LABORATORY TESTS OF THERMAL PERFORMANCE OF EXTERIOR WALLS

by

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ABSTRACT

The Construction Technology Laboratories' calibrated hot box test facility to evaluate steady-state and dynamic thermal performance of wall assemblies is described. This facility consists of two highly insulated environmental chambers that enclose the test wall. Nominal overall dimensions of the test wall are 103x103 in.(2.62x2.62 m). Wall thicknesses can be varied. The facility was designed to accommodate test walls with thermal resistance values ranging from 1.5 to 20 $hr \cdot ft^2 \cdot F/Btu$ (0.26 to 3.52 $K \cdot m^2/W$).

One of the insulated chambers simulates an indoor environment and is maintained at a constant room temperature between 65 and 80 F (18 and 27 C). The other chamber simulates an outdoor environment where temperatures are held constant or cycled between -20 and 120 F (-29 and 49 C). Instrumentation is provided to monitor air and surface temperatures on each side of the test wall, and energy required to maintain constant indoor temperature.

Examples of steady-state and dynamic test procedures and results are given. Steady-state tests are used to obtain heat transmission coefficients such as thermal conductance (C) and resistance (R). Dynamic tests provide quantitative data on thermal response that include effects of thermal storage capacity as well as thermal resistance of wall assemblies.

INTRODUCTION

This paper describes development of laboratory equipment and test procedures for evaluation of thermal performance of building envelope systems under steady-state and dynamic conditions. Such tests, used in conjunction with analytical and field investigations, provide a quantitative basis for improved design criteria for building envelopes.[1]

Background

Currently, the most common laboratory method for obtaining steady-state heat transmission coefficients of building assemblies is the guarded hot box test.[2,3,4,5] This method has been developed over a number of years,[6,7,8,9] and is included as an ASTM Standard.[10]

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Using a guarded hot box, the test specimen is placed between a cold box and guard box as illustrated in Fig. 1. A metering box inside the guard box defines the test area. Once the test specimen is placed in the apparatus, a predetermined temperature differential is maintained between the cold box and guard box until constant heat flow conditions are established. The metering box and the guard box are held at the same temperature. Thus, heat input to the metering box is a measure of heat flow through the test specimen. After equilibrium conditions are established, measured heat input, air and surface temperatures, and test area are used to calculate steady-state heat transmission coefficients.

Although the guarded hot box is widely used as an established ASTM standard, it has limitations that are particularly apparent when large composite assemblies are to be evaluated.[1,11,12,13] For large test assemblies, size of the guarded hot box apparatus becomes cumbersome because of requirements for a guard box around the metering box. However, to evaluate assemblies with internal air cavities, or with doors or windows, it is necessary to accommodate full-size specimens. The metering box must cover a large portion of the test assembly for results to be representative.

To overcome limitations of the guarded hot box, the calibrated hot box method has been developed.[12,13,14] The calibrated hot box apparatus has no guard box. In effect, the laboratory space in which the apparatus is located serves as the guard. Heat transfer between the metering box, which encloses the entire test specimen area, and the laboratory environment is analyzed so that results can be corrected for heat losses or gains. The apparatus is calibrated using a "standard" homogeneous specimen of known thermal properties.

A standard test method for the calibrated hot box is currently being prepared under the jurisdiction of ASTM Committee C-16 on Thermal and Cryogenic Insulating Materials.[15] The calibrated hot box is specially suited for testing large nonhomogeneous building assemblies.*

Much of the work on test methods for thermal performance of building envelopes has concentrated on determination of steady-state heat transmission coefficients such as conductance (C) and resistance (R). However, building envelopes do not operate in a steady-state environment. To be realistic, evaluation of building thermal performance must consider heat storage capacity of the envelope as well as resistance to heat flow.[1]

Although computer simulations provide a means of estimating energy requirements under dynamic conditions, experimental data are needed to verify analytical models used in these simulations. Laboratory tests also provide a direct means of investigating dynamic response of assemblies under controlled conditions.

Dynamic tests have been conducted using a modified guarded hot box apparatus[17] and on a complete assembly housed in a large environmental chamber.[18] As another approach, a calibrated hot box for dynamic tests has been developed by the Construction Technology Laboratories (CTL), a Division of the Portland Cement Association.

Objective and Scope

The objective of this paper is to describe a calibrated hot box facility for evaluating thermal performance of wall assemblies under steady-state and dynamic temperature conditions. Details of the test apparatus and test procedures are discussed. Examples of steady-state and dynamic test results are given.

*Van Dusen and Finck used a variation of the calibrated hot box method to evaluate masonry and wood frame wall assemblies under steady-state conditions.[16] They faced the warm side of the test specimen with a "conductimeter" to obtain a measure of heat flow.

TEST FACILITY

A schematic and photograph of CTL's calibrated hot box facility are shown in Figs. 2 and 3.

General Description

The facility consists of an outdoor chamber, an insulating frame for the test specimen, and an indoor chamber. During tests, chambers are clamped tightly against the insulating frame surrounding the test specimen. Nominal overall dimensions of the test specimen are 103x103 in. (2.62x2.62 m). The facility was designed to accommodate specimens with thermal resistance values ranging from 1.5 to 20 $hr \cdot ft^2 \cdot F/Btu$ (0.26 to 3.52 $K \cdot m^2/W$).

The outdoor chamber can be held at constant temperature or cycled between -20 and 120 F (-29 and 49 C). Temperature cycles can be programmed to obtain the desired time-temperature relationship. The indoor chamber, which simulates an indoor environment, can be maintained at constant room temperature between 65 and 80 F (18 and 27 C).

Construction of Chambers and Test Specimen Frame

Outdoor and indoor chambers have nominal internal dimensions of 103x103x 41 in. (2.62x2.62x1.04 m). Chamber roof, floor, and walls consist of a 12-in. (305 mm) thick core constructed from 4x9x0.5-ft (1.22x2.74x0.15 m) urethane sheets. Sheets were glued together over all contact surfaces as shown in Fig. 4, which is a photograph of the chambers during construction.

The interior shell of the chambers consists of 3/8-in. (10-mm) plywood glued to the urethane. The exterior shell consists of 1/2-in. (13 mm) plywood with a white fiberglass reinforced resin coating. All joints between exterior plywood sheets are covered with extruded vinyl panel molding. Thermal resistance of chamber walls is approximately 70 $hr \cdot ft^2 \cdot F/Btu$ (12.3 $K \cdot m^2/W$).

