# THE ASSESSMENT OF ACCURACY OF THE IN-SITU METHODS FOR MEASURING BUILDING-ENVELOPE THERMAL RESISTANCE

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ABSTRACT

A series of field and laboratory tests were conducted to evaluate the accuracy of in-situ thermal resistance measurement techniques. The results of thermal performance evaluation of the exterior walls of six thermal mass test houses situated in Gaithersburg, Maryland are presented. The wall construction of these one-room houses includes insulated lightweight wood frame, uninsulated lightweight wood frame, insulated masonry with outside mass, uninsulated masonry, log, and insulated masonry with inside mass. In-situ measurements of heat transfer through building envelopes were made with heat-flux transducers and portable calorimeters. A sufficiently long period of measurement, depending on the thermal mass of wall structure, is needed to provide reliable thermal resistance data. The comparison of the results from these field measurements with those derived from sections of the same wall structures tested in a guarded hot box facility in a laboratory are presented. A well-insulated, double-stud test wall was also tested under simulated thermal conditions, including steady-state and periodically varying outdoor temperatures, using a calibrated hot box and the in-situ measurement procedures.

From these test results, the in-situ methods are shown to provide thermal resistance data within 9% of hot box results. The extent of variability in wall resistance values measured by a single calorimeter or heat-flux transducer is found to range from 0.3% to 9% with an average of 4%.

## INTRODUCTION

The thermal integrity of a building envelope has a great impact on both heating and cooling fuel costs and on maintenance expenditure for a building. This necessitates increased attention to the design and construction of more thermally efficient envelopes and to retrofit of existing buildings. Quantitative information about the thermal performance of exterior envelopes under actual use conditions is required for assessing the effectiveness of energy conservation measures and estimating peak heating and cooling loads for the sizing of heating, ventilation, and air-conditioning equipment.

Measured thermal resistance for building materials or components available for design of building envelopes has been derived largely from carefully prepared test specimens constructed for the sole purpose of obtaining test measurements under controlled conditions. However, those test specimens may not adequately reflect conditions in the field, such as substandard workmanship, defective insulation, and deterioration of building components caused by aging materials and moisture penetration. Also, the prescribed exposure conditions in the laboratory tests may differ from the actual exposure in the field due to dynamic variations of ambient temperature and solar radiation. Due to the continuing development of construction techniques and new types of building materials, there is a need to obtain data on thermal resistance of building components under actual use conditions. Field thermal measurements can provide

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information about whether the thermal performance of building components meets thermal design specifications and can be used for comparison with theoretical predictions of computer models.

Though the results of field measurements using heat-flux transducers and portable calorimeters have been reported in the literature (Brown and Schuyler 1979, 1982) little experimental work has been done to assess the accuracy of these in-situ measurement techniques. This is due primarily to the lack of knowledge regarding the heat flow characteristics of wall sections in these tests.

This paper compares the results of in-situ methods for measuring thermal resistance values of exterior walls of six test houses to the results obtained in a guarded hot box on identical wall structures. The walls tested are insulated lightweight wood frame, uninsulated lightweight wood frame, insulated masonry with outside mass, uninsulated masonry, log, and insulated masonry with inside mass. In addition, a highly insulated wall was tested both by in-situ methods and in the NBS calibrated hot box.

## DESCRIPTIONS OF TEST BUILDINGS

Field thermal measurements were carried out on six one-room test buildings that had the same floor area and orientation, and were identical except for the wall construction. These buildings in Gaithersburg, Maryland, had previously been used to investigate the effect of wall mass on space heating and cooling loads and indoor comfort of residential building (Burch et al. 1984). Each building had a different wall structure, described in detail in Table 1.

Each test building had a 20 x 20 ft (6.1 m 6.1 m) concrete floor covered with 2-in (51-mm) thick polystyrene foam insulation board, and a pitched roof with a gypsum-board ceiling located 90-in (2.29-m) above the floor. In the attic space, 11-in (280-mm) thick R-34 h·ft$^2$·F/Btu (R-6.0 m$^2$·K/W) glass-fiber blanket insulation was installed over the ceiling. Two nominal size 35 x 44 in (0.89 x 1.12 m) double-hung windows and single-glazed windows with exterior sashes were situated on both the south-facing and the north-facing walls, and a 19.5 ft$^2$ (1.81 m$^2$) insulated metal door was located on the east wall of each test building. The indoor air of each test building was conditioned by a centrally located 4.1 kW electric forced-air heating plant equipped with a 13,000 Btu/h (3,800 W) split-unit vapor-compression air-conditioning system.

## INSTRUMENTATION AND MEASURING TECHNIQUE

To obtain the wall thermal-resistance data, measurements are required of the heat flux through a building envelope and the air-to-air temperature difference across the envelope. The heat flow rate was measured with heat-flux transducers and portable calorimeters. The heat-flux transducer consisted of a 4-in (102-mm) diameter, flat circular wafer containing an embedded thermopile with its hot and cold junctions attached to the internal wafer surfaces. The thermopile produced a voltage signal directly proportional to the rate of heat flow passing through the wafer. The heat-flux transducers were installed using masking tape on the interior surfaces of both the north-facing and west-facing walls at the locations either midway between wood studs or furring strips, or over these wall-framing members.

Calibration of the heat-flux transducers was accomplished prior to the installation using a standard guarded hot plate apparatus (Powell and Rennex 1982; Rennex 1983). The heat-flux transducers to be calibrated were sandwiched between two insulation boards installed next to the hot and cold plates of the apparatus and exposed to a uniform heat flux at the desired mean temperature corresponding to that observed during the field measurements. After a 24-hour conditioning period, the sensitivity of each heat-flux transducer was determined by dividing the measured millivolt output by the applied heat flux. The accuracy of the transducer calibration was estimated to be with $\pm$ 1%.

The portable calorimeter was developed for in-situ measurement of heat flow through building envelopes (Brown and Schuyler 1979). Brown and Schuyler (1982) used this apparatus to quantify heat transmission through wood-frame walls of single-family houses. In order to measure the thermal resistance of wall structures, two different size portable calorimeters, similar to that employed by Brown and Schuyler (1982) were designed, fabricated, and instrumented. These portable calorimeters were used to determine the overall thermal performance of masonry and metal panel faced exterior walls of eight office buildings situated in different geographical and various climatic regions (Fang and Grot 1984, 1985; Grot et al. 1985).

