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Heat Transfer Characteristics of Walls With Similar Thermal Resistance Values

by S. C. Larson and M. G. VanGeem

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HEAT TRANSFER CHARACTERISTICS OF WALLS WITH SIMILAR THERMAL RESISTANCE VALUES

Final Report

by

S. C. Larson and M. G. Van Geem

Report Prepared by

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HEAT TRANSFER CHARACTERISTICS OF WALLS WITH SIMILAR THERMAL RESISTANCE VALUES

by

S. C. Larson and M. G. Van Geem*

ABSTRACT

Heat transfer characteristics of building elements must be known to evaluate energy losses through a building envelope. Laboratory tests of walls for dynamic outdoor temperature conditions provide data that can be used to determine thermal properties. Dynamic testing is particularly important for massive envelope components that store as well as transmit heat.

A normal weight concrete wall with board insulation on the outdoor surface was tested in the calibrated hot box facility at the Construction Technology Laboratories, a division of the Portland Cement Association. The wall consisted of 8 in. (200 mm) of normal weight concrete with 5/8-in. (16-mm) polyisocyanurate board insulation bonded to the outdoor surface.

Thermal performance of the normal weight concrete wall with insulation on the outdoor surface is compared to that of an 8-in. (200-mm) thick low density concrete wall and a 1-3/8-in. (35-mm) thick fiberglass board specimen. These two specimens were previously tested in the calibrated hot box. The three specimens have steady-state thermal resistances approximately equal to 7.0 hr•ft^2•°F/Btu (1.2 m^2•K/W).

Test specimens were subjected to steady-state, transient, and periodically varying temperature conditions. Steady-state results are used to define heat

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TABLE 1 - CALIBRATED HOT BOX TESTS PERFORMED ON 8-IN. (200-mm) NORMAL WEIGHT CONCRETE WALL

Wall Designation	Wall Description	Calibrated Hot Box Test Dates
C1	Normal weight concrete wall	October through December 1981
C6	Normal weight concrete wall with taped and embedded thermocouples for measuring surface temperatures	January through February 1984
C4	Normal weight concrete wall with polyisocyanurate insulation applied to outdoor surface	February through May 1984

TABLE 10 - THERMAL LAG FOR WALL C4

Test Cycle	Thermal Lag, hrs								Calc. Time Constant, hrs
	Measured								
	Calibrated Hot Box					Heat Flux Transducer			
	t_o vs t_i		q_{ss} vs q_w		Avg.	q_{ss} vs q_{hfm}		Avg.	
	@ Max.	@ Min.	@ Max.	@ Min.		@ Max.	@ Min.		
NBS	5	4	6	4	5	5	5	5	1.6
NBS+10	5.5	5.5	6	7	6	5.5	5.5	5.5	1.6
NBS-10	5.5	5	6	6	5.5	5	5	5	1.6

transmission coefficients, such as U and R-values. Data obtained during transient and periodic temperature variations are used to define dynamic thermal response of the wall. Dynamic response depends on heat storage capacity as well as heat transmission characteristics of the wall assembly.

The response of the three specimens to the same dynamic temperature cycle is compared. Dynamic thermal performance of the specimens differs because they have different heat storage capacities and relative placements of mass and insulation.

Laboratory test results provide a data base for evaluation of building envelope performance. Results also provide information on the benefits of thermal mass in the exterior envelopes of buildings.

HEAT TRANSFER CHARACTERISTICS OF WALLS WITH SIMILAR THERMAL RESISTANCE VALUES

by

Steven C. Larson and Martha G. Van Geem*

INTRODUCTION AND OBJECTIVES

Tests were conducted to evaluate thermal performance of a normal weight concrete wall with exterior insulation. The wall was tested under steady-state, dynamic, and transient temperature conditions in the calibrated hot box facility of Portland Cement Association's Construction Technology Laboratories (CTL). Steady-state tests were used to obtain average heat transmission coefficients including total thermal resistance (R_T) and thermal transmittance (U). Data obtained during transient and periodic temperature variations were used to define dynamic thermal response under selected temperature ranges. A simulated sol-air dynamic cycle was selected to permit comparison of results with those obtained in previous investigations.[1-7]**

Objectives of the experimental investigation were to evaluate thermal performance of the insulated normal weight concrete wall and compare it to thermal performance of previously tested speicmens with similar R-values. Specimens used for comparison are an 8-in. (200-mm) low density concrete wall and 1-3/8-in. (35-mm) fiberglass insulation board. Each specimen has a steady-state R-value approximately equal to 7.0 hr•ft^2•°F/Btu (1.2 m^2•K/W).

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**Superscript numbers in parentheses refer to references listed at the end of this report.

The three specimens compared in this investigation have different amounts of mass and insulation. The fiberglass board specimen consists of an insulating material with a relatively low mass. The insulated normal weight concrete wall has a large thermal mass isolated from the outdoor environment by board insulation. The low density concrete wall consists of one material that combines mass and insulating characteristics.

The report emphasizes comparison of the dynamic thermal performance of the three walls. Dynamic performance is dependent on heat transmission characteristics as well as heat storage capacity of the wall assembly.

Heat storage capacity of a homogeneous wall is given by the product of unit weight, specific heat, and thickness of the wall. Differences in heat storage capacities of wall assemblies are predominantly due to differences in mass, which is equal to the product of unit weight and thickness.

This report summarizes test results for the insulated concrete wall and compares thermal performance of the three walls. Calibrated hot box test results for the insulated normal weight concrete wall, designated Wall C4, are presented in the section of this report entitled "Concrete Wall with Board Insulation." Test results for the low density concrete wall, designated Wall C3, and the fiberglass board, designated Wall S1, are given in Appendix A. Calibrated hot box test results for the low density concrete wall have been previously published in References 6 and 8. Calibrated hot box test results for the fiberglass insulation specimen have been previously published in Reference 9.

CALIBRATED HOT BOX TEST FACILITY

Tests were conducted in the calibrated hot box facility shown in Figs. 1 and 2. Tests were performed in accordance with ASTM Designation: C976, "Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box."[10]

The following is a brief description of the calibrated hot box. Instrumentation and calibration details are described in Appendix B and Reference 11.

The facility consists of two highly insulated chambers as shown in Fig. 2. Walls, ceiling, and floors of each chamber are insulated with foamed urethane sheets to obtain a nominal thickness of 12 in. (300 mm). During tests, the chambers are clamped tightly against an insulating frame that surrounds the test wall. Air in each chamber is conditioned by heating and cooling equipment to obtain desired temperatures on each side of the test wall.

The outdoor (climatic) chamber can be held at a constant temperature or cycled within the range -15 to 130°F (-26 to 54°C). Temperatures can be programmed for a 24-hour cycle to obtain the desired temperature-time relationship. The indoor (metering) chamber, which simulates an indoor environment, can be maintained at a constant room temperature between 65 and 80°F (18 and 27°C).

The specimen is in a vertical position in CTL's calibrated hot box. Therefore, heat flows horizontally through the wall. The facility was designed to accommodate walls with thermal resistance values ranging from 1.5 to 20 $hr \cdot ft^2 \cdot °F/Btu$ (0.26 to 3.52 $m^2 \cdot K/W$).

CTL's calibrated hot box is not capable of maintaining a pressure differential across a specimen. The pressure in both the indoor and outdoor chambers is atmospheric.

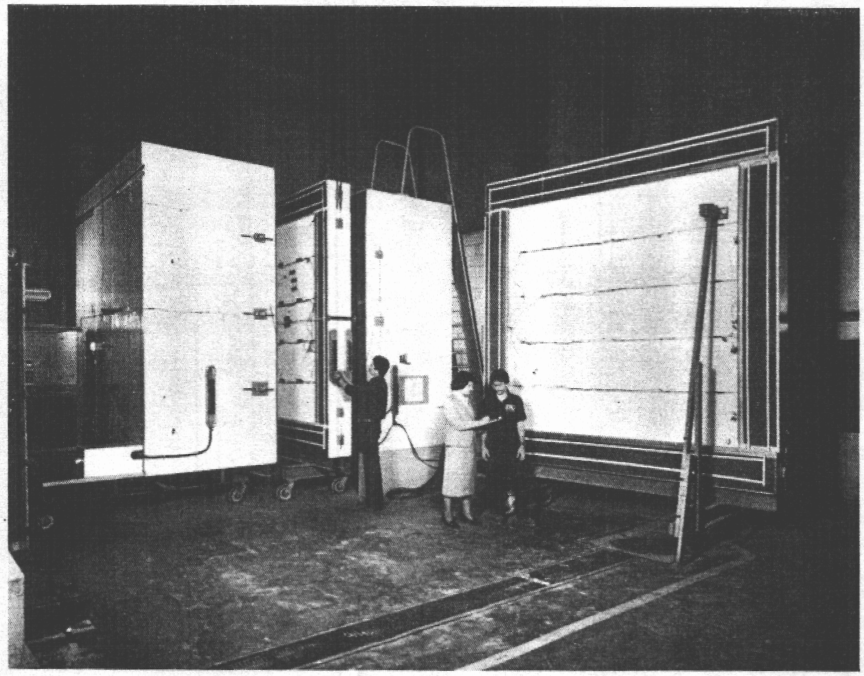


Fig. 1 Calibrated Hot Box Test Facility

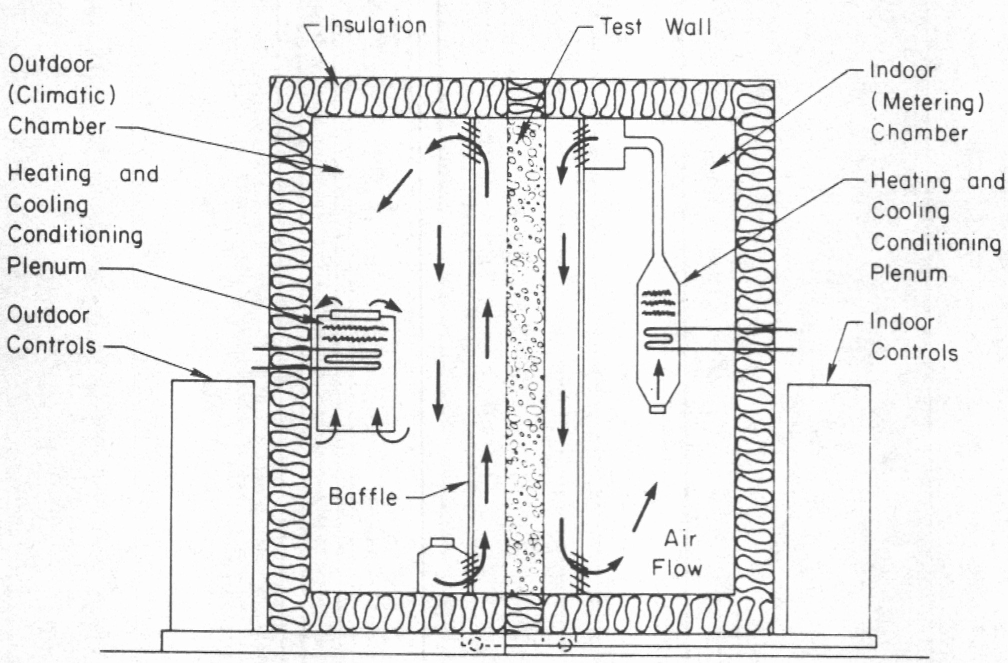


Fig. 2 Schematic of Calibrated Hot Box

CONCRETE WALL WITH BOARD INSULATION

An 8-in. (200-mm) normal weight concrete wall with 5/8-in. (16-mm) polyisocyanurate board insulation on the outdoor surface, designated Wall C4, was tested in CTL's calibrated hot box. The wall was built at CTL using techniques representative of field construction practices. Overall nominal wall dimensions were 103x103 in. (2.62x2.62 m).

Wall Construction

Wall C4 was constructed by applying polyisocyanurate insulation to an 8-in. (200-mm) thick concrete wall previously tested in the calibrated hot box. Table 1 lists dates of calibrated hot box tests performed on the 8-in. (200-mm) normal weight concrete wall.

Construction details and calibrated hot box test results for the 8-in. (200-mm) normal weight concrete wall, previously designated Wall C1, are presented in Reference 4. Wall C1 was reinforced with a single layer of No. 5 bars spaced 12-in. (300-mm) center-to-center in each direction. Bars were located at the approximate midthickness of the wall.

Wall C1 was cast horizontally in May 1981 and cured in formwork for seven days. After removing formwork, the wall was allowed to air cure in the laboratory at an air temperature of 73±5°F (23±3°C) and 45±15% RH for five months. Faces of Wall C1 were coated with a cementitious waterproofing material that seals minor surface imperfections. A textured, noncementitious off-white paint was used as a finish coat. Wall C1 was tested in the calibrated hot box from October to December 1981.

Physical properties of Wall C1 and companion control specimens are given in Table 2. Thermal properties of concrete used for Wall C1 are given in Table 3. Control specimens were cast from the same concrete used to construct the wall.