Two insulating frames were constructed to accommodate test specimens. Each frame is made up of four pieces that clamp together around the specimen. These pieces have a cross section that consists of a 12x12-in. (305 mm) urethane core. Interior faces in contact with the test specimen are 3/8-in. (10 mm) plywood and exterior faces are 1/2-in. (13 mm) coated plywood.

As shown in Fig. 3, the outdoor chamber is mounted on fixed piers. The test specimen frame and indoor chamber are mounted on 8-in. (0.2 m) diameter casters. When changing specimens, the indoor chamber is rolled back and the specimen is moved into position. Chambers are then drawn together and locked using toggle clamps.

A gasket was provided to minimize heat losses through the interface where chambers contact the insulating frame around the test specimen. First, 1/8-in. (3 mm) tempered hardboard was glued to facing edges of urethane in the chamber walls and in the insulating frame. Hardboard on the chambers was faced with 1-in. (25 mm) thick, 10-in. (254 mm) wide polyester urethane foam. Two plywood strips, 1/2-in. (13 mm) square, were attached to the hardboard on each piece of the insulating frame. Thus, when the chambers are clamped to the frame, a seal is provided as the plywood strips press into the urethane foam. This gasket can be replaced if damaged or worn under repetitive opening and closing of the chambers.

Outdoor Chamber Conditioning Equipment

Outdoor temperatures can be maintained constant or cycled over a range from -20 to 120 F (-29 to 49 C). Location of the conditioning plenum is shown schematically in Fig. 2.

The conditioning system consists of a direct expansion 2-hp R-502 refrigeration system, electrical resistance heaters (6.6 kW high heat and 1.1 kW low heat), a 1,000 cfm (0.47 m^3/s) fan to mix air in the conditioning plenum, and a 280 cfm (0.13 m^3/s) fan to circulate air over the test specimen.

Temperatures are maintained by a proportional controller. The sensing thermocouple for the controller is located in the air supply duct. During cooling, control is obtained by pulsing refrigerant through a solenoid valve. During heating, control is obtained by pulsing power to the heaters. Under steady-state conditions, average air temperatures can be maintained within $\pm$0.1 F ($\pm$0.06 C).

Air flow is upward and parallel to the test specimen. A 1/8-in. (3 mm) thick tempered hardboard baffle, located 6.5 in. (165 mm) from the open end of the chamber, defines the air stream. Linear diffusers are used at the bottom of the baffle for air supply and at the top for air return. Air deflectors were positioned to obtain reasonably uniform air velocity along the horizontal length of the specimen.

Maximum air velocity parallel to the specimen is 60 ft/min. (0.3 m/s). A portable air meter is used to measure velocity in the air stream.

For dynamic tests, temperature cycles are programmed using an electro-mechanical curve follower. This device has a photocell detector that tracks the selected time-temperature relationship drawn on a special program disk. The system provides a maximum response rate of approximately 50 to 100 F (28 to 56 C) per hour in the air supply temperature. The rate depends on absolute set point temperatures.

<u>Indoor Chamber Conditioning Equipment</u>

Indoor temperatures can be maintained constant within a range from 65 to 80 F (18 to 27 C). Location of the conditioning plenum is shown schematically in Fig. 2.

The conditioning system consists of a 1/2-hp R-12 refrigeration system, electrical resistance heaters (3.0 kW high heat and 1.5 kW low heat), a nominal 280 cfm (0.13 m^3/s) fan to circulate air over the test specimen, and measurement and control instruments.

Indoor chamber cooling equipment operates continuously and is designed to remove heat at a constant rate. Control of indoor chamber temperature is obtained by varying the amount of input heat required to balance the amount of heat removed by the refrigeration system, the amount of heat that flows through the test specimen, and the amount of heat lost to laboratory space.

The need for cooling in the indoor chamber results from requirements for dynamic tests. In cases where outdoor temperatures exceed indoor temperature, cooling capacity is required to maintain indoor temperature control. This design feature differentiates steady-state and dynamic test facilities. It also necessitates somewhat different operational procedures as will be explained later.

Temperature in the indoor chamber is controlled by a process controller. The sensor for the controller is a platinum resistance element which is located in the air supply duct. Variations in amount of heat called for by the controller are made through an SCR power controller. Under steady-state conditions, average air temperatures can be maintained within $\pm$0.05 F ($\pm$0.03 C).

Air flow is downward and parallel to the test specimen. A 1/8-in. (3 mm) thick tempered hardboard baffle, located 6.5 in. (165 mm) from the open end of the chamber, defines the air stream. Air distribution is handled in the same manner as for the outdoor chamber. Maximum air velocity parallel to the specimen is 60 ft/min. (0.3 m/s).

Instrumentation

Instrumentation is designed to monitor temperatures inside and outside of the chambers, air and surface temperatures on both sides of test specimens, laboratory air temperature, and heating energy input to the indoor chamber. Supplementary measurements monitor cooling water, cooling coil, and data acquisition reference temperatures as well as heat flux at selected locations on specimen and chamber surfaces.

Thermocouples corresponding to ASTM Designation: E230/Type T are used to measure temperatures. These are calibrated against reference platinum resistance temperature sensors. There are 16 thermocouples on each face of the test wall and 16 in the air space on each side of the test wall. Generally, thermocouples are uniformly distributed on a 20-in. (508 mm) square grid over the test area. Thermocouples in air are located approximately 3 in. (76 mm) from the face of the test wall. Additional thermocouples are available for surface measurements if required. Locations of these thermocouples are selected based on characteristics of the test specimen. Heat flux transducers are also used to evaluate heat flow through the test specimen.

Inside and outside surface temperatures are measured on each wall of the indoor chamber. These provide data for evaluating heat transfer between the chamber and the laboratory. Temperature data are supplemented with heat flux transducer measurements.

A watt/watt-hour transducer is used to measure cumulative electrical energy input to the indoor chamber which includes heater and fan power. The device provides an analog signal directly proportional to instantaneous watts and a digital signal directly proportional to watt-hours. The transducer is within a specified accuracy of $\pm 0.1\%$ of full scale output signal at an ambient temperature of 77 F (25 C).

