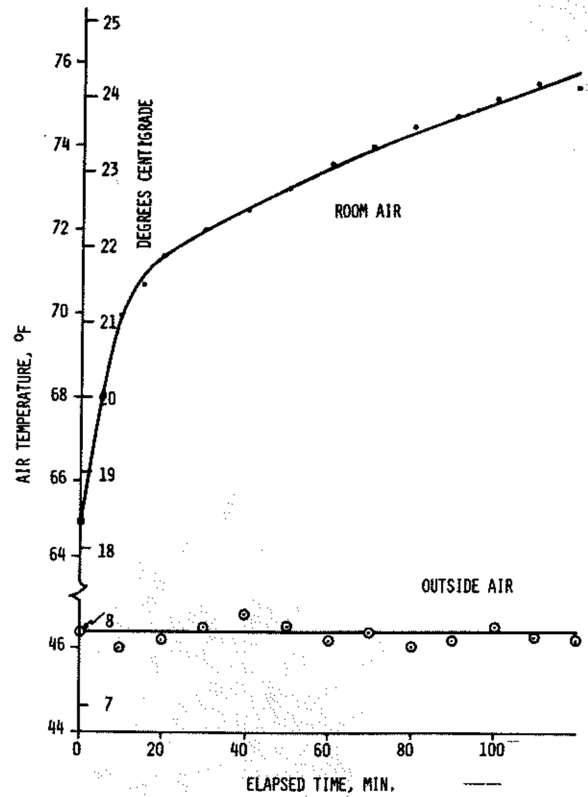


Fig. 4 Morning Warmup

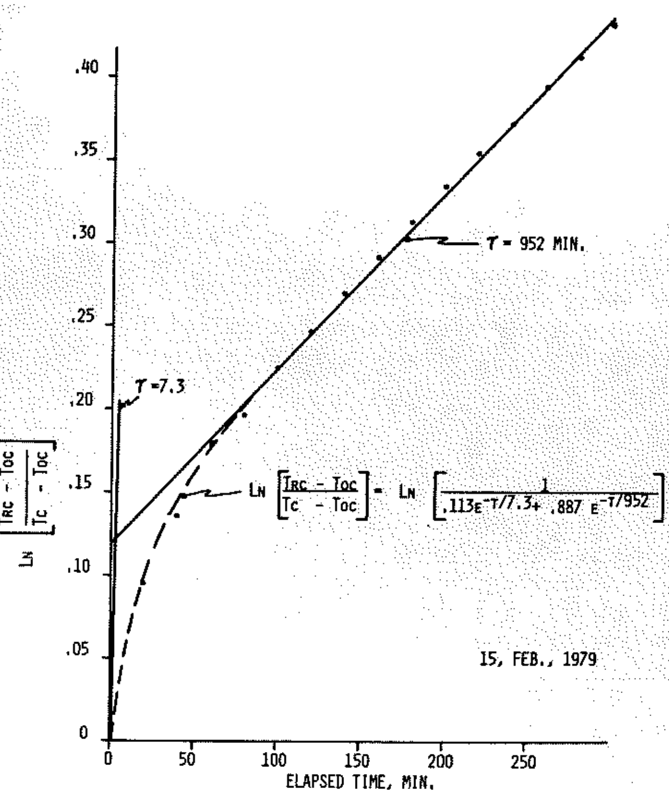


Fig. 5 Typical Cool Down Function

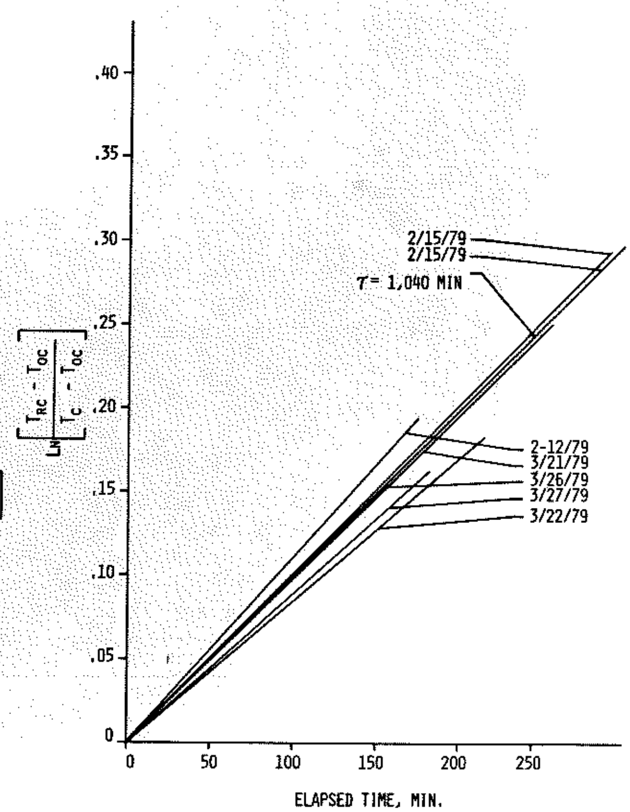


Fig. 6 Cooling Temperature Function