The calorimeter is a five-sided insulated box with an open side that is sealed against the wall of the test building. The construction details of the small portable calorimeter are given in Figure 1. The calorimeter walls were constructed from two layers of 2-in (50-mm) thick aluminum-foil-faced, semi-rigid glass-fiber insulation boards glued together with the foiled side exposed. The four exterior sides of the calorimeter were covered by 1/2-in (13-mm) plywood to provide structural support. The walls had an overall thermal resistance of R17.4 $ft^2 \cdot h \cdot F/Btu$ (3.06 $m^2 \cdot K/W$). In order to make an airtight seal between the calorimeter and the test wall, a rubber foam gasketing material was installed along the edges of the open face of the calorimeter box. The sizes of the metering area of these two calorimeters were 31 x 35 in (0.79 x 0.89 m) and 46 x 75 in (1.17 x 1.19 m), respectively.

Each portable calorimeter contained an electric resistance heater with an electrical power consumption rate of 90 W for the small size, and 140 W for the large one. A thermopile, with its many thermocouple junctions distributed evenly and attached on both the interior and the exterior surfaces of the calorimeter back wall, was used to monitor the temperature differential across the calorimeter wall.

The automatic measurement and control system used for the calorimeter is shown schematically in Figure 2. A voltage controller using the thermopile output as the feedback variable was employed to control the electrical energy supplied to the electric heater by maintaining a zero temperature difference between the inside and the outside surfaces of the calorimeter wall. A safety thermostat with a sensing element located in the calorimeter box controlled the air temperature inside the calorimeter within the safety limit. The total electric energy consumed by the heater was measured with a watt-hour meter equipped with an optoelectronic device consisting of a light-emitting diode and a detector. This device generated an electric pulse each time 1.8 watt-hours of electric energy were consumed. These pulses were totaled by an electronic counter. Since the heat losses through the box walls and the edges that contacted the metered surface were approximately zero, the electrical energy supplied to the heater was essentially equal to the heat flow through the metered area.

Bead-shaped thermistors were used to measure the temperatures of the outdoor and indoor air in the vicinity of heat-flux transducers and of the air inside the portable calorimeters. Each thermistor consisted of an external network with a fixed precision resistor. This temperature sensor produced an output voltage proportional to the temperature over a temperature range of -22 to 122F (-30 to 50°C). The measurement accuracy of the thermistors was ± 0.5F (0.3°C) based on the technical data provided by the manufacturer.

In-situ heat flow measurements were conducted on the exterior walls of the six test buildings from January to March, 1985. The duration of each test ranged from seven to 12 days. The indoor temperature of each test building was thermostatically controlled at 69F. During the field measurements, the heat-flux transducers were attached to the internal surfaces of the north- and west-facing walls in each building using masking tape. A stud finder was used to ensure that every heat-flux transducer was mounted either on wall-framing members or midway between them. The open side of the calorimeter was sealed against the inner surface of the test wall using duct tape. The outdoor air temperature was measured with a thermistor installed on a bracket extending 8-in (203-mm) from the outer surface of the north-facing wall. Each thermistor used for measuring indoor temperatures was secured with its sensing element positioned 6-in (152-mm) from the wall surface being measured. The output signals from the heat-flux transducers, the electric pulses from the watt-hour meters used with the portable calorimeters, and the thermistors were recorded simultaneously by a microcomputer-based data-acquisition system. This system was capable of recording data from 15 thermistors, 15 heat-flux transducers and six calorimeters simultaneously. Continuous readings of all transducers were taken at two second intervals. The computer averaged the readings over one-hour intervals and recorded the hourly averages on a floppy disk for further processing and analysis.

## TEST RESULTS

### FIELD MEASUREMENTS WITH TEST BUILDINGS

Table 2 presents thermal-resistance data for sections of the north-facing wall in each test building as measured with both the large and small portable calorimeters and with the heat-flux transducers. Heat flux was measured at locations where wall-framing members exist and also at locations midway between framings. The predicted steady-state resistance is shown in Table 2, along with the measured results from the guarded hot box for wall specimens with construction identical to that of the building walls. All of the measured data from the in-situ methods are mean values of the data collected over a 24-hour period for six to 12 consecutive days. Error due to transient effect can generally be minimized by averaging the air-temperature and surface-heat-flux data over a 24-hour period. The wall thermal resistance was determined by dividing the temperature difference between the indoor and the outdoor air across the wall structure by the measured heat flow rate. Since there are no wall-framing members contained within the exterior walls built either from logs or masonry construction insulated with inside mass, no data are presented.

The average R-value measured by heat-flux transducers and the predicted steady-state thermal resistance value were calculated using both the zone and the series resistance method (ASHRAE 1985). The overall thermal resistance value, including the correction for wall framing effect, can be calculated from the following equation:

$$R^{-1} = R_F^{-1}\ (\%\ \text{framing})/100 + R_C^{-1}\ (100 - \%\ \text{framing})/100 \qquad (1)$$

where R is the average thermal resistance value, $R_F$ is the thermal resistance value measured at the framing member, and $R_C$ is the resistance value measured at the cavity between framings. For computing the predicted values, the published data on thermal properties of the building materials involved were used along with the assumed thermal resistance values of 0.68 $ft^2 \cdot h \cdot F/Btu$ (0.12 $m^2 \cdot K/W$) and 0.17 $ft^2 \cdot h \cdot F/Btu$ (0.03 $m^2 \cdot K/W$) for air films at the warm and cold wall surfaces. These film resistances represent conditions when the room side of the exterior wall is exposed to still air and the exterior side is subject to a 15 mph (6.7 m/s) wind.

As illustrated in Table 2, there is a fairly good agreement existing between the measured wall thermal resistance values and the predicted results. The percentage deviation between the predicted value and the experimental results obtained from the portable calorimeters is found to vary from 4% to 20% with an average of 12%. The wall resistance values measured with heat-flux transducers deviated from the predicted values by an average of 13% with a range covering between 6% and 28%. The large differences between the predicted and measured values occurred for insulated and uninsulated masonry walls. Possible reasons for the discrepancy include the uncertainties in the handbook values for thermal resistances of the building components and the transient effects of massive thermal masses of these building walls. In general, the thermal resistances determined by the small calorimeter are lower than those measured with the large calorimeter because the metering wall area of the large calorimeter contains approximately 30% more wall framing area. This results in increased heat flow due to the presence of these conductive framing members.