A digital humidity and temperature measurement system is used to measure relative humidity and temperature in air streams on each side of the test specimen. Probes are located approximately at the midpoint of the specimen. Relative humidity is determined from a thin film moisture sensor to within $\pm 4\%$ (typical). The thermilinear temperature sensor is accurate to ± 0.7 F (± 0.35 C).

Data Acquisition and Reduction

Because of the frequency of readings, duration of testing, and number of data channels to be read, an automatic data acquisition system is required for operation of the facility. Data acquisition and processing equipment are shown in Fig. 5.

All measurements are monitored with a programmable digital data acquisition system. Although current capacity of the data acquisition is 124 independent channels, it is expandable to 248 channels.

Data can be sampled at preselected time intervals. General practice for steady-state tests has been to scan thermocouple, relative humidity, and heat flux transducer channels every two minutes, and the watt/watt-hour transducer every two hours. The 60 readings for each channel are then averaged for the two-hour period corresponding to the cumulative watt-hour reading.

For dynamic tests, channels are read every two minutes and the watt/watt-hour transducer is read every hour. Average temperature, humidity, and heat flux data are obtained from the 30 readings per hour.

The data acquisition system is interfaced with a programmable calculator system. At the end of each one or two hour interval, data are stored on magnetic tape cartridges for later reduction and analysis. Hard copy of results is obtained using a thermal line printer and a graphic plotter.

STEADY-STATE TESTS

Steady-state tests are conducted by maintaining constant temperature levels to provide a predetermined temperature differential between chambers. Temperatures are maintained until equilibrium conditions are established to provide an essentially constant rate of heat flow through the test specimen. Results of energy and temperature measurements are used to calculate average thermal properties.

Test Procedures

To illustrate steady-state procedures, tests of a 1.38-in. (35.1 mm) thick homogeneous "standard" specimen will be described.

The specimen was fabricated from specially manufactured fiberglass boards that had a uniform density of 8.17 pcf (130.9 kg/m^3) and nominal dimensions of 4x10-ft (1.22x3.05 m).[19] Faces were sanded to obtain a uniform thickness of 1.38 in. (35.1 mm). Boards were glued together along tongue and groove vertical joints to form the test specimen. Each face of the specimen was covered with 0.004-in. (0.10 mm) thick polyethylene film to prevent air infiltration. Measured weight and dimensions of the specimen, including facing material, indicated an average unit weight of 8.86 pcf (141.9 kg/m^3).

Figure 6 shows a test of the standard specimen at a nominal air-to-air temperature differential of 64 F (35 C). Indoor chamber air, t_i, was maintained at approximately 72 F (22 C) while outdoor chamber air, t_o, was maintained at approximately 8 F (-13 C). Figure 6 also shows average temperatures on the inside surface, t_1, and outside surface, t_2, of the specimen. Temperature of the laboratory air is shown as t_ℓ.

Energy expended in maintaining the indoor chamber temperature is denoted as Q_t. This energy is a measure of heat flow through the test specimen. It also includes heating energy to balance indoor cooling capacity and heat transferred to laboratory space.

Data shown in Fig. 6 are from that part of the measurement period after steady-state temperature and heat flow conditions were obtained. Energy expended during each two-hour sampling interval varied by less than 0.1% over the eight-hour test duration. However, this is not a final measure of heat flow through the test wall because results must be corrected for heating energy extracted by indoor cooling and heat transfer to laboratory space.

Correction for indoor cooling and laboratory losses was accomplished by running steady-state tests with equal indoor and outdoor air temperatures of 72 F (22 C) to obtain a nominal temperature differential of 0 F (0 C). In addition, laboratory temperature was nominally the same as that for the test at the 64 F (35 C) differential. This provided a measure of the "base calibration" energy, Q_o, for the system.

Heat flow through the test specimen for a particular temperature differential was determined from net energy input, $Q = Q_t - Q_o$. Once net energy was established, average thermal conductance for the specimen was calculated according to the following equation:

$$C = \frac{Q \times 3.413}{A \times (t_1 - t_2)} \tag{1}$$

where:

Q = net energy input to indoor chamber, W·hr/hr
A = area of wall surface normal to heat flow, ft^2
t_1 = average temperature of inside wall surface, F
t_2 = average temperature of outside wall surface, F
3.413 = conversion factor from W·hr/hr to Btu/hr
C = average thermal conductance, Btu/hr·ft^2·F

Several aspects of this steady-state test procedure should be emphasized because they differ from those used for calibrated hot box facilities without dynamic capabilities.

Because of the need for indoor cooling, the "dynamic facility" is inherently more susceptible to error. Indoor cooling capacity must be large enough to accommodate dynamic cycles. However, as cooling capacity is increased, "base calibration" energy is increased. This results in the need to consider small differences of large numbers when evaluating net heat flow through the test specimen. Therefore, operational procedures for the "dynamic facility" are somewhat different from those of conventional facilities. It is important to accurately determine Q_o, the "base calibration" energy. CTL's procedure is to run base calibration tests immediately before and after each test at a selected temperature differential. In addition, refrigeration system performance characteristics are monitored to verify measured values of indoor cooling capacity. This is done by comparing measured Q_o with calculated values of cooling capacity and heat transfer to laboratory space.

With regard to heat losses to laboratory space, the "dynamic facility" has some advantages. The indoor chamber is always operated near room temperature. Thus, temperature differentials between the laboratory space and indoor chamber are minimized. For CTL's facility it is estimated that conduction heat losses through the walls, floor, and roof of the indoor chamber are approximately 3.3 Btu/hr (1.0 W) for a temperature differential of 1.0 F (0.6 C). In addition, losses are accounted for since the "base calibration" test is run at the same indoor and laboratory temperature as that for the steady-state test being evaluated.

Test Results

Results of steady-state tests on the "standard" specimen are summarized in Fig. 7 which shows measured average thermal resistance as a function of mean temperature of the specimen.

The solid curve was obtained from tests conducted in accordance with ASTM Designation: C518 "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter" and ASTM Designation: C177 "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Guarded Hot Plate." Tests were run at nominal mean temperatures of 0, 75, and 130 F (-18, 24, and 54 C). These tests were conducted in January 1977.[19]

To check stability of the sample, a test in accordance with ASTM Designation: C518 was repeated in August 1979.[20] This was run at a mean temperature of 75 F (24 C). As shown in Fig. 7, the result was within 1% of the original calibration.