TABLE 2 - PHYSICAL PROPERTIES OF WALL C1[4]

Property	Measured Value
Unit Weight of Wall, pcf (kg/m^3)	144 (2310)
Estimated Moisture Content of Wall, % ovendry weight	2.1
Average Thickness, in. (mm)	8.31 (211)
Area, ft^2 (m^2)	73.64 (6.84)
Concrete Compressive Strength, psi (MPa)	
moist cured*	5040 (34.7)
air cured**	5717 (39.4)
Concrete Splitting Tensile Strength, psi (MPa)	
moist cured*	522 (3.60)
air cured***	514 (3.54)

*Measured on 6x12-in. (150x300-mm) cylinders cured in molds for first 24 hours, moist cured for 27 days.
**Measured on 6x12-in. (150x300-mm) cylinders cured in molds for first 7 days, air cured for 184 days.
***Measured on 6x12-in. (150x300-mm) cylinders cured in molds for first 7 days, air cured for 188 days.

TABLE 3 - THERMAL PROPERTIES OF WALL C1[4]

Property	Test Method	Specimen Condition	Mean Temperature, °F (°C)	Measured Value
Specific Heat, Btu/lb·°F (J/kg·K)	Similar to CRD-C124-73	saturated	73 (23)	0.214 (896)
Specific Heat, Btu/lb·°F (J/kg·K)	Calculated	air dry	73 (23)	0.193 (808)
Thermal Conductivity, Btu·in./hr·ft^2·°F (W/m·K)	Hot Wire	air dry	—	20.3 (2.93)
Thermal Conductivity, Btu·in./hr·ft^2·°F (W/m·K)	ASTM C177	ovendry	70 (21)	16.1 (2.32)
Thermal Conductivity, Btu·in./hr·ft^2·°F (W/m·K)	ASTM C976	air dry	70 (21)	11.7 (1.69)
Thermal Diffusivity, ft^2/hr (mm^2/s)	CRD-C36-73	saturated	--	0.037 (0.955)

Table 3 presents thermal conductivity values of Wall C1 concrete specimens ranging from 11.7 to 20.3 Btu•in./hr•ft^2•°F (1.69 to 2.93 W/m•K), depending on the test method. Thermal conductivity of normal weight concrete depends on the specimen moisture content and whether the test method uses embedded or taped thermocouples for measuring specimen temperatures. More information on specimen conditioning and test methods is given in Ref. 4.

After calibrated hot box testing was completed, Wall C1 was stored at an air temperature of 73±5°F (23±3°C) and 45±15% RH until January 1984. At this time, thermocouples were embedded in each surface of Wall C1 and the wall was redesignated Wall C6. This wall was tested in the calibrated hot box in January and February 1984.(12)

After calibrated hot box testing of Wall C6 was completed, board insulation was applied to the outdoor surface and the wall was redesignated Wall C4. This wall was tested in the calibrated hot box from February to May 1984.

Celotex Tuff-R Insulating Sheathing was applied to Wall C6 to construct Wall C4. This insulation is a rigid, foil-faced polyisocyanurate foam board with a nominal thickness of 5/8-in. (16-mm). The material had a rated R-value of 5.4 hr•ft^2•°F/Btu (0.95 m^2•K/W) at time of manufacture.(13) The insulation had a measured thickness of 0.69 in. (17 mm) and a measured density of 2.2 pcf (36 kg/m^3) when received at CTL.

The insulation was bonded to the outside surface of the wall with an all-purpose construction adhesive applied in vertical ribbons. Figure 3 shows Wall C4 during application of the board insulation. Four rows of thermocouples placed between the concrete and insulation can be seen in Fig. 3.

Since the standard insulation board size is 48x96 in. (1.22x2.44 m), two full boards plus smaller cut pieces were used to cover the 103x103 in.

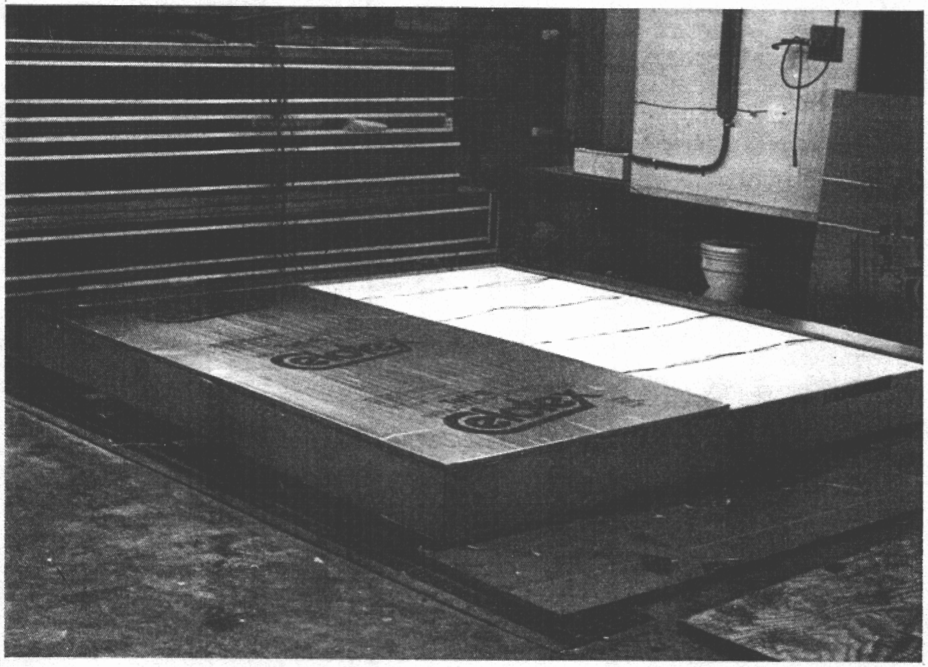


Fig. 3 Application of Board Insulation to Wall C4

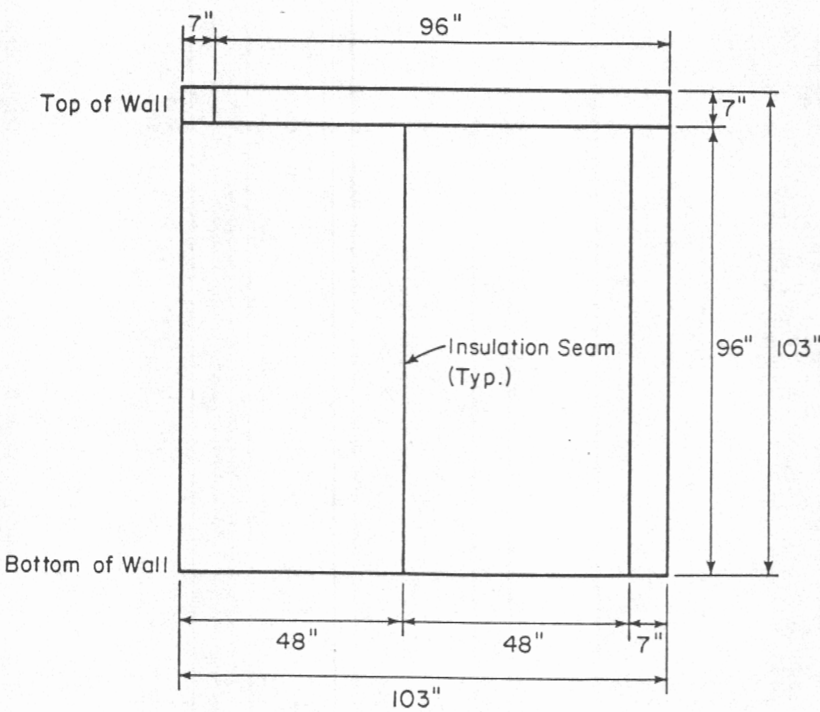


Fig. 4 Location of Wall C4 Insulation Seams

(2.62x2.62 m) wall. All insulation seams were covered with duct tape. Locations of insulation seams are shown in Fig. 4.

Figure 5 shows the outside surface of Wall C4 after application of insulation. Two coats of off-white latex flat wall paint were applied to the insulation surface.

The measured overall thickness of Wall C4 was 8.90 in. (225 mm). The measured area perpendicular to heat flow was 73.75 ft^2 (6.85 m^2). Unit weight of Wall C4 was 98.5 psf (480 kg/m^2). The estimated moisture content of the concrete after completion of calibrated hot box testing was 0.8% of ovendry weight.

Instrumentation

A total of 104 thermocouples corresponding to the American National Standard for Temperature Measurement Thermocouples (ANSI MC96.1), Type T, 20 gauge, were used to measure temperatures. Sixteen thermocouples were located in the air space of each chamber, 16 on each face of the test wall, 16 at the interface of concrete and insulation, 8 embedded in the concrete of the indoor face of the test wall, and 16 at the approximate midthickness of concrete. Thermocouples were uniformly distributed on a 20-3/5-in. (525-mm) square grid over the wall area.

Thermocouples measuring temperatures in the air space of each chamber were located approximately 3 in. (75 mm) from the face of the test wall.

Surface thermocouples were securely taped to the wall for a length of approximately 3 in. (75 mm). Duct tape covering the sensors was painted the same color as the test wall surface. Thermocouples attached to indoor and outdoor surfaces are shown in Figs. 6 and 7, respectively.

Internal thermocouples were placed at the approximate midthickness of the concrete. Prior to concrete placement, thermocouples were secured to reinforcement or suspended by wire between reinforcement. Thermocouple junctions