The air-to-air thermal resistances measured with a guarded hot box apparatus for wall specimens having the same construction as the walls of the six test buildings are also presented in Table 2. Six 6 x 6 ft (1.8 x 1.8 m) wall specimens were tested in accordance with the standard calibrated hot box test procedure by an independent test laboratory. Each test wall was placed between an environmental chamber and a metering box that was maintained at 70F (21$^\circ$C) inside a guarded hot chamber. The cold chamber temperature was maintained at 5F (-15$^\circ$C) until the test wall achieved thermal equilibrium; the temperature was then raised to 35F (2$^\circ$C) for six hours. The airflow rates parallel to the warm-side and cold-side surfaces of the test wall were 0.7 mph (0.3 m/s) and 0.4 mph (0.2 m/s), respectively. Thermocouples were used to measure the hot and cold test wall surface temperatures and the temperatures of air in the proximity of the test wall on the hot and cold sides. The heat flow through the test wall was determined by using precision resistor networks to measure the total electric power input to the heater and the fan in the metering box. Overall thermal resistance of each test wall was derived from these wall surface temperature and electrical energy consumption data. The air-to-air thermal resistance values in Table 2 were based on the results of the calibrated hot box measurements along with air film thermal resistances of 0.68 $ft^2 \cdot h \cdot F/Btu$ (0.12 $m^2 \cdot K/w$) at the warm surface and 0.40 $ft^2 \cdot h \cdot F/Btu$ (0.07 $m^2 \cdot K/w$) at the cold surface.

Table 2 shows that the experimental values obtained by the guarded hot box are in good agreement with the thermal resistance results derived from steady-state thermal resistance predictions. The average percentage deviation between the predicted and measured results from the guarded hot box for each wall was approximately 8%. The average indoor and outdoor air temperatures recorded during the field thermal resistance measurements are presented in Table 3 along with the observed air temperatures at the warm and cold sides of the wall structures measured with the laboratory guarded hot box. The air temperature difference across the building walls during in-situ measurements ranged widely from approximately 16 to 47F with an average of 33F.

LABORATORY MEASUREMENTS WITH DOUBLE-STUDDED WALL

In order to check the overall performance and assess the level of accuracy of the portable calorimeters and the heat-flux transducers, in-situ thermal resistance measurements were performed on a well-insulated double-studded wall installed in the calibrated hot box apparatus at the National Bureau of Standards, Gaithersburg, MD. This series of tests allowed comparison of the thermal resistances measured using the calorimeters and transducers with those determined with the calibrated hot box test. The wall specimen had dimensions of 15 x 8 ft (4.57 x 2.44 m) high and 6.75-in (172-mm) thick. It consisted of a 0.002-in (0.051-mm) thick polyethylene vapor barrier and 1/2-in (12.7-mm) gypsum wallboard on the inside, a double layer of R-11 $ft^2$·h·F/Btu (1.94 $m^2$·K/w) glass-fiber insulation installed in the cavities formed between nominal 2 x 3-in. (51 x 76 mm) wood studs placed 16-in (406-mm) on center, and a 3/4-in (19-mm) thick isocyanurate sheathing and a 1/2-in (12.7-mm) wood siding on the outside. The construction details of the wall specimen and the locations of the portable calorimeters and the heat-flux transducers are shown in Figure 3. In order to accommodate the width of wood stud used, the glass-fiber blanket insulation in the stud cavities was compressed from 3.5-in (89-mm) to 2.5-in (64-mm) thickness. The steady-state thermal resistance of this double-stud wall was 23.75 $ft^2$·h·F/Btu calculated using the series resistance method (ASHRAE 1985). A thermal resistance value of 8.77 $ft^2$·h·F/Btu, determined by the guarded hot plate apparatus, was used for the compressed glass-fiber blanket insulation (Zarr et al. 1985).

The NBS calibrated hot box can evaluate the thermal performance of composite wall specimens having dimensions of up to 10 ft (3.05 m) wide by 15 ft (4.57 m) high by 2 ft (0.61 m) thick. This apparatus is capable of providing steady-state temperatures ranging from -40 to 65°C for the climatic chamber and 10 to 65°C for the metering chamber. The construction of this test facility has been described in detail by Jones (1982) and Zarr et al. (1985). During the laboratory measurements, the double-stud wall specimen was held in the test frame with its outer-wall surface sealed against the climatic chamber. The air temperature in the chamber was maintained at a constant value or changed with time in a controlled manner to simulate outdoor weather conditions. The interior side of the test wall was exposed to ambient air in a large environmental chamber controlled at a fixed temperature to represent indoor conditions. Both the large and small portable calorimeters were sealed tightly against the inside surface of the test wall using duct tape and a rubber foam gasket installed at the edges of the calorimeters. The heat-flux transducers were taped on the inside surface of wall areas over both the wood studs and the thermal-insulation-filled cavities between studs as shown in Figure 3.

Two tests were performed, one with the temperature of air in the climatic chamber held at a constant value of 34.4F (1.3°C) and the other test with the chamber air temperature varied periodically to simulate diurnal air temperature conditions. The apparatus was programmed to control the temperature of the air within the climatic chamber according to the following cosine function:

$$T = 16.2 \cos(\pi t/12 - \pi/2) + 42.8 \qquad (2)$$

where T is the climatic chamber air temperature in F, and t is the time in hours.

Table 4 presents the average wall resistance values measured by the portable calorimeters and heat-flux transducers, and the air temperatures as determined by thermistors, for the double-stud wall for both steady-state and dynamic climatic conditions. For the test wall exposed to a steady-periodic temperature condition, it was found after completion of the test that the duration time for each temperature cycle was 23.33 hours. The values for constant outdoor temperature in the table are averaged over two consecutive 24-hour cycles, and the values for the dynamic climatic condition was averaged over three successive 23-hour cycles. The wall thermal resistance value measured by the calibrated hot box and the corresponding predicted value calculated by the series resistance method are listed in Table 4 for comparison. The resistance value determined by the calibrated hot box was obtained with the apparatus operated in a steady-state mode with the test wall in the test frame clamped between the metering chamber and the climatic chamber. The thermal resistance value obtained from the calibrated hot box measurements included estimated air film resistances of 0.68 $ft^2$·h·F/Btu (0.12 $m^2$·K/w) at warm surface and 0.36 $ft^2$·h·F/Btu (0.06 $m^2$·K/w) at the cold surface based on a measured air velocity of 1.9 mph (0.8 m/s).