Results from CTL's calibrated hot box are also shown in Fig. 7. These are within 3% at a mean temperature of 42 F (6 C) and 6% at a mean temperature of 99 F (37 C). Results obtained by other investigators indicate a correlation of approximately 5% between calibrated hot box and guarded hot plate data.[13]

Differences between calibrated hot box and heat flow meter/guarded hot plate data may result from several factors. Test procedures for the calibrated hot box do not directly account for flanking losses that can occur from heat transfer through the insulating frame around the specimen. Flanking losses may be reflected in the comparison of data in Fig. 7. In addition, heat flow meter/guarded hot plate tests were conducted on 16-in. (406 mm) square samples selected from the same production material used for the calibrated hot box specimen. Variations in measured thermal conductivity of 10 samples ranged from 1% at a mean temperature of 75 F (24 C) to 4% at a mean temperature of 0 F (-18 C). Therefore, even with the precautions taken to insure uniformity, the variation in results between test methods includes a component related to size and homogeneity of specimens.

A final factor that could have contributed to differences between test methods is that the calibrated hot box specimen had two vertical joints between fiberglass sheets. Joints were not present in the heat flow meter/ guarded hot plate samples. The joints were carefully prepared to insure a tight seal. However, it is likely that thermal properties are affected at such an interface because of geometric fit and influence of the glue layer.

Tests of the "standard" specimen provide initial information on accuracy of the calibrated hot box test method. Work is currently in progress on a detailed error analysis. Tests will also be conducted on "standard" specimens with higher R-values. This will provide quantitative data on accuracy over the entire range of R-values for walls to be tested.

DYNAMIC TESTS

Although properties determined from steady-state tests are commonly used for thermal design of building envelopes, dynamic tests provide more realistic conditions for evaluating thermal performance. Under dynamic testing, effects of wall mass and thermal storage capacity can be quantified.

Test Procedures

A dynamic test of the "standard" specimen is shown in Fig. 8 to illustrate procedures. An arbitrary diurnal sol-air temperature cycle was simulated in the air of the outdoor chamber, t_o, while the indoor chamber air, t_i, was maintained at room temperature. The sol-air cycle was essentially the same as that used by the National Bureau of Standards in their evaluation of dynamic thermal performance of an experimental masonry building.[18] It represents a large variation in temperature over a 24-hour cycle. Also shown in Fig. 8 are measured indoor, t_1, and outdoor, t_2, surface temperatures, and laboratory temperature, t_ℓ.

With temperatures established in indoor and outdoor chambers, energy required to maintain indoor chamber air temperature was monitored. This energy, corrected for the "base calibration" energy, Q_o, is a measure of heat flow through the test specimen. It is plotted as a function of time in Fig. 8.

The 24-hour dynamic cycle was repeated until conditions of equilibrium were obtained. Equilibrium conditions were evaluated in terms of consistency of the applied temperature cycle and measured energy response. Results in Fig. 8 are for two consecutive 24-hour cycles under equilibrium conditions. Depending on thermal resistance and thermal storage capacity of the wall under test, it may take from one to four days to establish equilibrium.

Test Results

Basic data obtained from dynamic tests are shown in Fig. 8. Outdoor and indoor air temperatures are controlled as a function of time. Response is defined in terms of surface temperatures and heat flow (energy) through the specimen which are measured as a function of time. Response of surface temperatures and heat flow to fluctuations in outdoor air temperature is indicative of thermal resistance and heat storage capacity of the test specimen. Each of these factors influence rate of heat flow.

To illustrate how differences in thermal properties affect response, as observed in dynamic tests, results from tests of a hollow concrete block specimen are shown in Fig. 9. These results are presented for comparison with Fig. 8. The hollow block specimen had perlite loose full insulation in the cores. It was tested under the same nominal diurnal temperature cycle as used for the "standard" specimen.[21] Weight of the block wall was 40.9 psf (200 kg/m^2).

Comparison of results in Figs. 8 and 9 indicates measured differences in response characteristics between the "standard" specimen, which had an average thermal resistance of 5.6 hr·ft^2·F/Btu (0.99 K·m^2/W), and the insulated hollow block specimen, which had an average thermal resistance of 3.7 hr·ft^2·F/Btu (0.65 K·m^2/W).

Outside surface temperatures, t_2, for the "standard" specimen responded rapidly to changes in outdoor air temperature, t_o. Changes in outdoor air temperature were also quickly reflected in changes in indoor surface temperatures, t_1, and in corresponding changes in measured energy, Q. Essentially, thermal lag was not discernable within the one-hour sampling interval used in the test. Rapid response of the homogeneous fiberglass specimen was consistent with its estimated characteristic time constant of 0.2 hr, calculated in accordance with Ref. 22 as shown in Table 1.

A similar estimate for the hollow block wall indicates a time constant of 3.8 hr. Results in Fig. 9 show that measured peaks in indoor surface temperatures and energy lagged peaks in outdoor air temperatures by approximately four hours for the hollow block specimen.

Although beyond the scope of this paper, data such as shown in Figs. 8 and 9 can be used to derive dynamic R-values. This would be done by analyzing temperature differentials between the inside and outside of the specimens and corresponding heat flow as a function of time.

Data obtained from dynamic tests are particularly valuable for complex assemblies that are not easily characterized by analytical means. Dynamic tests provide a direct means of determining response factors and should serve as a basis for improvement of analytical procedures.

In addition to providing quantitative information on response characteristics of building assemblies, dynamic tests provide a basis for evaluation and comparison of thermal efficiency of envelope components. This will permit optimization of use of insulation and thermal mass in development of energy efficient building envelopes.

TABLE 1 - ESTIMATE OF CHARACTERISTIC TIME CONSTANTS[1]

Specimen	Resistivity, r hr·ft·F/Btu (m·K/W)	Specific Heat, c Btu/lb·ft^3 (J/kg·K)	Density, ρ lb/ft^3 (kg/m^3)	Thickness, x ft (m)	$t_c = \frac{rc\rho x^2}{\pi^2}$ hr
"Standard" Fiberglass	50.0 (28.9)	0.26 (1088.6)	8.2 (131.4)	0.12 (0.04)	0.2
Insulated Hollow Block	5.6[2] (3.2)	0.24[3] (1004.8)	61.3[4] (981.9)	0.67 (0.20)	3.8

(1) Calculations based on nominal physical properties. See Reference 22 for discussion of method of calculation and significance of time constant.
(2) Based on average measured resistance.
(3) Weighted average for perlite and concrete.
(4) Based on measured weight and overall volume of specimen.