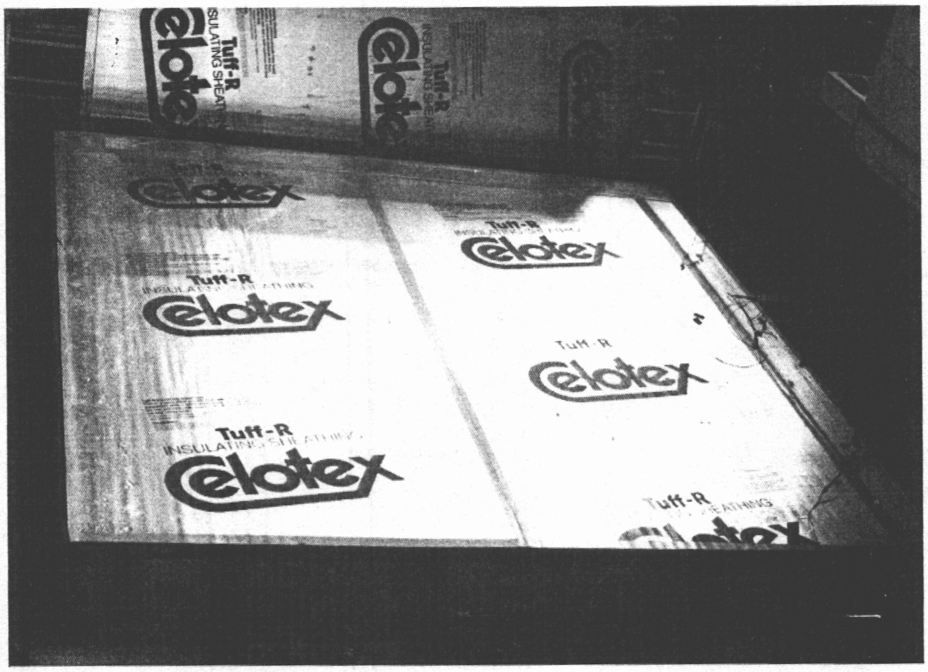


Fig. 5 Board Insulation on Outside Surface of Wall C4

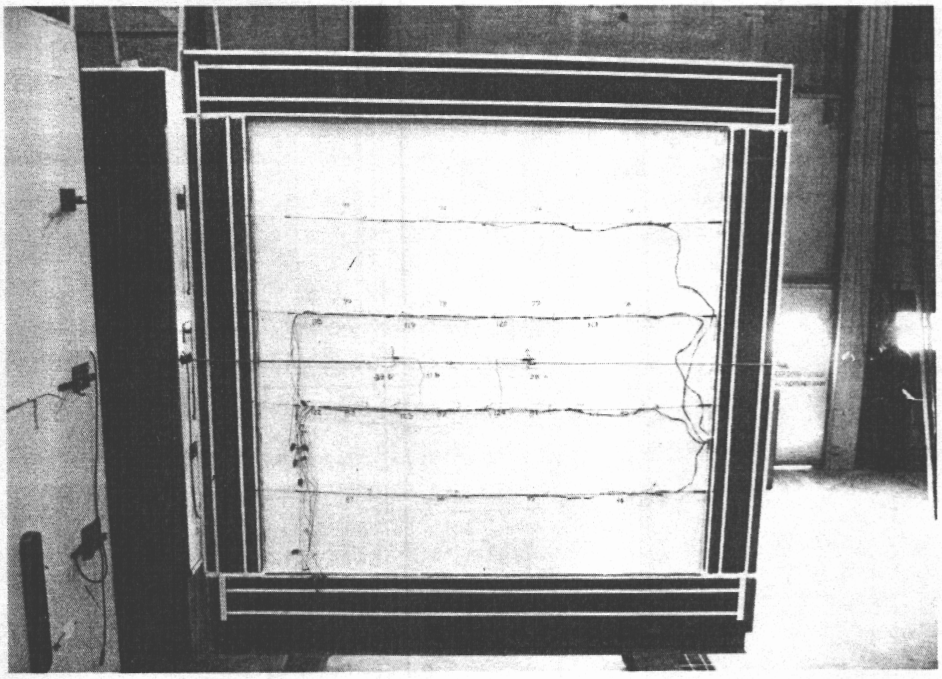


Fig. 6 Indoor Surface of Wall C4 Before Calibrated Hot Box Testing

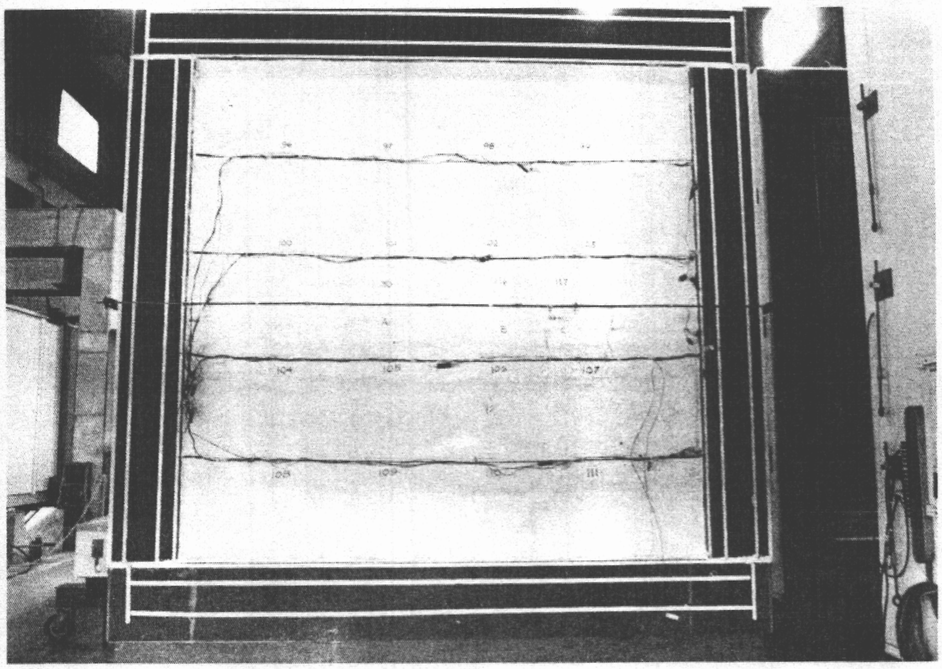


Fig. 7 Outdoor Surface of Wall C4 Before Calibrated Hot Box Testing

were not placed in contact with the reinforcement. This was done for all internal thermocouples to avoid any influence on internal heat flow through reinforcement. Thermocouples were wired such that electrical averages of four thermocouple junctions, located along horizontal lines across the grid, were obtained.

Thermocouples were taped to the surface of the concrete before insulation was attached. These thermocouples monitored temperatures at the interface of concrete and insulation on Wall C4. Thermocouples were distributed on the same 20-3/5-in. (525-mm) square grid as the air and surface thermocouples. Interface thermocouples were wired such that electrical averages of four thermocouple junctions, located along horizontal lines across the grid, were obtained.

The 8 embedded thermocouples on the indoor side of Wall C4 were located in the second and third rows of the 20-3/5-in. (525-mm) square grid. Eight grooves measuring 1/8-in. (3 mm) deep by 6 in. (150 mm) long were cut in the wall in line with the second and third rows of surface thermocouples. The embedded thermocouple sensors were located 2 in. (50 mm) from the surface thermocouples. At least 4 in. (100 mm) of the thermocouple wires were embedded. The grooves were filled flush with the wall surface using cement paste. The hardened paste was painted off-white to match the surface of the test wall.

Heat flux transducers measuring 4x4-in. (100x100-mm) were mounted near the center of the indoor and outdoor wall surfaces. The transducers were mechanically fastened to the wall surfaces to ensure contact throughout the calibrated hot box test program. To mount the heat flux transducer on the indoor concrete surface, 3/8-in. (10-mm) holes were drilled at selected mounting locations. Wood dowels 3/8-in. (10-mm) in diameter were epoxied in place and sanded flush with the wall surface. The heat flux transducer surface in contact with the wall surface was coated with a thin layer of high conductivity silicon grease.

The heat flux transducer was then mounted on the wall using screws into the wood dowels. The silicon grease provided uniform contact between the heat flux transducer and wall surface.

The heat flux transducer mounted on the outdoor insulation surface was also coated with a thin layer of high conductivity silicon grease. Duct tape was used to secure this heat flux transducer to the wall. The duct tape was painted the same color as the test wall surface.

Steady-State Tests

Two steady-state calibrated hot box tests were performed on Wall C4. Heat flow and temperature measurements were used to calculate average thermal properties including total thermal resistance (R_T) and transmittance (U).

Design heat transmission coefficients are calculated for the wall and compared to measured values. Results are compared to values for Walls C3 and S1 in the section of this report entitled "Comparison of Test Results for Walls with Similar R-Values."

Design Heat Transmission Coefficients

Design values of total resistance and transmittance for Wall C4 are shown in Table 4. Design values were calculated in accordance with procedures established by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers.[14]

Total resistance values, R_T, include standard surface resistances equal to 0.68 hr•ft^2•°F/Btu (0.12 m^2•K/W) for indoor and 0.17 hr•ft^2•°F/Btu (0.03 m^2•K/W) for outdoor. These values are commonly used in design and are considered to represent still air on the indoor wall surface and an air flow of 15 mph (24 km/hr) on the outdoor wall surface. Thermal transmittance, U, is equal to the reciprocal of total thermal resistance, R_T.

TABLE 4 - DESIGN HEAT TRANSMISSION COEFFICIENTS FOR WALL C4

Component	R, Thermal Resistance hr·ft^2·°F/Btu (m^2·K/W)
1. Outside Air Film	0.17* (0.03)
2. 5/8-in. (16-mm) Board Insulation	5.4** (0.95)
3. 8-in. (200-mm) Normal Weight Weight Concrete	0.69* (0.12)
3. Inside Air Film	0.68* (0.12)
Total R	6.94 (1.22)
Total U+	0.14 (0.82)

*Source: <u>ASHRAE Handbook - 1981 Fundamentals</u>, American Society of Heating, Refrigerating, and Air-Conditioning Engineers,Inc., Atlanta, 1981, Chapter 23.

**Source: R-value at time of manufacture per manufacturer's specifications.

+Units for thermal transmittance are Btu/hr·ft^2·°F (W/m^2·K).

Resistances for construction materials were taken from the ASHRAE Handbook - 1981 Fundamentals[14] or other similar listings of thermal properties. Resistances used in Table 4 were not measured.

Test Procedures

Steady-state calibrated hot box tests are conducted by maintaining constant indoor and outdoor chamber temperatures. Results are calculated from data collected when specimen temperatures reach equilibrium and the rate of heat flow through the test wall is constant.

Steady-state tests for Wall C4 were run at two temperature differentials. For the first case, indoor air temperature was maintained at approximately 73°F (23°C) while outdoor air temperature was maintained at approximately 129°F (54°C). This provided a nominal temperature differential of 56°F (31°C) and a mean temperature of 101°F (38°C). In the second case, indoor air temperature was maintained at approximately 71°F (21°C) while outdoor air temperature was maintained at approximately -10°F (-23°C). This provided a nominal temperature differential of 81°F (44°C) and a mean temperature of 32°F (0°C).

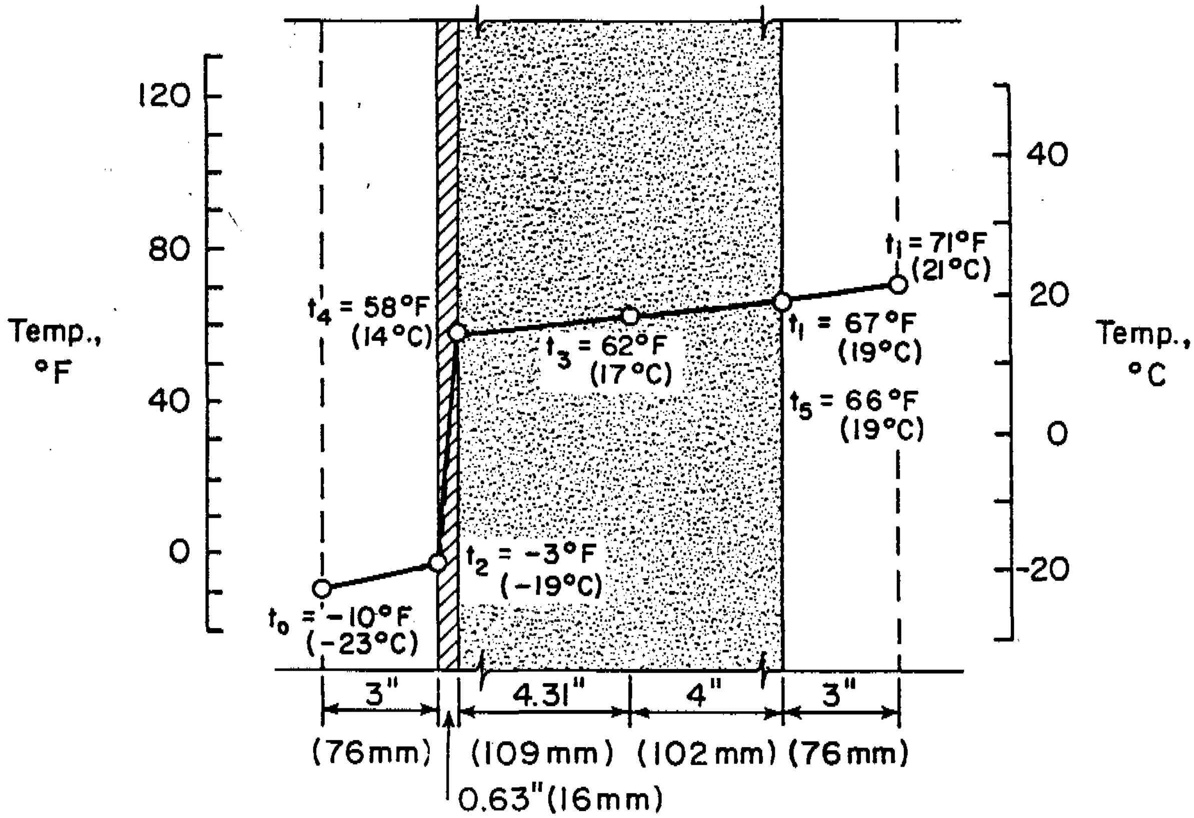
Steady-State Temperature Profiles

Temperature profiles for the steady-state tests are illustrated in Fig. 8. Data are averages for 16 consecutive hours of testing. Temperatures are averages from thermocouples uniformly distributed across the wall as described in the "Instrumentation" Section. The following notation is used to designate average measured temperatures:

t_0 = outdoor air temperature

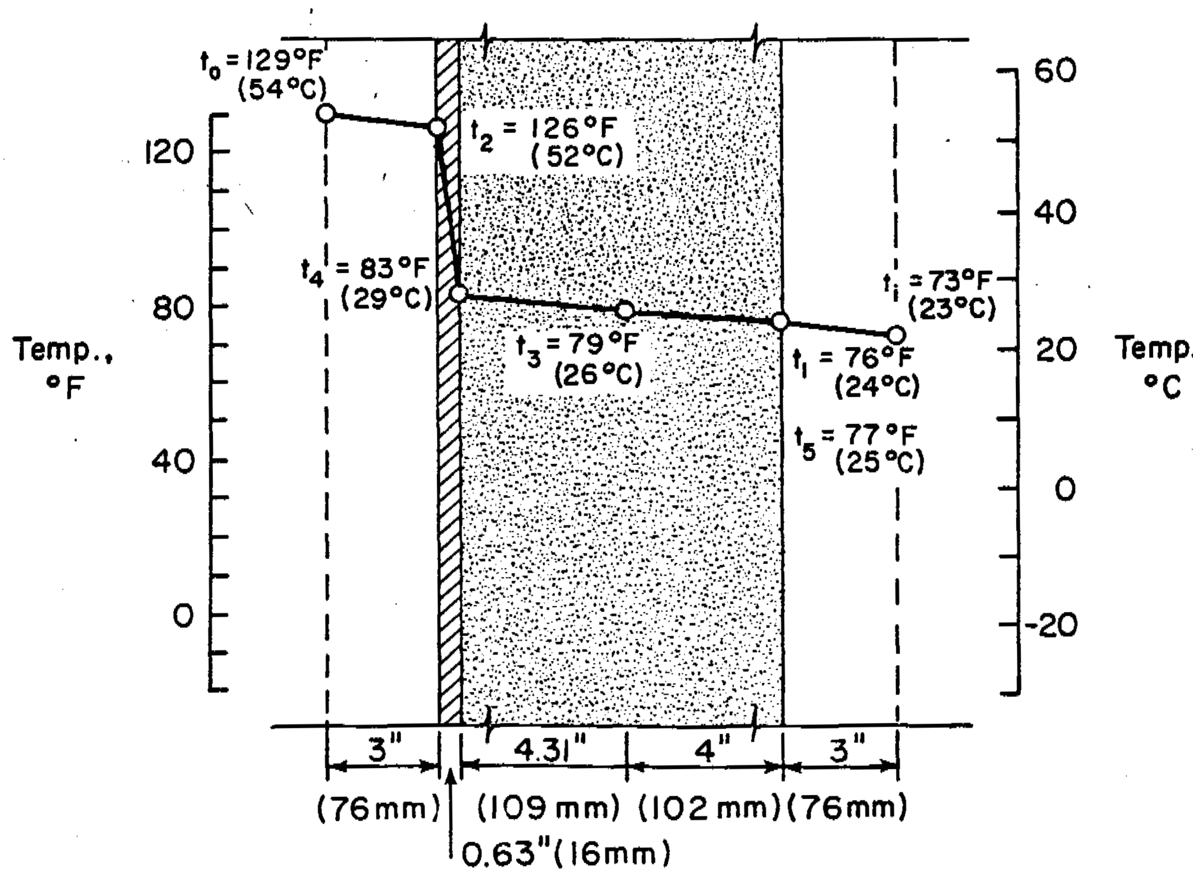
t_2 = wall surface temperature, outdoor side

t_4 = internal wall temperature at interface of concrete and insulation



(a) Wall Mean Temperature = 32°F (0°C)

Fig. 8 Steady-State Temperature Profiles Across Wall C4



(b) Wall Mean Temperature = 101°F (38°C)

Fig. 8 Steady-State Temperature Profiles Across Wall C4

t_3 = internal wall temperature at approximate midthickness of concrete

t_5 = wall surface temperature, indoor side (embedded thermocouples)

t_1 = wall surface temperature, indoor side (taped thermocouples)

t_i = indoor air temperature

Measurements of thermocouples taped to a concrete surface do not indicate the true surface temperature. A contact resistance is introduced because of thin air gaps and imperfect thermal contact between the thermocouple and the wall surface. As a result, the taped thermocouple measurements are between the true wall surface temperature and the adjacent air temperature. For materials with high thermal conductivity, such as normal weight concrete, surface temperatures are more accurately measured by thermocouples embedded in the wall surface. Contact resistance is reduced using this temperature measurement technique.