Inspection of Table 4 indicates that the measured thermal resistance values are generally in good agreement with the predicted results. The wall resistance values determined by the large and small portable calorimeters, the heat-flux transducer, and the calibrated hot box apparatus are within 6%, 5%, 6% and 4% respectively, of the corresponding predicted value. Based on the results of these two laboratory tests involving in-situ measurements, it appears that the dynamic climatic condition gave a slightly smaller value of wall resistance than the steady-state condition. This is probably a result of the transient effects of varying temperature on thermal conductivities of component materials in the test wall. More test data are need to evaluate these preliminary experimental observations.

## COMPARISON OF TEST RESULTS BETWEEN IN-SITU MEASUREMENTS AND THE HOT BOX METHOD

The thermal resistance values measured with the portable calorimeters for the exterior walls of six test buildings and the well-insulated double-stud wall are plotted in Figure 4 against the resistance values determined by the hot box for the identical wall sections. A similar plot for comparing the thermal resistance results from heat-flux transducer measurements with values obtained in the laboratory using the hot box test is shown in Figure 5. All the data points lie close to the line of perfect agreement, indicating that a good correlation exists between the wall resistance results of in-situ measurements and the laboratory hot box data. The percentage deviation between the wall resistances measured with the portable calorimeter and the resistance values determined by the hot box apparatus were found to vary between 1% and 20% with an average of 9% for the seven walls. The greater departures were found in the thermally massive insulated walls. The thermal resistance values obtained from in-situ measurements with heat-flux transducers departed from the hot box data by an average of 8% with a range varying between 1% and 15%.

## THE VARIABILITY OF MEASURED THERMAL RESISTANCE VALUES

In order to determine the extent of variation in the values measured with the portable calorimeters and heat-flux transducers, calculations of the coefficient of variation were made with the daily averaged wall resistance data obtained from field and laboratory measurements. The coefficient of variation is equal to the percentage of the ratio of the standard deviation to the mean value. The results of the statistical analysis for each wall structure are summarized in Table 5. The measurement period for the field tests varied between three and 12 days. The measurement periods of several tests were shortened due to the occurrence of unseasonably warm weather, with the outdoor temperature greater than 60F (15.6°C) for a few days. In addition, some difficulties were experienced with the temperature controller of the heating system during the course of the test. Excluding one test that had considerable variability of the measured resistance values attributed to malfunction of the thermostat (insulated masonry wall with outside mass), the coefficients of variation, which are a measure of the degree of variability of the resistance data within a single instrument, for the large and small calorimeters, and the heat-flux transducer are found on the average to be 3.8%, 5.8% and 4.3%, respectively.

Table 6 lists the number of heat-flux transducers installed between framing members and over the wall framings, and the range of measured wall resistance values. The coefficient of variation of the measured resistance results between different heat-flux transducers for each exterior wall is also listed. As illustrated in the table, the coefficient of variation varies significantly from wall to wall depending upon the wall mass and thermal insulation property. These coefficients of variation ranged from 0.2% to 16% with an average of 6%. This average value representing the between-transducer variability is slightly greater than the corresponding within-transducer variability. However, all of the heat-flux transducers are essentially in agreement because the difference between these two variability values is small.

## CONCLUSION

The portable calorimeter and heat-flux transducer are reliable and practical tools for thermal resistance measurements of exterior envelopes in the field. The performance evaluation of both instruments involved the exterior walls of six thermal-mass test houses, and a comparative test of calibrated hot box measurements and the in-situ methods in a laboratory controlled environment. The exterior walls tested had thermal resistance values ranging from 3.6 to 22.8 $ft^2 \cdot h \cdot F$ (0.6 to 4.0 $m^2 \cdot K/W$) and wall mass varying from 4.2 to 83 $lb/ft^2$ (21 to 405 $kg/m^2$). The portable calorimeter can measure a sufficiently large wall area to provide a representative bulk performance of the wall with a minimum disturbance to the heat transmission measurements. Due to the dynamic response of an exterior wall to diurnal variations in heat flow caused by outdoor air temperature, a sufficiently long measurement period, especially for a massive insulated wall system, is required to obtain reliable thermal resistance data using the in-situ methods. Portable calorimeters and properly calibrated heat-flux transducers can produce wall thermal resistance values with an average deviation of less than 9% in comparison with values obtained in the laboratory using a calibrated hot box. The wall resistance values measured by a single calorimeter varied from 0.3% to 9% with an average of 3.8%, while the measurements taken with the heat-flux transducer varied from 0.3% to 7% with a mean of 4.3%. To determine the overall thermal resistance value for a framed wall, heat-flux transducers must be mounted on wall areas backed by both framing members and cavities between the framings. Corrections have to be made for the effect of framing members. Based on the data from the tests, the variation in the measured wall resistance values among the heat-flux transducers varied between 0.2% and 16% with a mean value of 6%.

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TABLE 1

Construction Details of Exterior Walls of Test Buildings

No. 1 Insulated Lightweight Wood Frame
5/8-in (16-mm) exterior plywood, nominal 2 x 4-in (50 x 100-mm) wood studs placed 16 in (410-mm) on center with R-11 h·ft$^2$·F/Btu (R-1.94 m$^2$·K/W) blanket glass insulation installed between the studs, a 0.002-in (0.05-mm) polyethylene film and 1/2-in (13-mm) gypsum board.

No. 2 Uninsulated Lightweight Wood Frame
Same as No. 1, except no insulation in the stud cavities.

No. 3 Insulated Masonry (Outside Mass)
4-in (100-mm) face brick, 4-in (100-mm) two-core hollow concrete block at 105 lb/ft$^3$ (1680 kg/m$^3$), a 1/4-in (6.4-mm) air space, 2-in (51-mm) thick extruded polystyrene foam insulation placed between 1.5 x 2-in (38 x 51-mm) wood furring strips placed 24 in (610-mm) on center, a 0.002-in (0.05-mm) polyethylene film, and 1/2-in (13-mm) gypsum board.