SUMMARY AND CONCLUSIONS

This paper has presented a detailed description of a calibrated hot box facility for evaluating thermal performance of walls under steady-state and dynamic conditions. Examples of steady-state and dynamic tests are given.

The calibrated hot box is a practical method for evaluating thermal performance of full-size assemblies. Steady-state tests are used to determine heat transmission coefficients such as conductance (C) and resistance (R). Dynamic tests are used to obtain data on thermal response under cyclic temperature conditions. This permits evaluation of effects of heat storage capacity as well as thermal resistance of the specimen.

Data from dynamic tests provide a means to verify analytical models for building envelopes used in computer simulations of thermal performance of buildings. They also provide a direct means of investigating and comparing thermal response of assemblies under controlled conditions. For complex assemblies, which are not amenable to analysis, dynamic tests are especially valuable as a quantitative basis for evaluation of heat transfer characteristics.

The primary difference between calibrated hot box facilities with and without capability for dynamic tests is that "dynamic facilities" require cooling capacity in the indoor or metering chamber. Therefore, for dynamic facilities, it is necessary to define heat extracted by the indoor chamber cooling system to evaluate heat flow through the test wall.

Future work at CTL will include quantitative analysis of system accuracy and calibration procedures for dynamic tests over a wide range of specimen R-values. This will provide a basis for evaluation and standardization of test procedures.

NOMENCLATURE

A	=	area of wall surface normal to heat flow, ft^2
Btu	=	British thermal unit
c	=	specific heat, Btu/lb·F
cfm	=	cubic feet per minute
C	=	thermal conductance, Btu/hr·ft^2·F
C	=	degrees Centigrade
F	=	degrees Fahrenheit
ft	=	feet
hp	=	horsepower
hr	=	hour
in.	=	inch
J	=	joule
kg	=	kilogram
K	=	degrees Kelvin
lb	=	pound
m	=	meter
mm	=	millimeter
pcf	=	pounds per cubic foot
psf	=	pounds per square foot
Q	=	$Q_t - Q_o$ = net energy input to indoor chamber
Q_o	=	energy input to indoor chamber with $t_1 - t_2 = 0$, W·hr/hr
Q_t	=	energy input to indoor chamber with $t_1 - t_2 = 0$, W·hr/hr
R	=	1/C = thermal resistance, hr·ft^2·F/Btu
r	=	1/K = resistivity, hr·ft·F/Btu
s	=	seconds
t_1	=	average temperature of inside of wall surface, F
t_2	=	average temperature of outside of wall surface, F
t_c	=	characteristic time constant, hr
t_o	=	average temperature of outdoor chamber air, F
t_i	=	average temperature of indoor chamber air, F
t_ℓ	=	average temperature of laboratory air, F
x	=	specimen thickness, ft
W	=	watts
π	=	density, pcf

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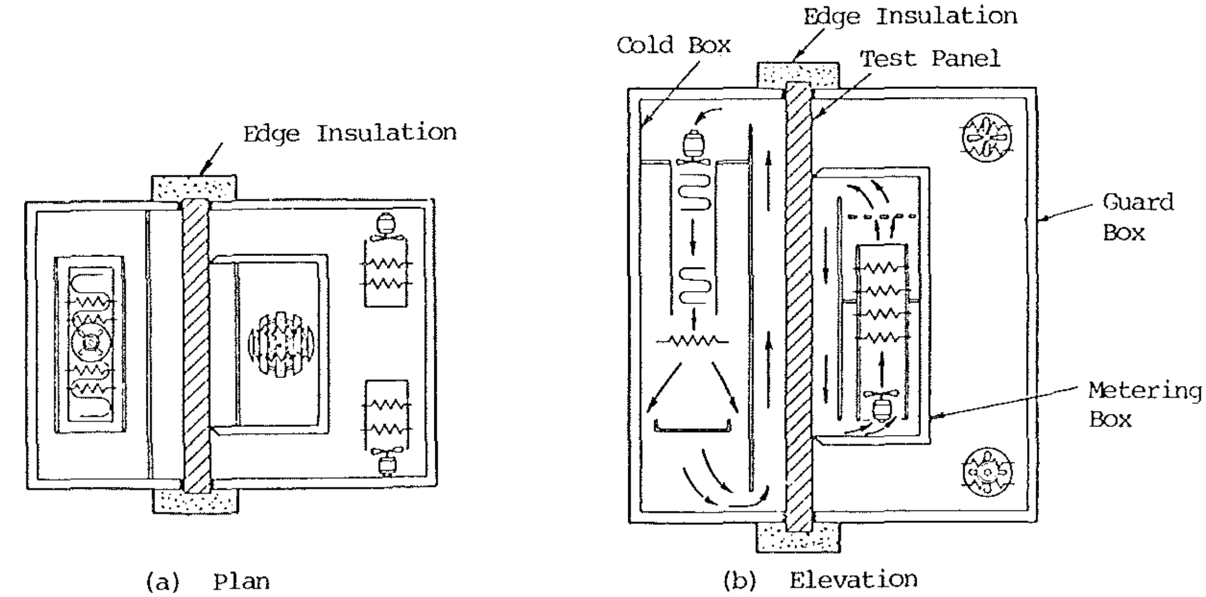

Fig. 1 Schematic of guarded hot box (after Ref. 10)