Previous calibrated hot box tests were performed on Wall C6 to investigate contact resistance. Wall C6 is the normal weight concrete wall used for construction of Wall C4. Thermocouples for measuring surface temperatures were embedded in and taped to the wall surfaces. Comparison of calibrated hot box test results using the two surface measurement techniques are given in Reference 12.

As can be seen in Fig. 8, temperatures measured on the indoor surface of Wall C4 by taped and embedded thermocouples differ by 1°F (0.6°C). Taped thermocouple temperature measurements (t_1) are between air temperatures (t_i) and embedded thermocouple temperature measurements (t_5). Temperatures measured by taped and embedded thermocouples on the indoor surface of Wall C6 differed by 5 to 6°F (2 to 3°C) for similar steady-state tests.[12] The smaller difference between taped and embedded thermocouple readings for Wall C4 is due to the added insulation on the surface of this specimen. The temperature gradient through the concrete and surface film portion of an insulated wall is significantly smaller than that through an uninsulated concrete wall.

Thermal Resistance and Transmittance

Steady-state calibrated hot box test results are summarized in Table 5. Data are averages for 16 consecutive hours of testing. Mean wall temperature, heat flux measured by the calibrated hot box, total thermal resistance, and thermal transmittance are listed for steady-state tests.

Total thermal resistance and transmittance coefficients were calculated using heat flux measured by the calibrated hot box, measured surface-to-surface temperature differentials, and standard surface resistance coefficients. Heat transmission coefficients were determined from temperature differentials for both embedded and taped indoor surface thermocouples.

Measured surface-to-surface temperature differentials from taped thermocouple measurements are greater than the true temperature differential across the wall. As a result, the measured total thermal resistance of the wall calculated from taped thermocouple measurements includes a surface contact resistance and is greater than the actual thermal resistance. Embedded thermocouple measurements reduce contact resistance.

Thermal resistances calculated from embedded thermocouple measurements are 2% less than resistances calculated from taped thermocouple measurements. The average difference in thermal resistance is 0.15 $hr \cdot ft^2 \cdot °F/Btu$ (0.03 $m^2 \cdot K/W$). This is close to the contact resistance for normal weight concrete of 0.13 $hr \cdot ft^2 \cdot °F/Btu$ (0.02 $m^2 \cdot K/W$) determined in Reference 12.

TABLE 5 - WALL C4 STEADY-STATE TEST RESULTS

Nominal Test Condition	q_w* Heat Flux, Btu/hr·ft^2 (W/m^2)	R_T,** hr·ft^2·°F/Btu (m^2·K/W)		U,** Btu/hr·ft^2·°F (W/m^2·K)		Relative Humidity		Laboratory Air Temperature	
		Taped Thermocouples+	Embedded Thermocouples++	Taped Thermocouples+	Embedded Thermocouples++	Indoor Chamber, %	Outdoor Chamber, %	Max. °F (°C)	Min. °F (°C)
t_m*** = 32°F (0°C)	-10.0 (-31.5)	7.85 (1.38)	7.74 (1.36)	0.13 (0.72)	0.13 (0.73)	18	19	72 (22)	71 (21)
t_m*** = 101°F (38°C)	7.6 (23.8)	7.49 (1.32)	7.31 (1.29)	0.13 (0.76)	0.14 (0.78)	18	13	72 (22)	71 (22)
Design Values	-	6.94 (1.22)		0.14 (0.82)		-	-	-	-

*Measured by the calibrated hot box.
**Total thermal resistance, R_T, and transmittance, U, for steady-state tests were calculated using the design surface resistance coefficients and measured values of heat flux.
***Mean of wall surface temperatures.
+Determined from temperature differential measured using taped thermocouples on the indoor surface.
++Determined from temperature differential measured using embedded thermocouples on the indoor surface.

Design heat transmission coefficients are shown in the last row of Table 5 for comparison.

Thermal resistance of Wall C4 at a mean temperature of 72°F (22°C) may be interpolated from measured data. Thermal resistances determined from thermocouples taped to and embedded in the concrete surface are 7.64 and 7.49 $hr \cdot ft^2 \cdot °F/Btu$ (1.25 and 1.32 $m^2 \cdot K/W$), respectively. These values are within 10% of the design values.

Relative humidity within the indoor and outdoor chambers is not controlled by CTL's calibrated hot box. However, relative humidity was measured and is listed in Table 5.

Maximum and minimum laboratory air temperatures obtained during each steady-state test are also listed in Table 5. The laboratory acts as a guard for the indoor chamber for tests conducted in CTL's calibrated hot box.

Dynamic Tests

Exterior building walls are seldom in a steady-state condition. Outdoor air temperatures and solar effects cause cyclic changes in outdoor surface temperatures. Generally, indoor surface temperatures are relatively constant compared to outdoor surface temperatures.

Dynamic tests are a means of evaluating thermal response under controlled conditions that simulate temperature changes actually encountered in building envelopes. Response of walls to temperature changes is a function of both thermal resistance and heat storage capacity.

Test Procedures

Dynamic tests were conducted by maintaining calibrated hot box indoor air temperature constant while outdoor air temperatures were cycled over a predetermined temperature versus time relationship. The rate of heat flow through a test specimen was determined from hourly averages of data.

Three 24-hour (diurnal) temperature cycles were applied to Wall C4. One dynamic temperature cycle, denoted the NBS Test Cycle, has been applied to every wall tested in the calibrated hot box. This cycle is based on a simulated sol-air* cycle used by the National Bureau of Standards in their evaluation of dynamic thermal performance of an experimental masonry building.(15) It represents a large variation in outdoor temperature over a 24-hour period. The mean outdoor temperature of the cycle is approximately equal to the mean indoor temperature.

The two additional sol-air diurnal temperature cycles applied to Wall C4 were both based on the NBS cycle previously described. The NBS+10 cycle was derived by increasing hourly outdoor air temperatures by 10°F (6°C). The NBS-10 cycle was derived by decreasing hourly outdoor air temperatures by 10°F (6°C).

Outdoor chamber air temperatures for the three dynamic temperature cycles are illustrated in Fig. 9. Average indoor temperature over the 24-hour period for each cycle was approximately 72°F (22°C). This is shown as a reference line in Fig. 9.

For all tests, dynamic cycles were repeated until conditions of equilibrium were obtained. Equilibrium conditions were evaluated by consistency of applied temperatures and measured heat flux. After equilibrium conditions were reached, tests were generally continued for a period of three days. Results are based on average readings for three consecutive 24-hour cycles, unless otherwise noted. Each test required approximately eight days for completion.

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*Sol-air temperature is that temperature of outdoor air that, in the absence of all radiation exchanges, would give the same rate of heat entry into the surface as would exist with the actual combination of incident solar radiation, radiant energy exchange, and convective heat exchange with outdoor air.(14)

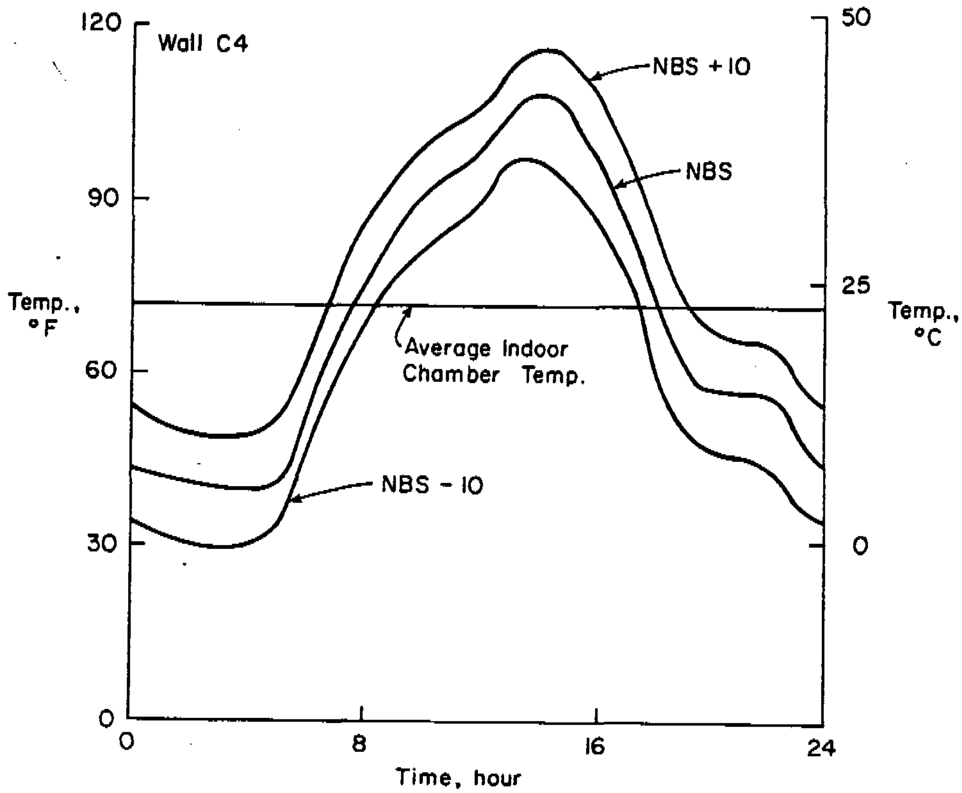


Fig. 9 Outdoor Chamber Air Temperatures for Dynamic Test Cycles Applied to Wall C4

Test Results

The following sections present results for Wall C4. Dynamic test results for Walls C3 and S1 are presented in Appendix A. Dynamic test results are compared in the section of this report entitled "Comparison of Test Results for Walls with Similar R-Values."

Brief descriptions of symbols used in figures and tables are listed in Table 6. Symbols are described in detail in the following section.

Hourly Test Data

Measured temperatures, temperature differentials, and heat flux for dynamic temperature cycles applied to Wall C4 are illustrated in Figs. 10 through 12 and listed in Tables 7 through 9.

Tables 7 through 9 denoted (a) and (b), respectively, list hourly dynamic test data in U.S. and SI units.

Measured temperatures are listed in Tables 7 through 9. Values are illustrated in the portion of Figs. 10 through 12 denoted (a). Outdoor air (t_o), indoor air (t_i), outdoor surface (t_2), indoor surface (t_1, t_5), and internal wall (t_3, t_4) temperatures are average readings of thermocouples placed as described in the "Instrumentation" section of this report.

Air-to-air (t_o-t_i), surface-to-surface (t_2-t_1), and surface-to-air (t_o-t_2, t_1-t_i) temperature differentials for Wall C4 are illustrated in the portion of Figs. 10 through 12 denoted (b).

Measured and calculated heat flux values are listed in Tables 7 through 9 and illustrated in the portion of Figs. 10 through 12 denoted (c). Heat flux is positive when heat flows from the calibrated hot box outdoor chamber to the indoor chamber.

Heat flux determined from calibrated hot box tests is denoted q_w.