No. 4 Uninsulated Masonry
8-in (200-mm) two-core hollow concrete block of 105 lb/ft$^3$ (1680 kg/m$^3$), a 3/4-in (20-mm) air space created by 2 x 1-in (50 x 25-mm) wood furring strips placed 16-in (410-mm) on center, a 0.002-in (0.05-mm) polyethylene film, and 1/2-in (13-mm) gypsum board.

No. 5 Log
7-in (180-mm) square lodge-pole-pine logs (butt-jointed with a compressible foam backer-rod and a caulking compound applied to interior and exterior joints).

No. 6 Insulated Masonry (Inside Mass)
4-in (100-mm) face brick, 3.5-in (89-mm) perlite loose-fill insulation in cavity, 8-in (200-mm) two-core hollow concrete block at 105 lb/ft$^3$ (1680 kg/m$^3$), and a 1/2-in (13-mm) plaster.

TABLE 2

Comparison of Wall Thermal Resistances Measured with Portable Calorimeters (PC) and Heat-Flux Transducers (HFT) to Corresponding Predicted Values and Measured Results from Guarded Hot Box

| | | Thermal Resistance (ft$^2$·h·F/Btu) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Measured Value | | | | | | |
| | | PC | | HFT | | | | |
| Wall Construction | Mass (lb/ft$^2$) | Large | Small | Between Framings | At Framing | Avg. | Predicted Value | Guarded Hot Box |
| Insulated wood frame | 4.4 | 11.43 | 10.14 | 14.27 | 10.41 | 13.79 | 11.91 | 12.22 |
| Uninsulated wood frame | 4.2 | 3.55 | 3.34 | 3.43 | 4.01 | 3.48 | 3.14 | 3.60 |
| Insulated masonry with outside mass | 64.0 | 11.01 | 13.31 | 15.15 | 9.39 | 14.59 | 13.77 | 13.69 |
| Uninsulated masonry | 42.0 | 4.41 | 4.18 | 4.95 | 5.08 | 4.97 | 3.89 | 4.63 |
| Log | 17.0 | 10.08 | 9.83 | 10.27 | - | 10.27 | 9.60 | 10.33 |
| Insulated masonry with inside mass | 83.0 | 10.20 | 9.53 | 14.32 | - | 14.32 | 12.65 | 12.42 |

Note: 1 ft$^2$·h·F/Btu = 0.176 m$^2$·K/W
1 lb/ft$^2$ = 4.882 kg/m$^2$

TABLE 3

The Measured Average Air Temperatures Across Wall Structures During Field and Laboratory Wall Thermal Resistance Measurements

| | Air Temperature (F) | | | |
|---|---|---|---|---|
| | In-Situ Measurements | | Guarded Hot Box | |
| Wall Construction | Indoor | Outdoor | Warm Side | Cold Side |
| Insulated wood frame | 69.2 | 45.2 | 74.9 | 32.0 |
| Uninsulated wood frame | 70.3 | 43.5 | 77.9 | 33.6 |
| Insulated masonry with outside mass | 69.9 | 54.2 | 73.3 | 24.2 |
| Uninsulated masonry | 74.1 | 27.3 | 83.2 | 31.4 |
| Log | 68.4 | 26.8 | 83.6 | 37.4 |
| Insulated masonry with inside mass | 68.2 | 26.3 | 76.5 | 23.9 |

Note: $^{o}C = 5/9\ (F - 32)$

TABLE 4

Comparison of Measured and Predicted Thermal Resistances of Well-Insulated Double-Stud Wall Under Steady-State and Dynamic Climatic Conditions

| | | | Thermal Resistance ($ft^2 \cdot h \cdot F/Btu$) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Measured Value | | | | | |
| | Air Temp. (F) | | | Calorimeter | | Flux Transducer | | | |
| Climatic Condition | Warm Side | Cold Side | Predicted Value | Large | Small | Between Studs | At Stud | Avg. | Calibrated Hot Box |
| Steady-State | 69.5 | 34.4 | 23.75 | 25.25 | 24.07 | 26.37 | 20.98 | 25.16 | 22.84 |
| Dynamic | 70.0 | 42.1* | - | 23.86 | 23.56 | 25.30 | 20.47 | 24.23 | - |

Note: $^{o}C = 5/9\ (F - 32)$
$1\ ft^2 \cdot h \cdot F/Btu = 0.176\ m^2 \cdot K/W$
* The average value of periodically varying air temperatures ranging from 26.5 to 52.2F.

TABLE 5

The Variability of Wall Thermal Resistance Values Measured by a Single Portable Calorimeter or Heat-Flux Transducer

| Wall Assembly | Portable Calorimeter: Large Duration (day) | Portable Calorimeter: Large C.V.* (%) | Portable Calorimeter: Small Duration (day) | Portable Calorimeter: Small C.V.* (%) | Heat-Flux Transducer: Test Duration (day) | Heat-Flux Transducer: C.V.* (%) Between Framings | Heat-Flux Transducer: C.V.* (%) At Framing |
|---|---|---|---|---|---|---|---|
| Insulated wood frame | 11 | 4.14 | 8 | 7.34 | 8 | 7.23 (7.2-7.3) | 7.01 (6.6-7.4) |
| Uninsulated wood frame | 9 | 3.05 | 7 | 3.24 | 7 | 2.20 (2.2-2.4) | 2.96 (2.5-3.4) |
| Insulated masonry with outside mass | 10 | 9.09 | 3 | 20.6 | 3 | 15.2 (13.4-18.2) | 15.3 (14.9-15.7) |
| Uninsulated masonry | 12 | 3.13 | 5 | 6.86 | 5 | 7.02 (6.6-7.5) | 7.92 |
| Log | 10 | 7.12 | 10 | 7.77 | 10 | 6.42 (6.3-6.5) | - |
| Insulated masonry with inside mass | 4 | 1.80 | 3 | 10.9 | 4 | 4.94 (4.1-5.8) | - |
| Double-stud wood frame: | | | | | | | |
| Steady-state condition | 2 | 0.34 | 2 | 3.41 | 2 | 0.27 (0.03-0.4) | 0.74 (0.1-1.4) |
| Dynamic case | 3 | 2.03 | 3 | 1.29 | 3 | 1.85 (0.7-3.2) | 2.83 (1.9-3.8) |

*Coefficient of variation = (Standard Deviation/Mean) x 100.