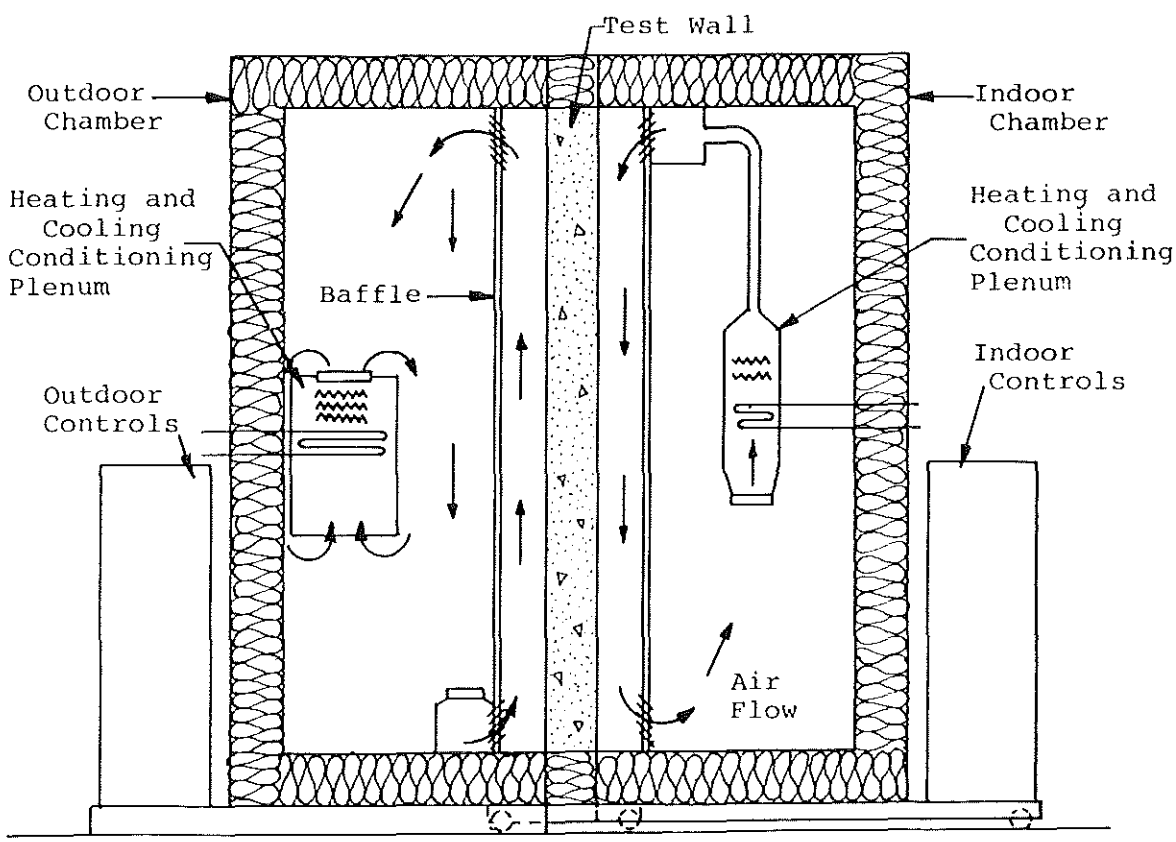

Fig. 2 Schematic of calibrated hot box

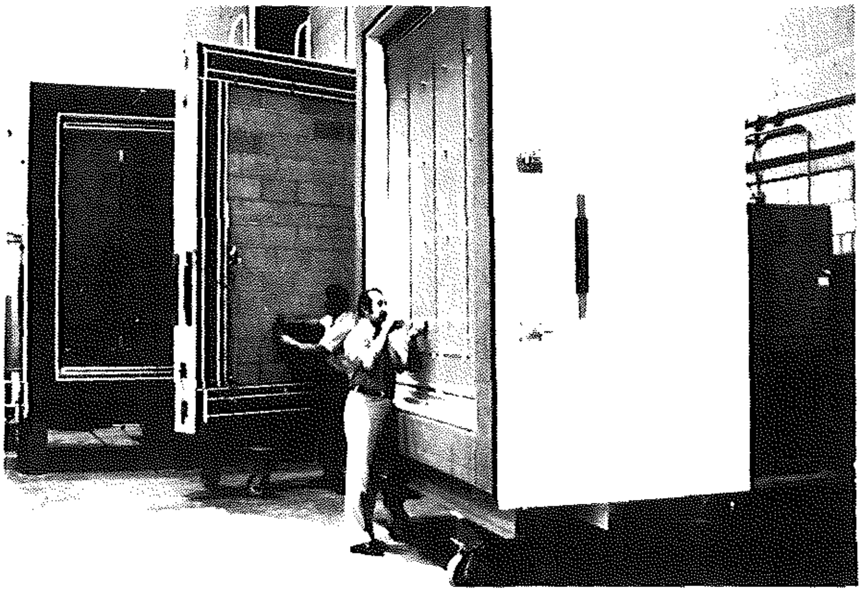

Fig. 3 Calibrated hot box test facility

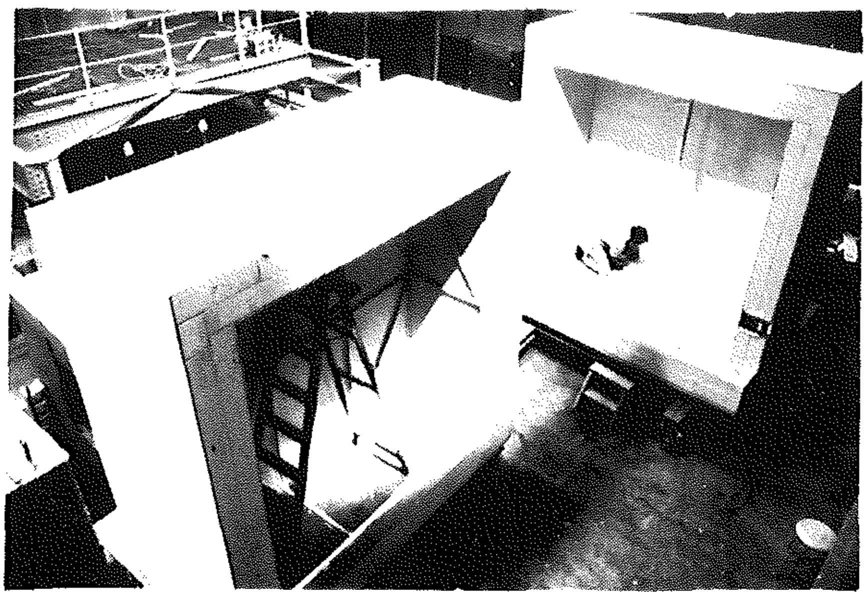

Fig. 4 Construction of chambers