TABLE 6 - ABBREVIATIONS FOR HEAT FLUX AND TEMPERATURE

q_{hfm} = heat flux measured by heat flux transducer mounted on indoor wall surface

q'_{hfm} = heat flux measured by heat flux transducer mounted on outdoor wall surface

q_{ss} = heat flux predicted from steady-state analysis

q_w = heat flux measured by calibrated hot box

t_o = outdoor air temperature

t_2 = wall surface temperature, outdoor side

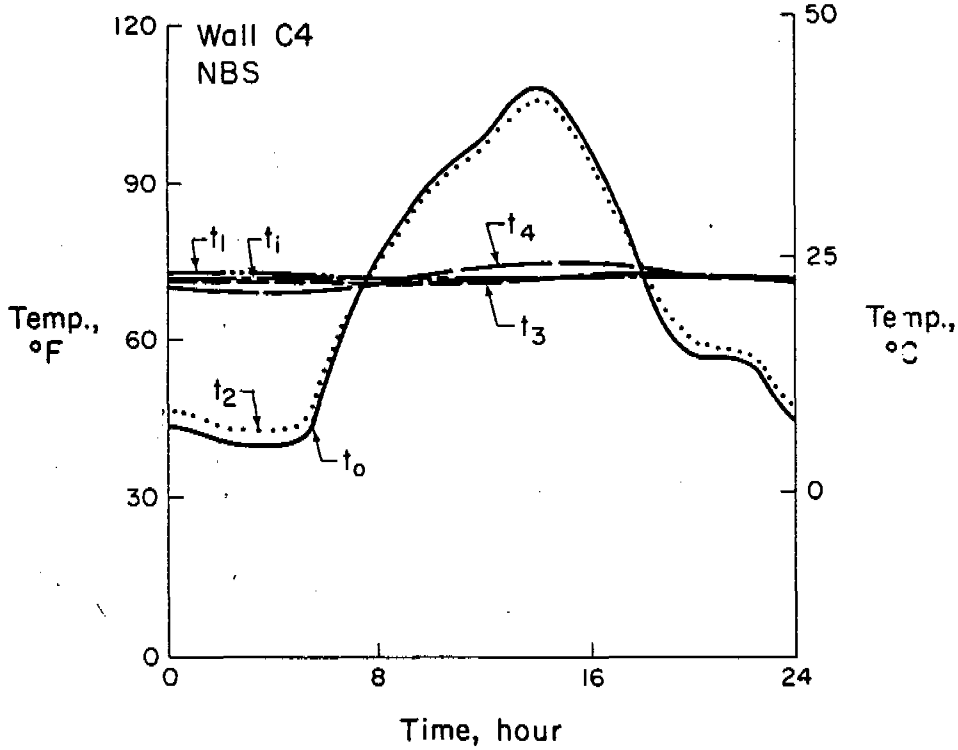
t_4 = internal wall temperature at interface of concrete and insulation

t_3 = internal wall temperature at midthickness of concrete

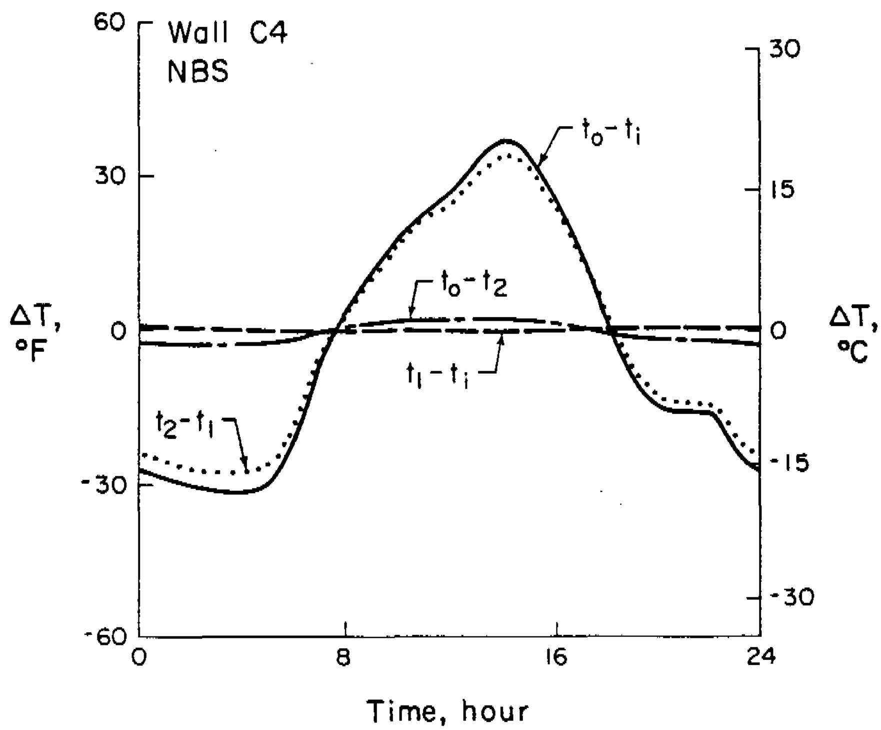
t_5 = wall surface temperature, indoor side (embedded thermocouples)

t_1 = wall surface temperature, indoor side (taped thermocouples)

t_i = indoor air temperature

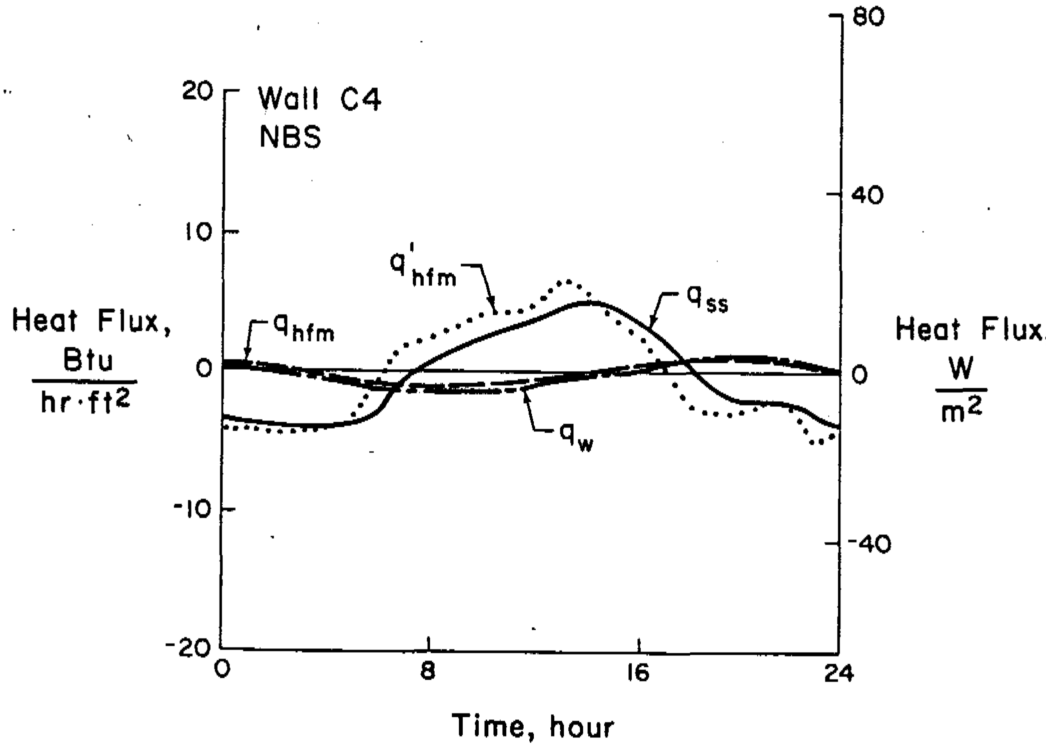


(a) Measured Temperatures



(b) Temperature Differentials

Fig. 10 Dynamic Test Results for NBS Test Cycle Applied to Wall C4



(c) Heat Flux

Fig. 10 Dynamic Test Results for NBS Test Cycle Applied to Wall C4

TABLE 7(a) - DYNAMIC TEST RESULTS (PERIODIC) FOR NBS TEST CYCLE APPLIED TO WALL C4

Time, hr	Measured Temperatures, °F							Measured Heat Flux, Btu/hr·ft^2			Calculated Heat Flux, Btu/hr·ft^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_4 Conc./ Insul.	t_3 Internal Conc.	t_5* Indoor Surf., Embed.	t_1 Indoor Surf., Taped	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	42.8	45.7	70.2	71.4	72.1	71.9	71.7	0.14	0.14	-4.30	-3.82
2	40.7	43.7	69.8	71.2	72.0	71.8	71.7	-0.25	-0.02	-4.64	-4.09
3	40.3	43.2	69.6	71.0	71.8	71.6	71.6	-0.45	-0.23	-4.32	-4.15
4	40.1	43.1	69.3	70.8	71.7	71.5	71.6	-0.84	-0.44	-4.32	-4.15
5	41.2	44.0	69.2	70.6	71.6	71.4	71.5	-1.10	-0.64	-3.87	-4.01
6	50.4	51.9	69.4	70.5	71.4	71.3	71.5	-1.28	-0.84	-0.72	-2.83
7	66.3	66.4	70.3	70.5	71.3	71.3	71.5	-1.49	-1.02	1.66	-0.71
8	75.9	75.3	71.1	70.6	71.3	71.2	71.5	-1.45	-1.11	2.20	0.59
9	83.4	82.5	71.7	70.7	71.3	71.3	71.5	-1.42	-1.09	3.09	1.64
10	90.4	89.0	72.4	70.9	71.4	71.3	71.6	-1.44	-1.01	4.07	2.58
11	94.6	93.1	72.9	71.1	71.5	71.4	71.6	-1.33	-0.85	4.00	3.16
12	98.3	96.5	73.4	71.4	71.6	71.6	71.6	-0.91	-0.62	4.73	3.64
13	105.3	102.8	74.1	71.7	71.8	71.7	71.7	-0.84	-0.41	6.50	4.54
14	109.0	106.6	74.7	72.0	72.0	71.8	71.7	-0.46	-0.16	5.89	5.09
15	104.7	103.0	74.8	72.3	72.1	72.0	71.8	-0.33	0.09	3.81	4.53
16	97.7	96.5	74.6	72.5	72.3	72.1	71.8	-0.08	0.33	2.48	3.57
17	87.9	87.7	74.2	72.6	72.5	72.2	71.9	0.64	0.59	0.29	2.26
18	73.5	74.5	73.4	72.6	72.6	72.3	71.8	0.89	0.76	-2.49	0.32
19	62.8	64.4	72.6	72.5	72.6	72.3	71.9	1.15	0.85	-2.95	-1.15
20	57.4	59.2	72.1	72.4	72.6	72.3	71.8	1.18	0.83	-2.95	-1.91
21	56.4	58.1	71.8	72.2	72.6	72.2	71.8	1.06	0.74	-2.34	-2.06
22	56.2	58.0	71.6	72.0	72.5	72.2	71.8	0.88	0.60	-2.49	-2.07
23	48.5	51.3	71.1	71.9	72.4	72.1	71.8	0.54	0.46	-4.99	-3.02
24	44.0	46.8	70.5	71.6	72.3	72.0	71.7	0.40	0.31	-4.24	-3.68
Mean	69.5	70.1	71.9	71.5	72.0	71.8	71.7	-0.28	-0.11	-0.25	-0.24

*Data are averages of 8 thermocouples, not 16.

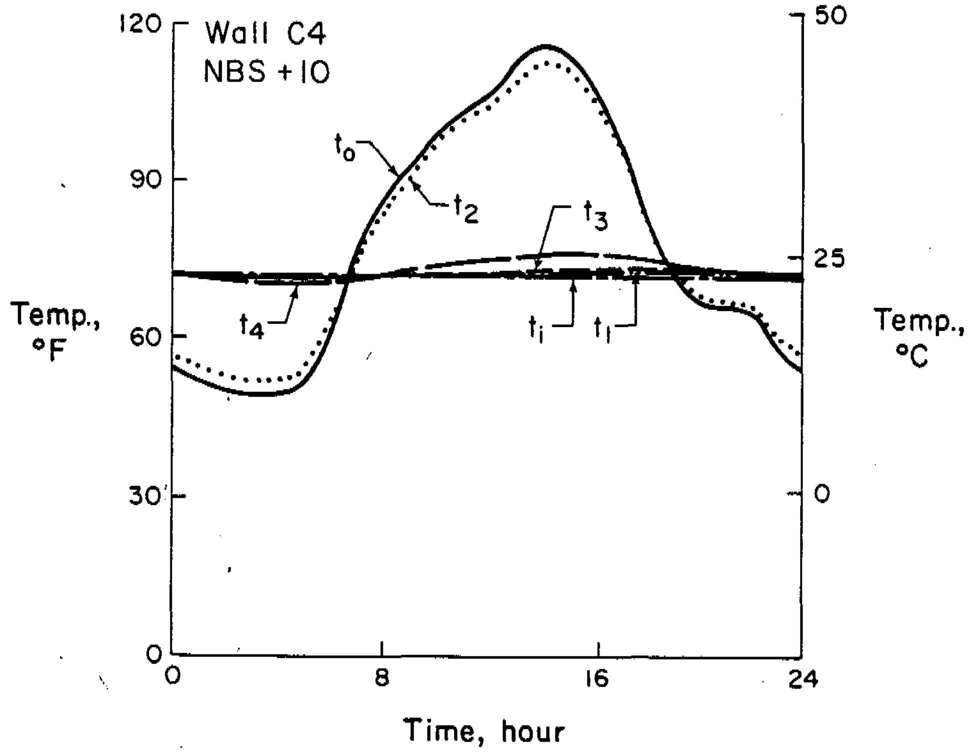
Calibrated Hot Box Relative Humidity:
Indoor Chamber - 19%
Outdoor Chamber - 15%

Laboratory Air Temperature:
Max. - 71°F - (22°C)
Min. - 70°F - (21°C)