TABLE 6

The Variations in the Measured Thermal Resistance Values Among Heat-Flux Transducers

| Wall Assembly | Between Wall Framings: No. of Sensors | Between Wall Framings: Range of R-Values ($ft^2 \cdot h \cdot {}^\circ F/Btu$) | Between Wall Framings: Coefficient of Variation (%) | At Wall Framing: No. of Sensors | At Wall Framing: Range of R-Values ($ft^2 \cdot h \cdot {}^\circ F/Btu$) | At Wall Framing: Coefficient of Variation (%) |
|---|---|---|---|---|---|---|
| Insulated wood frame | 2 | 13.8 - 14.7 | 4.56 | 2 | 10.2 - 10.6 | 3.06 |
| Uninsulated wood frame | 2 | 3.42 - 3.43 | 0.21 | 2 | 3.9 - 4.1 | 3.36 |
| Insulated masonry with outside mass | 3 | 13.5 - 16.2 | 9.63 | 2 | 9.1 - 9.7 | 4.52 |
| Uninsulated masonry | 2 | 4.7 - 5.2 | 6.00 | 1 | 5.1 | - |
| Log | 3 | 9.8 - 10.8 | 5.06 | | | |
| Insulated masonry with inside mass | 2 | 12.7 - 16.0 | 16.2 | | | |
| Double-stud wood frame: Steady-state condition | 3 | 24.8 - 29.4 | 10.1 | 2 | 20.6 - 21.3 | 2.29 |
| Dynamic case | 3 | 23.6 - 28.1 | 9.79 | 2 | 20.1 - 20.9 | 2.63 |