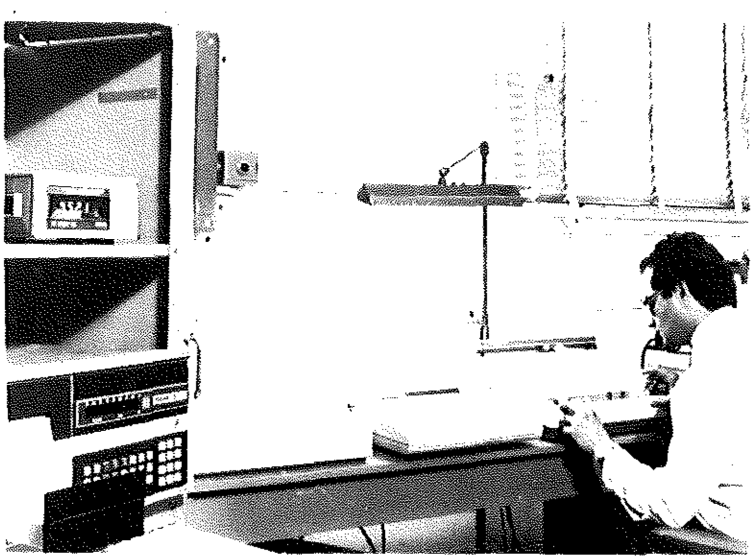

Fig. 5 Data acquisition and processing equipment

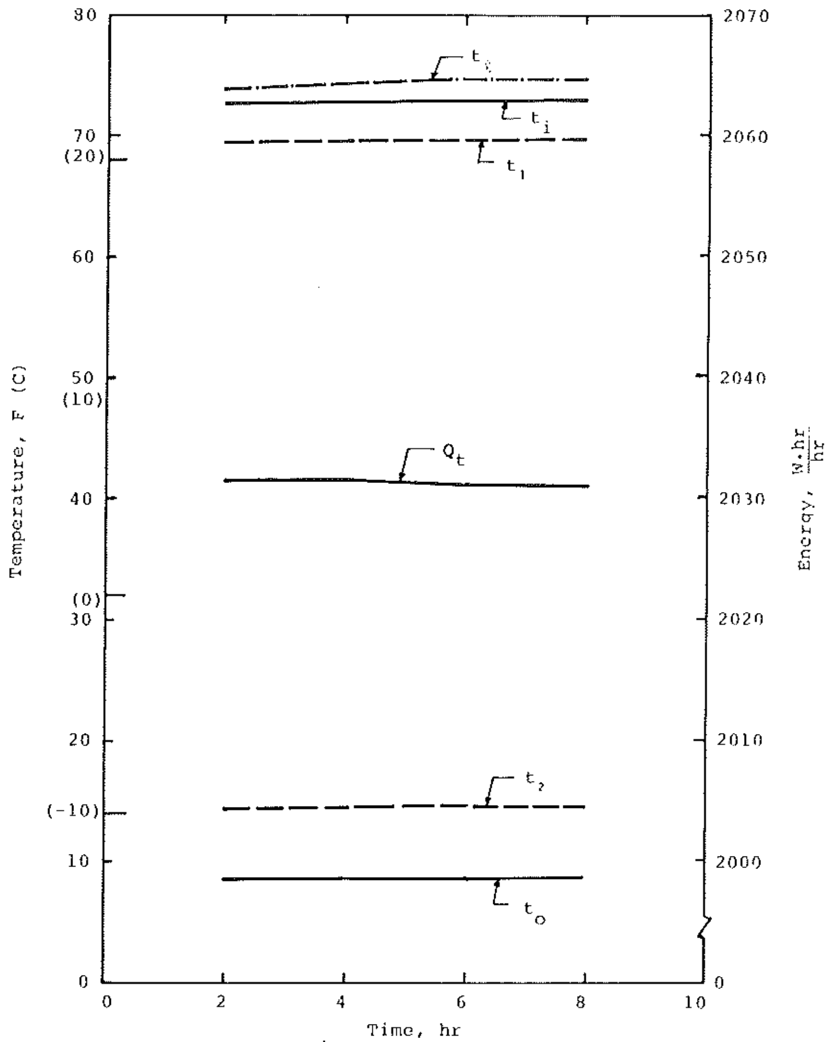

Fig. 6 Steady-state test

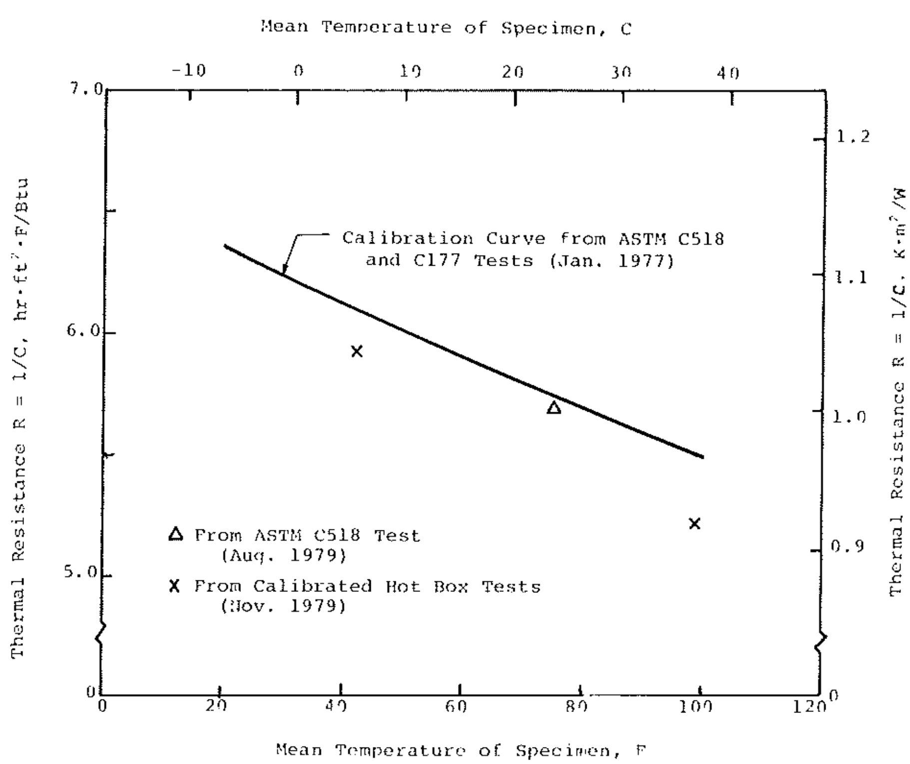