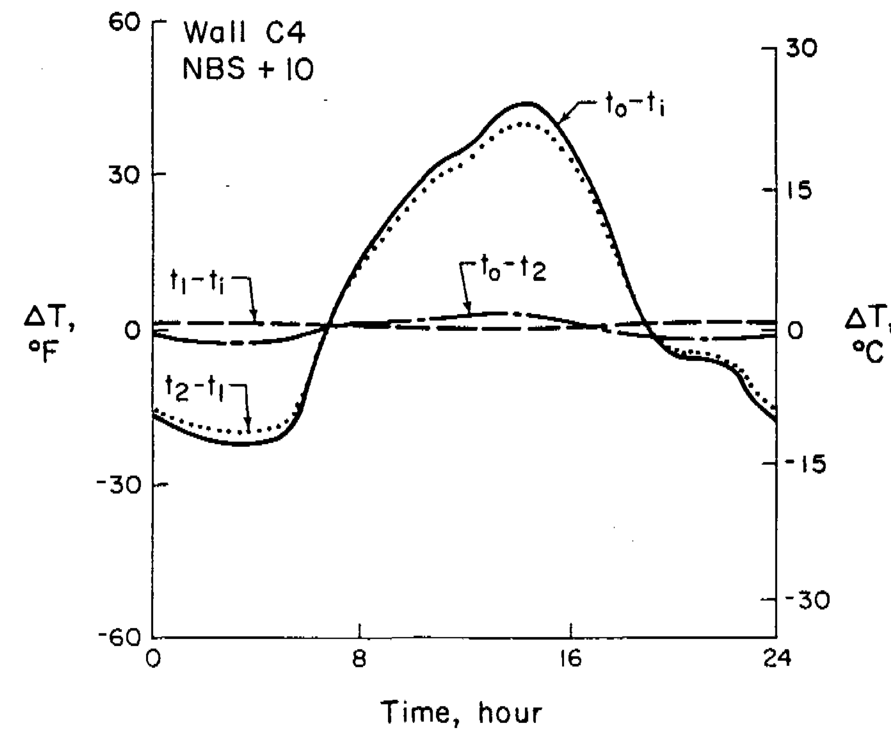
TABLE 7(b) - DYNAMIC TEST RESULTS (PERIODIC) FOR NBS TEST CYCLE APPLIED TO WALL C4, SI UNITS

Time, hr	Measured Temperatures, °C							Measured Heat Flux, W/m^2			Calculated Heat Flux, W/m^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_4 Conc./ Insul.	t_3 Internal Conc.	t_5* Indoor Surf., Embed.	t_1 Indoor Surf., Taped	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	6.0	7.6	21.2	21.9	22.3	22.2	22.1	0.45	0.45	-13.57	-12.05
2	4.8	6.5	21.0	21.8	22.2	22.1	22.0	-0.77	-0.07	-14.63	-12.91
3	4.6	6.2	20.9	21.7	22.1	22.0	22.0	-1.41	-0.73	-13.62	-13.08
4	4.5	6.2	20.7	21.6	22.0	22.0	22.0	-2.65	-1.40	-13.61	-13.09
5	5.1	6.6	20.7	21.5	22.0	21.9	22.0	-3.46	-2.01	-12.21	-12.64
6	10.2	11.1	20.8	21.4	21.9	21.9	22.0	-4.04	-2.67	-2.26	-8.93
7	19.1	19.1	21.3	21.4	21.8	21.8	21.9	-4.71	-3.21	5.22	-2.23
8	24.4	24.1	21.7	21.4	21.8	21.8	22.0	-4.57	-3.49	6.96	1.87
9	28.6	28.0	22.1	21.5	21.8	21.8	22.0	-4.47	-3.43	9.74	5.17
10	32.5	31.7	22.4	21.6	21.9	21.9	22.0	-4.56	-3.19	12.84	8.15
11	34.8	33.9	22.7	21.7	21.9	21.9	22.0	-4.18	-2.69	12.62	9.97
12	36.8	35.8	23.0	21.9	22.0	22.0	22.0	-2.86	-1.94	14.93	11.47
13	40.7	39.3	23.4	22.0	22.1	22.0	22.0	-2.65	-1.29	20.50	14.34
14	42.8	41.5	23.7	22.2	22.2	22.1	22.1	-1.46	-0.50	18.58	16.05
15	40.4	39.4	23.8	22.4	22.3	22.2	22.1	-1.05	0.29	12.02	14.30
16	36.5	35.8	23.7	22.5	22.4	22.3	22.1	-0.26	1.04	7.82	11.26
17	31.0	30.9	23.5	22.6	22.5	22.3	22.1	2.02	1.86	0.92	7.13
18	23.1	23.6	23.0	22.5	22.6	22.4	22.1	2.81	2.40	-7.86	1.01
19	17.1	18.0	22.6	22.5	22.6	22.4	22.1	3.63	2.68	-9.31	-3.63
20	14.1	15.1	22.3	22.4	22.6	22.4	22.1	3.71	2.61	-9.30	-6.03
21	13.6	14.5	22.1	22.3	22.5	22.4	22.1	3.34	2.33	-7.39	-6.51
22	13.5	14.4	22.0	22.2	22.5	22.3	22.1	2.77	1.90	-7.85	-6.53
23	9.2	10.7	21.7	22.1	22.4	22.3	22.1	1.72	1.47	-15.75	-9.54
24	6.6	8.2	21.4	22.0	22.4	22.2	22.1	1.26	0.97	-13.38	-11.61
Mean	20.8	21.2	22.2	22.0	22.2	22.1	22.0	-0.89	-0.36	-0.78	-0.75

*Data are averages of 8 thermocouples, not 16.

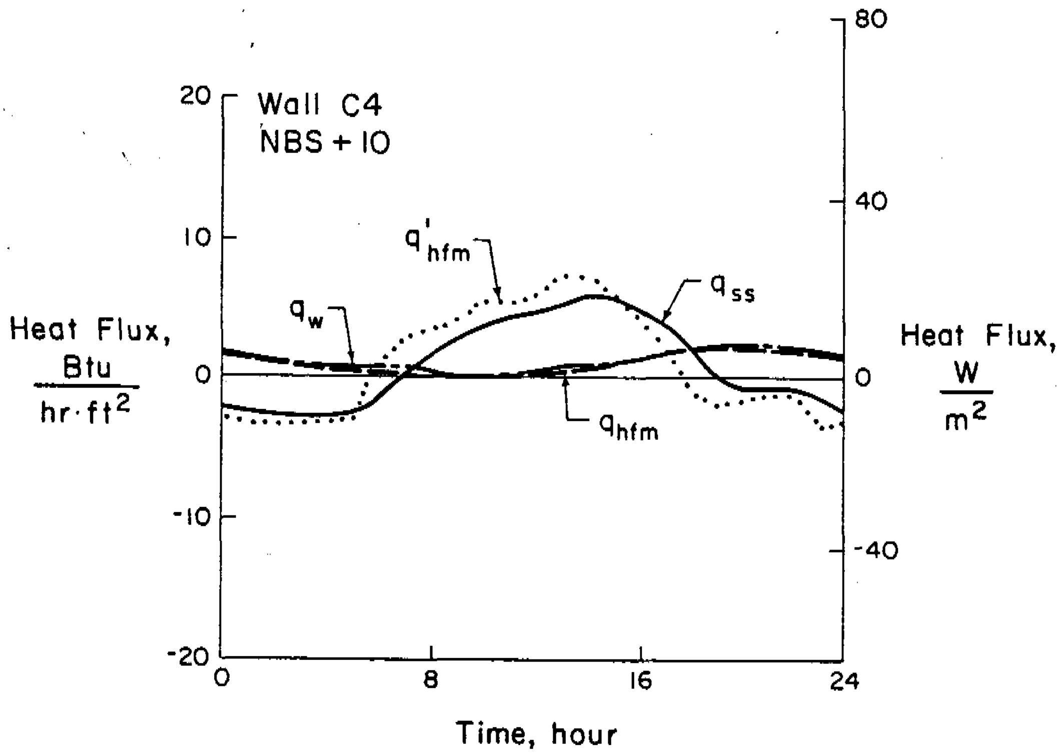


(a) Measured Temperatures



(b) Temperature Differentials

Fig. 11 Dynamic Test Results for NBS+10 Test Cycle Applied to Wall C4



(c) Heat Flux

Fig. 11 Dynamic Test Results for NBS+10 Test Cycle Applied to Wall C4

TABLE 8(a) - DYNAMIC TEST RESULTS (PERIODIC) FOR NBS+10 TEST CYCLE APPLIED TO WALL C4

Time, hr	Measured Temperatures, °F							Measured Heat Flux, Btu/hr·ft^2			Calculated Heat Flux, Btu/hr·ft^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_4 Conc./ Insul.	t_3 Internal Conc.	t_5* Indoor Surf., Embed.	t_1 Indoor Surf., Taped	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	52.7	55.0	72.2	72.7	73.2	72.8	72.1	1.57	1.36	-3.41	-2.60
2	50.8	53.2	71.9	72.5	73.1	72.7	72.1	1.43	1.15	-3.47	-2.84
3	49.9	52.4	71.6	72.3	72.9	72.6	72.0	1.21	0.93	-3.43	-2.95
4	50.3	52.6	71.4	72.1	72.7	72.4	71.9	0.92	0.72	-3.00	-2.89
5	51.3	53.5	71.2	71.9	72.6	72.3	71.9	0.78	0.52	-2.94	-2.74
6	60.9	61.6	71.5	71.7	72.4	72.2	71.8	0.88	0.33	0.79	-1.54
7	76.1	75.5	72.3	71.7	72.3	72.0	71.8	0.75	0.17	2.80	0.50
8	85.4	84.3	72.9	71.8	72.2	72.0	71.8	0.32	0.10	3.45	1.80
9	91.9	90.5	73.5	71.9	72.2	72.0	71.8	0.19	0.10	4.07	2.70
10	99.3	97.2	74.1	72.0	72.2	72.0	71.8	0.15	0.15	5.50	3.68
11	104.0	101.9	74.8	72.3	72.4	72.1	71.8	0.37	0.30	5.34	4.34
12	106.5	104.2	75.2	72.6	72.5	72.3	71.9	0.48	0.48	5.80	4.67
13	112.2	109.3	75.8	72.8	72.6	72.3	71.9	0.98	0.76	7.42	5.41
14	115.9	113.0	76.4	73.1	72.8	72.5	71.9	0.91	0.98	7.11	5.92
15	114.0	111.6	76.7	73.4	73.0	72.7	72.0	1.14	1.25	5.69	5.69
16**	108.0	106.2	76.6	73.6	73.2	72.9	72.0	1.45	1.53	4.21	4.87
17	99.2	98.3	76.3	73.8	73.4	73.0	72.2	1.67	1.77	1.91	3.68
18	84.5	84.9	75.4	73.9	73.6	73.2	72.2	1.96	1.96	-1.26	1.71
19	72.5	73.5	74.5	73.8	73.7	73.2	72.2	2.29	2.05	-1.94	0.04
20	67.4	68.6	74.1	73.6	73.7	73.2	72.2	2.47	2.06	-1.62	-0.68
21	66.3	67.4	73.8	73.5	73.7	73.2	72.2	2.35	1.98	-1.26	-0.84
22	65.8	67.0	73.6	73.3	73.6	73.1	72.2	2.13	1.83	-1.31	-0.89
23	58.9	61.0	73.1	73.2	73.4	73.0	72.1	1.96	1.69	-3.71	-1.76
24	54.8	56.9	72.6	72.9	73.4	72.9	72.1	1.70	1.54	-3.03	-2.34
Mean	79.1	79.2	73.8	72.8	72.9	72.6	72.0	1.25	1.07	0.99	0.96

*Data are averages of 8 thermocouples, not 16.
**Data for this hour are two-day, not three-day averages.

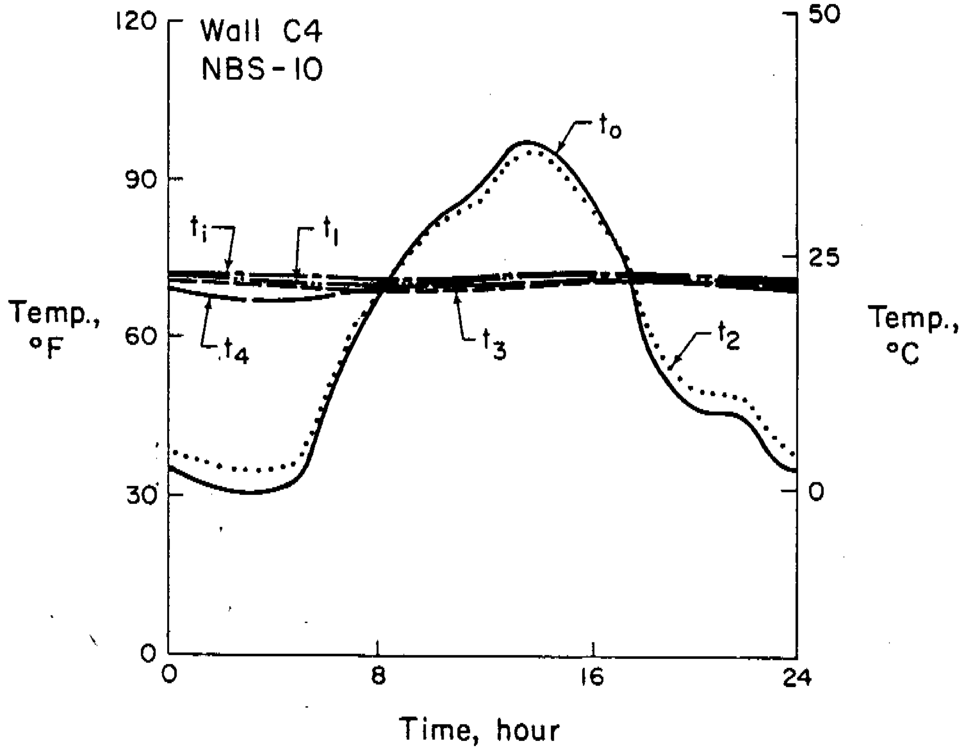
Calibrated Hot Box Relative Humidity:
Indoor Chamber - 23%
Outdoor Chamber - 15%