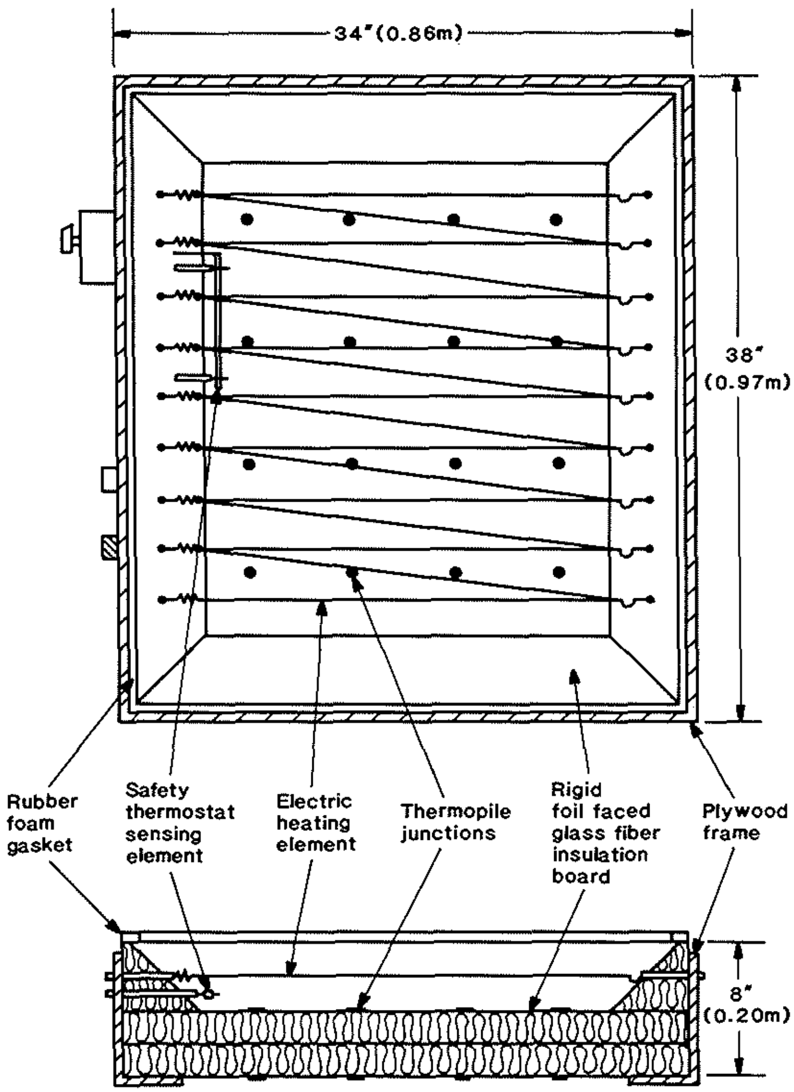


*Figure 1. Construction details of small portable calorimeter*

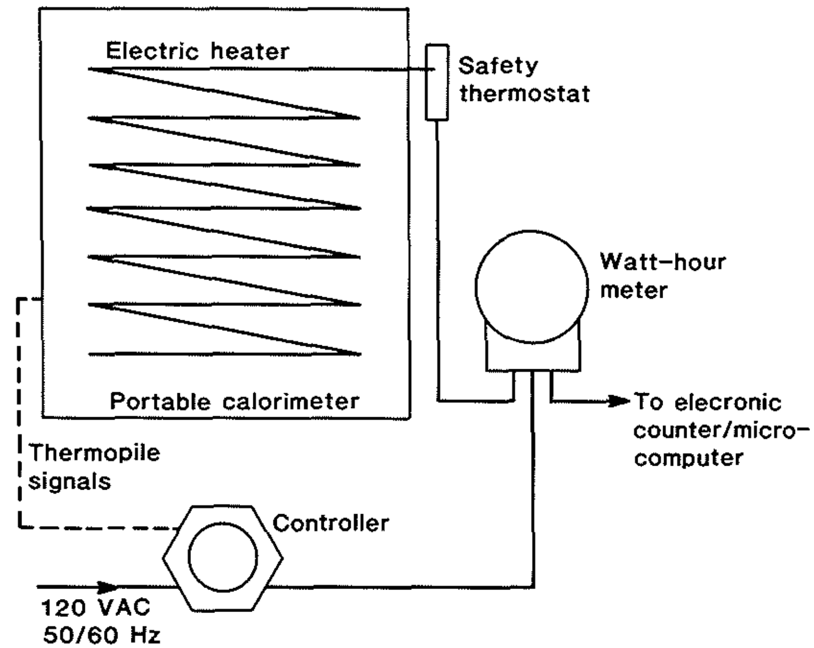


*Figure 2. Schematic of measurement/control system for portable calorimeter*

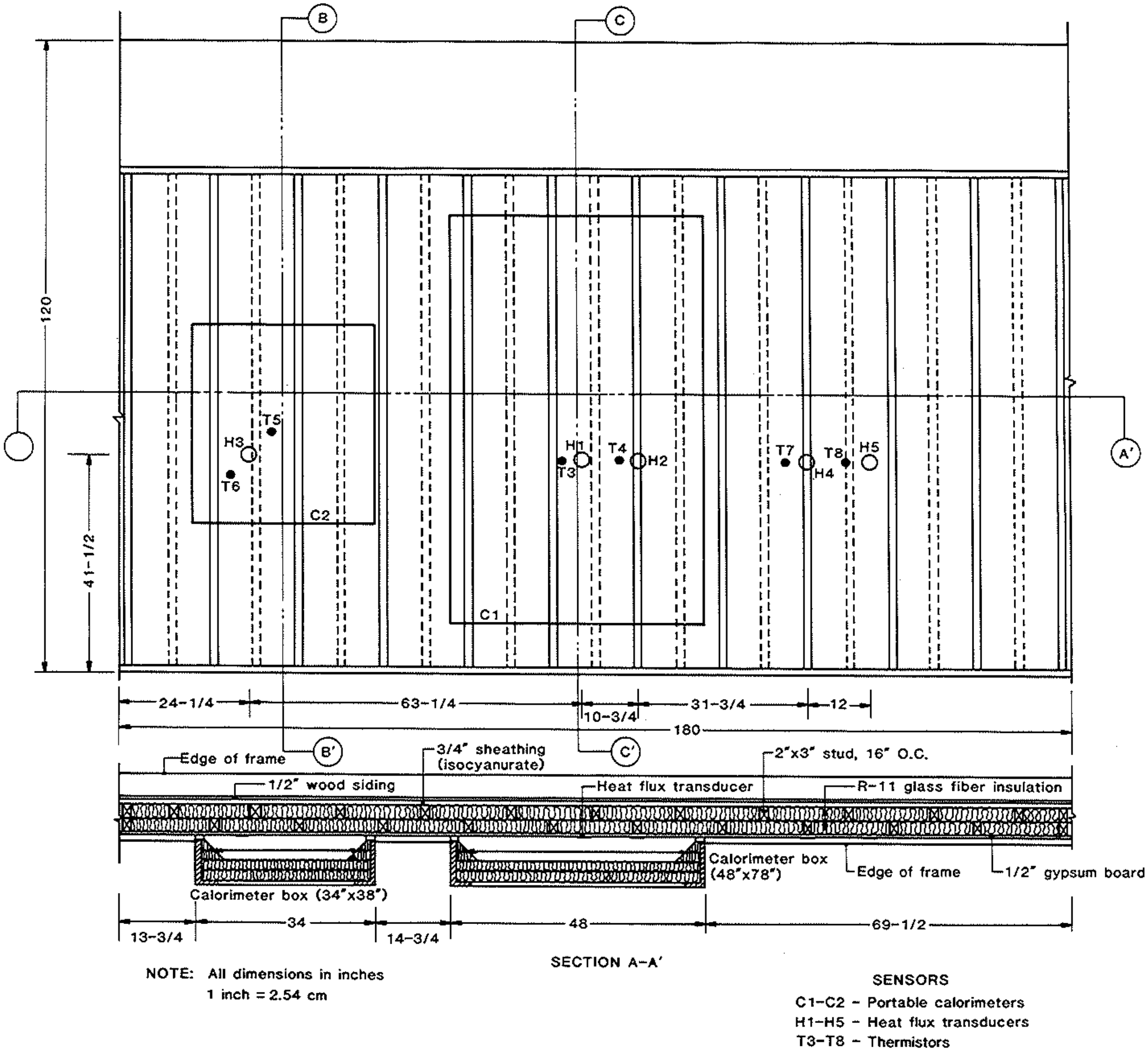


*Figure 3. Construction details and sensor locations on well-insulated double-stud test walls*