Fig. 7 Steady-state test results for "standard" specimen

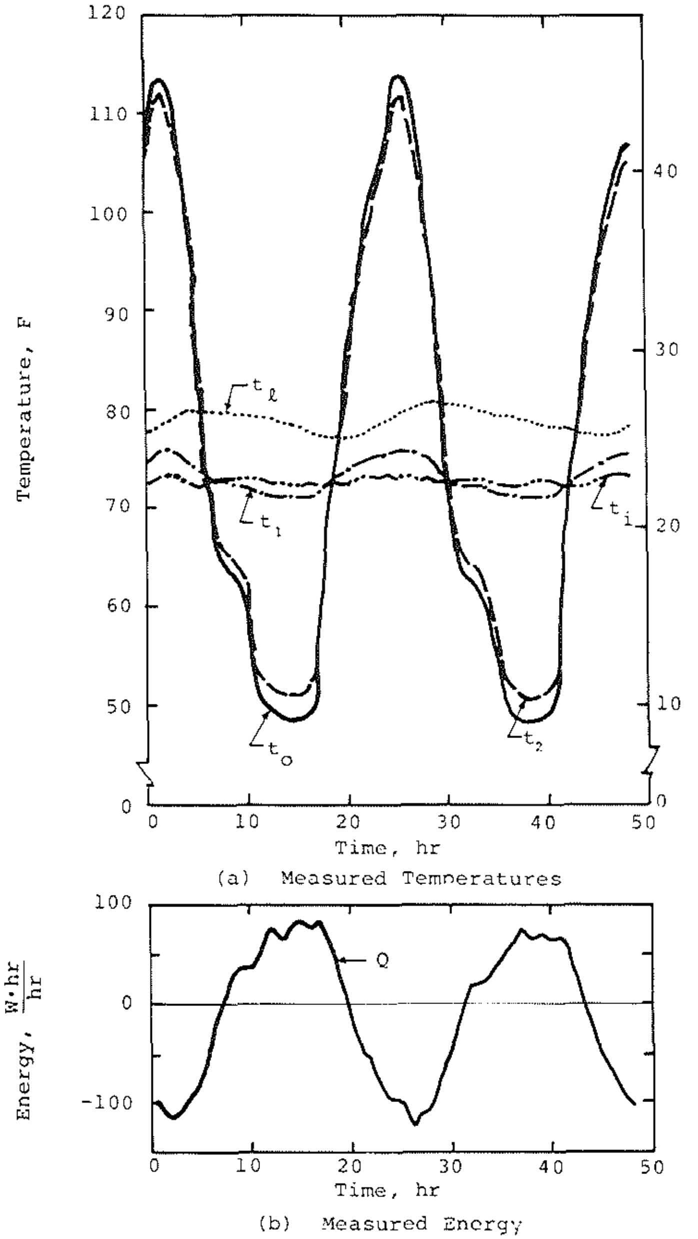

Fig. 8 Dynamic test of "standard" specimen

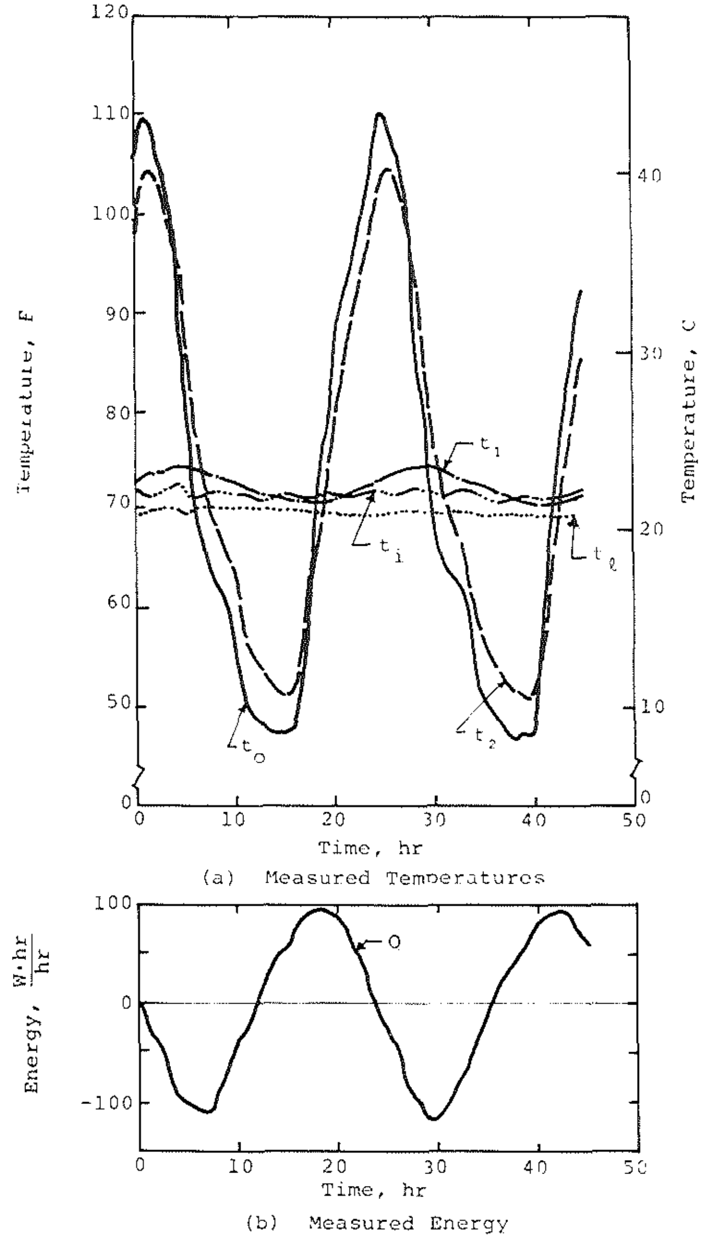

Fig. 9 Dynamic test of hollow block specimen with loose fill insulation