Laboratory Air Temperature:
Max. - 73°F - (23°C)
Min. - 69°F - (20°C)

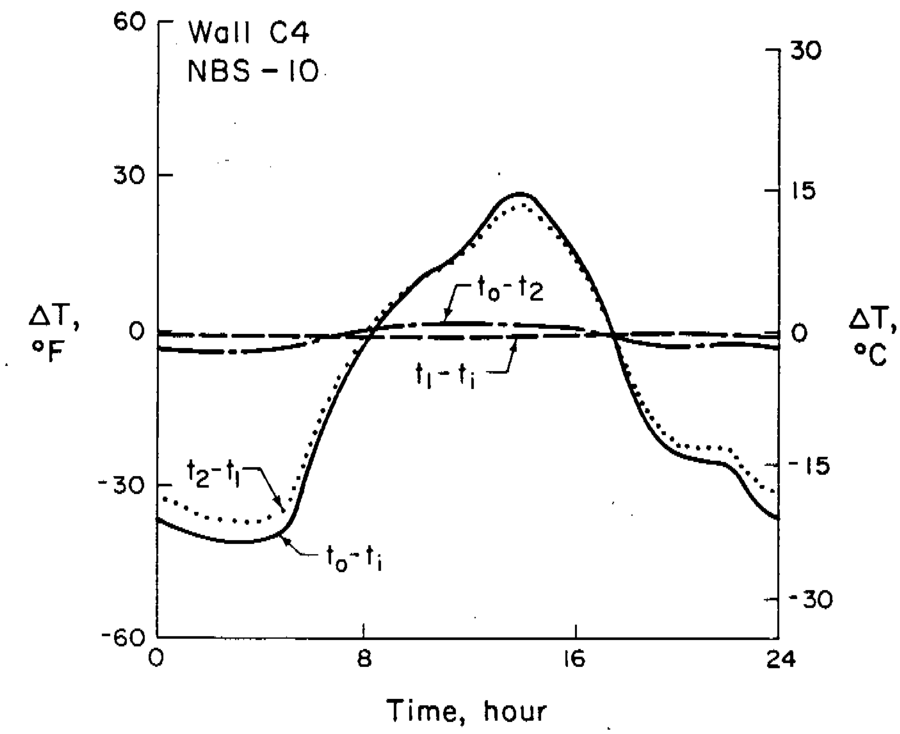
TABLE 8(b) - DYNAMIC TEST RESULTS (PERIODIC) FOR NBS+10 TEST CYCLE APPLIED TO WALL C4, SI UNITS

Time, hr	Measured Temperatures, °C							Measured Heat Flux, W/m^2			Calculated Heat Flux, W/m^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_4 Conc./ Insul.	t_3 Internal Conc.	t_5* Indoor Surf., Embed.	t_1 Indoor Surf., Taped	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	11.5	12.8	22.4	22.6	22.9	22.7	22.3	4.96	4.28	-10.77	-8.19
2	10.4	11.8	22.1	22.5	22.8	22.6	22.3	4.52	3.62	-10.94	-8.96
3	9.9	11.3	22.0	22.4	22.7	22.5	22.2	3.81	2.93	-10.81	-9.29
4	10.2	11.5	21.9	22.3	22.6	22.5	22.2	2.90	2.28	-9.47	-9.11
5	10.7	12.0	21.8	22.2	22.5	22.4	22.2	2.45	1.63	-9.28	-8.63
6	16.1	16.5	21.9	22.1	22.5	22.3	22.1	2.77	1.03	2.50	-4.85
7	24.5	24.2	22.4	22.1	22.4	22.2	22.1	2.37	0.54	8.84	1.59
8	29.6	29.1	22.7	22.1	22.3	22.2	22.1	1.00	0.30	10.88	5.66
9	33.3	32.5	23.0	22.2	22.3	22.2	22.1	0.60	0.30	12.83	8.51
10	37.4	36.2	23.4	22.2	22.4	22.2	22.1	0.47	0.47	17.35	11.60
11	40.0	38.8	23.8	22.4	22.4	22.3	22.1	1.15	0.93	16.83	13.69
12	41.4	40.1	24.0	22.5	22.5	22.4	22.2	1.53	1.51	18.29	14.72
13	44.5	43.0	24.3	22.7	22.5	22.4	22.1	3.09	2.40	23.39	17.06
14	46.6	45.0	24.7	22.8	22.6	22.5	22.2	2.86	3.10	22.42	18.68
15	45.6	44.2	24.8	23.0	22.8	22.6	22.2	3.61	3.95	17.96	17.93
16**	42.2	41.2	24.8	23.1	22.9	22.7	22.2	4.57	4.83	13.29	15.36
17	37.3	36.8	24.6	23.2	23.0	22.8	22.3	5.28	5.57	6.03	11.62
18	29.2	29.4	24.1	23.3	23.1	22.9	22.4	6.18	6.18	-3.96	5.39
19	22.5	23.0	23.6	23.2	23.2	22.9	22.3	7.22	6.48	-6.12	0.11
20	19.6	20.3	23.4	23.1	23.2	22.9	22.3	7.80	6.51	-5.11	-2.16
21	19.0	19.7	23.2	23.0	23.2	22.9	22.3	7.41	6.25	-3.96	-2.65
22	18.8	19.5	23.1	23.0	23.1	22.8	22.3	6.72	5.78	-4.14	-2.81
23	14.9	16.1	22.9	22.9	23.0	22.8	22.3	6.17	5.34	-11.70	-5.55
24	12.7	13.8	22.6	22.7	23.0	22.7	22.3	5.36	4.86	-9.55	-7.38
Mean	26.2	26.2	23.2	22.7	22.7	22.6	22.2	3.95	3.38	3.12	3.01

*Data are averages of 8 thermocouples, not 16.
**Data for this hour are two-day, not three-day averages.

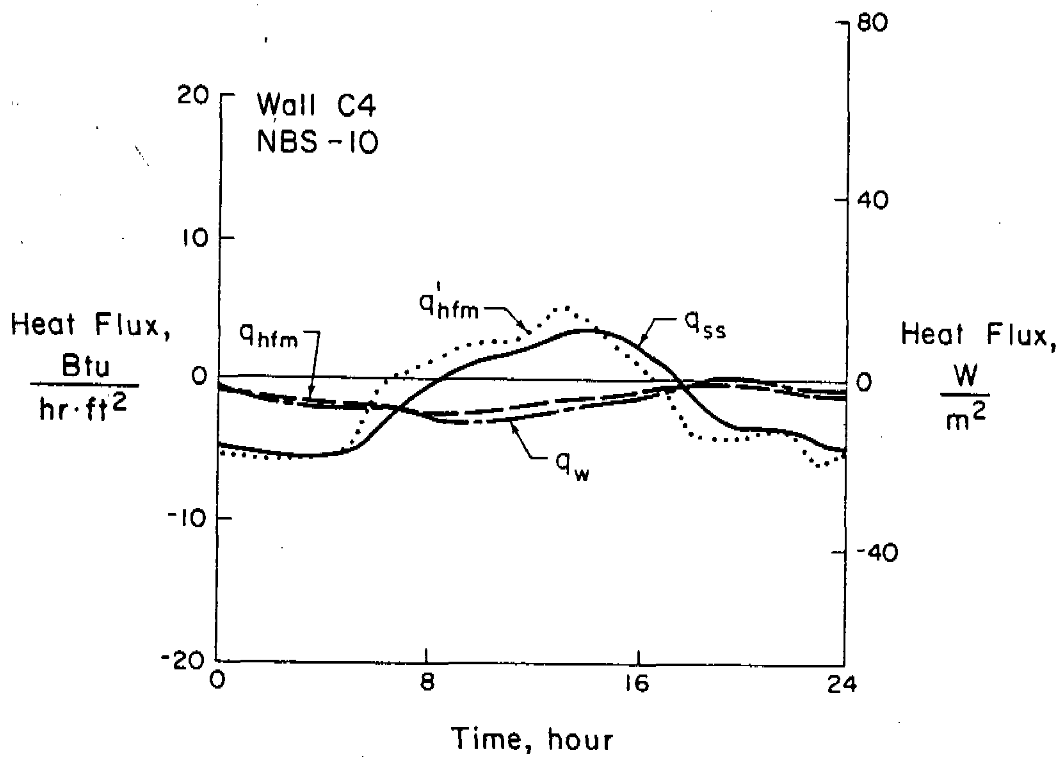


(a) Measured Temperatures



(b) Temperature Differentials

Fig. 12 Dynamic Test Results for NBS-10 Test Cycle Applied to Wall C4



(c) Heat Flux

Fig. 12 Dynamic Test Results for NBS-10 Test Cycle Applied to Wall C4

TABLE 9(a) - DYNAMIC TEST RESULTS (PERIODIC) FOR NBS-10 TEST CYCLE APPLIED TO WALL C4

Time, hr	Measured Temperatures, °F							Measured Heat Flux, Btu/hr·ft^2			Calculated Heat Flux, Btu/hr·ft^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_4 Conc./Insul.	t_3 Internal Conc.	t_5* Indoor Surf., Embed.	t_1 Indoor Surf., Taped	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	33.5	37.1	68.7	70.4	71.5	71.4	71.6	-1.04	-0.96	-5.56	-5.01
2	31.4	35.1	68.4	70.2	71.3	71.3	71.6	-1.30	-1.17	-5.66	-5.28
3	31.1	34.7	68.1	70.0	71.2	71.2	71.5	-1.63	-1.36	-5.38	-5.32
4	31.4	34.9	67.9	69.8	71.0	71.0	71.5	-1.79	-1.59	-5.16	-5.27
5	33.3	36.6	67.9	69.6	70.9	70.9	71.5	-2.04	-1.79	-4.55	-5.01
6	46.1	47.8	68.3	69.5	70.8	70.8	71.4	-1.80	-1.97	-0.79	-3.36
7	59.9	60.5	69.0	69.5	70.6	70.7	71.3	-2.26	-2.10	0.47	-1.48
8	69.2	69.1	69.7	69.6	70.6	70.7	71.3	-2.82	-2.17	1.37	-0.23
9	76.2	75.6	70.3	69.7	70.6	70.7	71.3	-2.95	-2.13	2.01	0.71
10	82.5	81.6	70.9	69.9	70.7	70.8	71.4	-2.89	-2.05	2.90	1.57
11	85.2	84.4	71.4	70.2	70.8	70.9	71.5	-2.58	-1.89	2.59	1.97
12	89.0	87.7	71.8	70.4	71.0	71.0	71.5	-2.19	-1.71	3.53	2.44
13	96.4	94.4	72.5	70.7	71.1	71.2	71.5	-2.05	-1.51	5.29	3.40
14	98.7	97.0	73.0	70.9	71.3	71.3	71.6	-1.82	-1.25	4.17	3.75
15	94.6	93.4	73.1	71.2	71.5	71.5	71.6	-1.73	-0.99	2.50	3.21
16	88.1	87.5	73.0	71.4	71.7	71.6	71.7	-1.19	-0.75	1.34	2.33
17	79.3	79.5	72.6	71.5	71.8	71.7	71.7	-0.73	-0.51	-0.80	1.15
18	63.9	65.6	71.8	71.5	72.0	71.8	71.7	-0.24	-0.34	-3.82	-0.90
19	53.6	55.9	71.1	71.5	72.0	71.8	71.8	0.12	-0.24	-4.04	-2.32
20	47.8	50.5	70.6	71.3	72.0	71.8	71.8	0.21	-0.27	-4.04	-3.11
21	47.1	49.6	70.3	71.2	71.9	71.8	71.8	-0.01	-0.37	-3.49	-3.23
22	46.5	49.2	70.1	71.0	71.9	71.7	71.8	-0.17	-0.50	-3.74	-3.29
23	38.5	42.1	69.6	70.9	71.7	71.6	71.7	-0.33	-0.63	-6.01	-4.31
24	35.2	38.6	69.1	70.7	71.6	71.5	71.7	-0.69	-0.78	-5.07	-4.81
Mean	60.8	62.0	70.4	70.5	71.3	71.3	71.6	-1.41	-1.21	-1.33	-1.35

*Data are averages of 8 thermocouples, not 16.