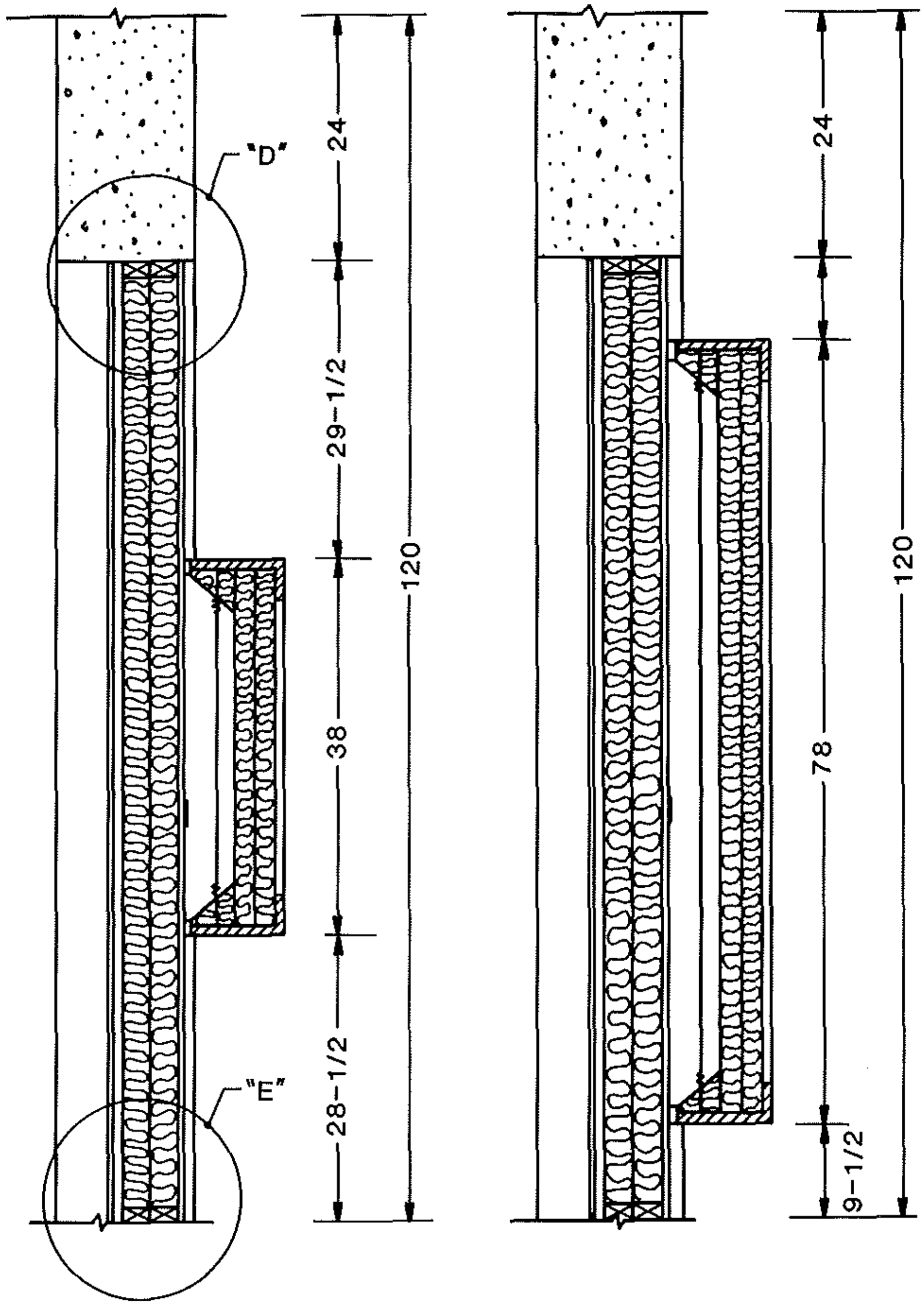


*Figure 3 continued*

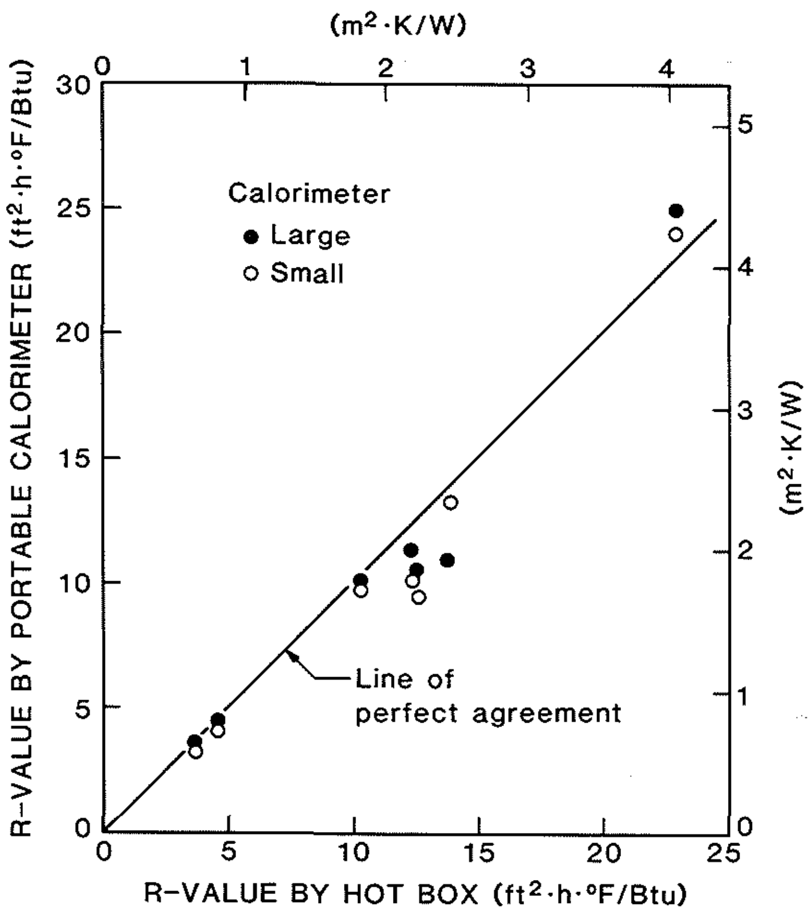


Figure 4. *Comparison between the wall thermal resistance values measured with portable calorimeter and values obtained with calibrated hot box*

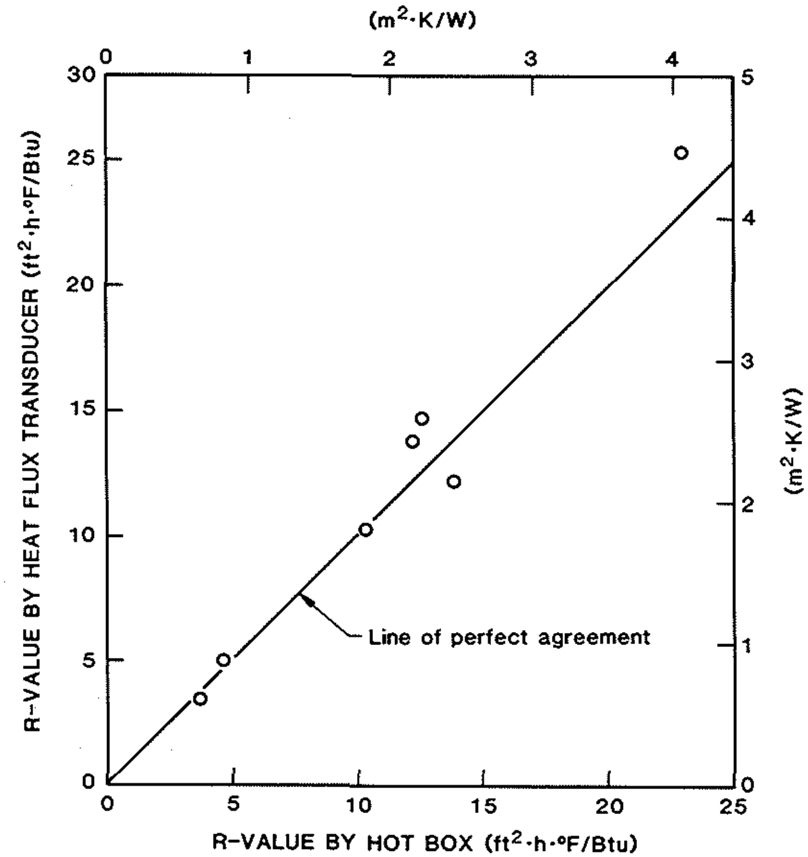


Figure 5. *Comparison of wall resistance values measured by heat-flux transducers and calibrated hot box data*