Calibrated Hot Box Relative Humidity:
Indoor Chamber - 23%
Outdoor Chamber - 16%

Laboratory Air Temperature:
Max. - 71°F - (22°C)
Min. - 66°F - (19°C)

TABLE 9(b) - DYNAMIC TEST RESULTS (PERIODIC) FOR NBS-10 TEST CYCLE APPLIED TO WALL C4, SI UNITS

Time, hr	Measured Temperatures, °C							Measured Heat Flux, W/m^2			Calculated Heat Flux, W/m^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_4 Conc./ Insul.	t_3 Internal Conc.	t_5* Indoor Surf., Embed.	t_1 Indoor Surf., Taped	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	0.8	2.8	21.3	20.4	21.9	21.9	22.0	-3.27	-3.04	-17.54	-15.82
2	-0.3	1.7	21.2	20.2	21.8	21.8	22.0	-4.10	-3.70	-17.87	-16.66
3	-0.5	1.5	21.1	20.1	21.8	21.8	22.0	-5.13	-4.29	-16.97	-16.77
4	-0.4	1.6	21.0	20.0	21.7	21.7	21.9	-5.65	-5.00	-16.29	-16.64
5	0.7	2.6	20.9	19.9	21.6	21.6	21.9	-6.42	-5.64	-14.37	-15.79
6	7.8	8.8	20.8	20.2	21.5	21.6	21.9	-5.68	-6.21	-2.48	-10.60
7	15.5	15.9	20.8	20.6	21.5	21.5	21.9	-7.14	-6.64	1.48	-4.68
8	20.7	20.6	20.9	20.9	21.4	21.5	21.8	-8.89	-6.85	4.31	-0.73
9	24.6	24.2	21.0	21.3	21.5	21.5	21.9	-9.31	-6.73	6.34	2.25
10	28.1	27.5	21.1	21.6	21.5	21.6	21.9	-9.12	-6.45	9.15	4.96
11	29.6	29.1	21.2	21.9	21.6	21.6	21.9	-8.13	-5.96	8.17	6.20
12	31.7	31.0	21.3	22.1	21.7	21.7	22.0	-6.90	-5.39	11.14	7.69
13	35.8	34.7	21.5	22.5	21.7	21.8	22.0	-6.46	-4.76	16.68	10.72
14	37.1	36.1	21.6	22.8	21.8	21.8	22.0	-5.73	-3.95	13.16	11.82
15	34.8	34.1	21.8	22.9	21.9	21.9	22.0	-5.47	-3.13	7.89	10.11
16	31.2	30.8	21.9	22.8	22.0	22.0	22.0	-3.76	-2.35	4.24	7.34
17	26.3	26.4	22.0	22.6	22.1	22.1	22.1	-2.30	-1.61	-2.53	3.61
18	17.7	18.7	22.0	22.1	22.2	22.1	22.1	-0.77	-1.08	-12.05	-2.84
19	12.0	13.3	21.9	21.7	22.2	22.1	22.1	0.39	-0.77	-12.74	-7.32
20	8.8	10.3	21.9	21.4	22.2	22.1	22.1	0.65	-0.87	-12.74	-9.81
21	8.4	9.8	21.8	21.3	22.2	22.1	22.1	-0.02	-1.18	-11.00	-10.20
22	8.1	9.5	21.7	21.2	22.1	22.1	22.1	-0.53	-1.59	-11.81	-10.38
23	3.6	5.6	21.6	20.9	22.1	22.0	22.1	-1.05	-1.99	-18.96	-13.58
24	1.8	3.7	21.5	20.6	22.0	22.0	22.0	-2.19	-2.47	-16.01	-15.18
Mean	16.0	16.7	21.4	21.3	21.8	21.8	22.0	-4.46	-3.82	-4.20	-4.26

*Data are averages of 8 thermocouples, not 16.

Heat flux measured on Wall C4 using 4x4-in. (100x100-mm) heat flux transducers located on indoor and outdoor wall surfaces are denoted q_{hfm} and q'_{hfm}, respectively. Heat flux transducer data were calibrated using results from steady-state calibrated hot box tests for the wall.

Heat flux predicted by steady-state analysis is denoted q_{ss}. Values were calculated on an hourly basis from wall surface temperatures using the following equation:

$$q_{ss} = (t_2 - t_1)/R \tag{1}$$

where

q_{ss} = heat flux through wall predicted by steady-state analysis, Btu/hr•ft^2 (W/m^2)

R = measured wall thermal resistance, hr•ft^2•°F/Btu (m^2•K/W)

t_2 = average temperature of outdoor wall surface, °F (°C)

t_1 = average temperature of indoor wall surface, °F (°C)

Thermal resistance is dependent on wall mean temperature and was derived from steady-state calibrated hot box tests.

Tables 7 through 9 also list calibrated hot box indoor and outdoor chamber relative humidities, and maximum and minimum laboratory air temperatures measured during tests.

Thermal Lag

One measure of dynamic thermal performance is thermal lag. Thermal lag is a measure of the response of indoor surface temperatures and heat flow to fluctuations in outdoor air temperatures. Lag is dependent on thermal resistance and heat storage capacity of the test specimen, since both of these factors influence the rate of heat flow.

For each dynamic test cycle, Table 10 lists thermal lags determined from calibrated hot box test results and measured heat flux transducer readings.

Calibrated hot box thermal lag is quantified by two methods. In one measure, denoted t_0 vs t_1, lag is calculated as the time required for the maximum or minimum indoor surface temperature to be reached after the maximum or minimum outdoor air temperature is attained. In the second measure, denoted q_{ss} vs q_w, lag is calculated as the time required for the maximum or minimum heat flow rate, q_w, to be reached after the maximum or minimum heat flow rate based on steady-state predictions, q_{ss}, is attained. This is illustrated in Fig. 13. Both measures give similar results. The second measure is also used to determine thermal lag for heat flux transducer data.

Average thermal lag values for Wall C4 range from 5 to 6 hours for the three dynamic cycles as shown in Table 10. Therefore, the peak heat flow through Wall C4 occurs between 5 and 6 hours after the time at which the peak heat flow predicted using steady-state analysis would occur.

Data from the heat flow meter mounted on the indoor surface of Wall C4, denoted q_{hfm} in the figures, show approximately the same lag time as heat flow measured by the hot box, q_w.

The time constant for Wall C4 is also listed in Table 10. A time constant is a theoretical value of heat flow delay calculated from the conductivity, specific heat, density, and thickness for each layer of building material in a wall system.

If the difference in temperature across a wall is changed abruptly from the steady-state condition, as in a step change, then the heat flow through the wall will theoretically reach 63.2% of the new steady-state equilibrium heat flow after a time period equal to the time constant.(16)

The following equation was used to calculate time constants:(16)

$$t_c = \frac{a_k}{\pi^2}\left(\sum_{n=1}^{n}(g_n X_n)\right)^2 \tag{2}$$

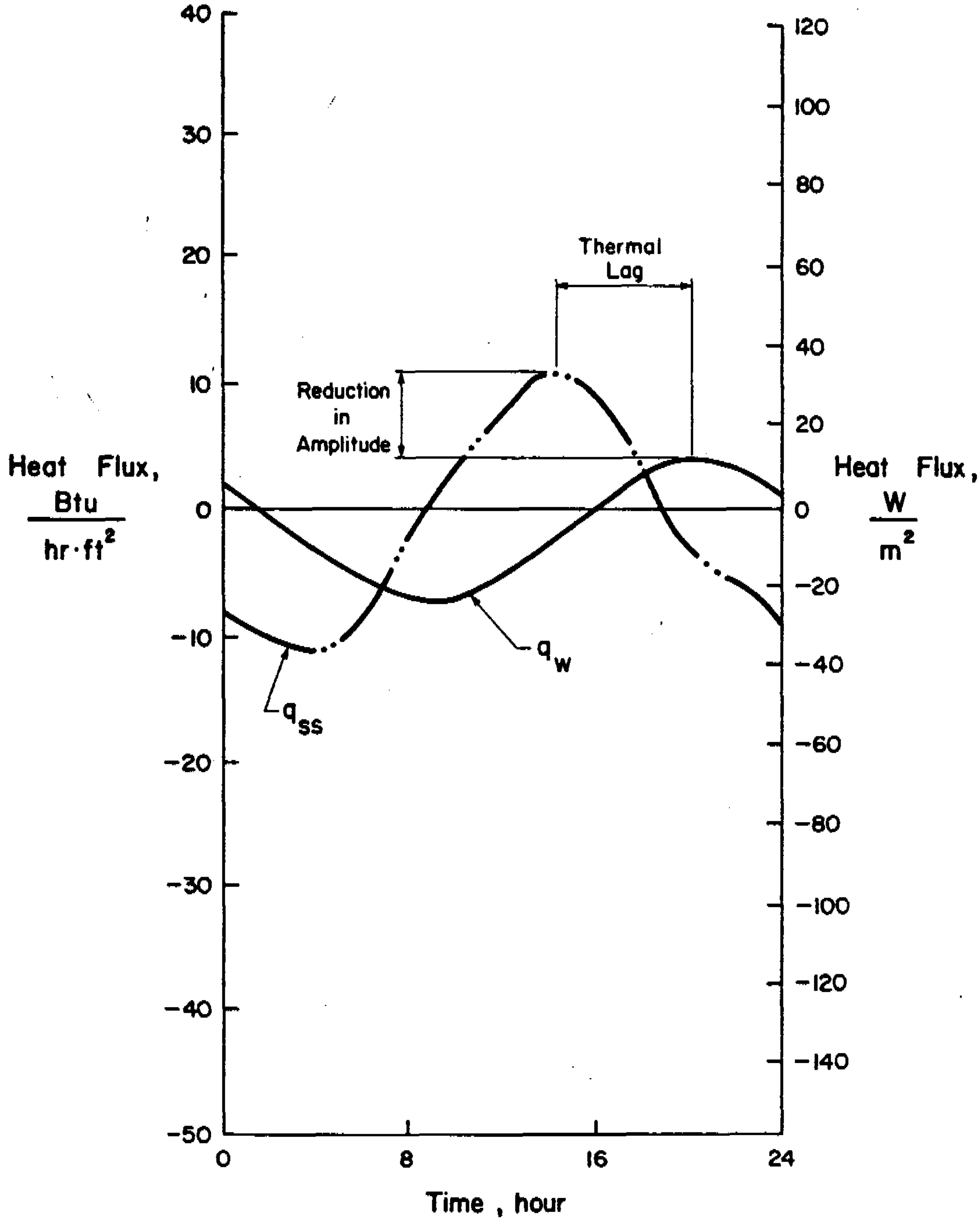


Fig. 13 Definition of Thermal Lag and Reduction in Amplitude

where

t_c = characteristic time constant of building component, hr (s)

g_n = $(a_n/a_k),^{1/2}$ conversion constant adjusting thickness of layer to make material uniform throughout wall

a_n = $r_n c_n d_n$, reciprocal of diffusivity of n-th layer, hr/ft^2 (s/m^2)

a_k = a_n at layer k chosen for normalization

r_n = resistivity of n-th layer, or reciprocal of conductivity of n-th layer, hr•ft•°F/Btu (m•K/W)

c_n = specific heat of n-th layer, Btu/lb•°F (J/kg•K)

d_n = density of n-th layer, lb/ft^3 (kg/m^3)

X_n = thickness of n-th layer, ft (m)

All properties used to calculate the time constant for Wall C4 were determined from measurements performed at CTL with the following exceptions. The specific heat of the insulation was taken from Reference 14. Thermal resistance of the insulation was taken from manufacturer's specifications.(13)

Details on the derivation, calculation, and significance of time constants are available in Reference 16.

Reduction in Amplitude

Reduction in amplitude is a second measure of dynamic thermal performance. Reduction in amplitude, as well as thermal lag, is influenced by both wall thermal resistance and heat storage capacity. Reduction in amplitude is dependent on the temperature cycle applied to the test specimen.

Reduction in amplitude is defined as the percent reduction in peak heat flow when compared to peak heat flow calculated using steady-state theory.

Reduction in amplitude is illustrated in Fig. 13. Values for reduction in amplitude were calculated using the following equation:

$$A = [1-(q' - \bar{q})/(q'_{ss} - \bar{q}_{ss})]\cdot 100 \qquad (3)$$

where

A = reduction in amplitude, %

q' = maximum or minimum measured heat flow through wall

$\bar{q}$ = mean measured heat flow through wall

q'_{ss} = maximum or minimum heat flow through wall predicted by steady-state analysis

$\bar{q}_{ss}$ = mean heat flow through wall predicted by steady-state analysis

Table 11 lists reduction in amplitude values for each dynamic temperature cycle applied to Wall C4. Average reduction in amplitude values for measured heat flow, q_w, for Wall C4 range from 65% for the NBS-10 Test Cycle to 74% for the NBS+10 Test Cycle. Reduction in amplitude values calculated from heat flux transducer measurements range from 78 to 79%.

Amplitudes for heat flux transducer data, q_{hfm}, are generally not the same as those for measured heat flow, q_w. Heat flux transducer measurements are affected by discontinuities in contact between the heat flux transducer and wall surface. Heat flux amplitudes also differ because of the physical presence of the instrument mounted on a wall. A wall's thermal properties are altered at the location of a heat flux transducer. In addition, heat flux transducer calibration using steady-state results does not correct for dynamic effects of the instrument location.

Actual maximum heat flow through a wall is important in determining the peak energy load for a building envelope. Test results show anticipated peak energy demands based on actual heat flow are less than those based on steady-state predictions for massive wall systems. Calculations based on steady-state

TABLE 11 - REDUCTION IN AMPLITUDE FOR WALL C4

Test Cycle	Measured, %					
	Calibrated Hot Box			Heat Flux Transducer		
	@ Max.	@ Min.	Avg.	@ Max.	@ Min.	Avg.
NBS	73	69	71	82	75	79
NBS+10	75	72	74	80	75	78
NBS-10	68	61	65	81	76	79

analysis overestimate peak heat flow for the three dynamic temperature cycles applied to Wall C4.

Total Heat Flux

Results of dynamic tests are also compared using measures of total heat flux through a test specimen, illustrated in Fig. 14 and listed in Table 12. The curve marked "q_w" is measured heat flux through the test wall. Areas enclosed by the measured heat flux curve and the horizontal axis were used to provide an indication of total heat flux through the wall. The sum of the areas above and below the horizontal axis is total heat flux for a 24-hr period, denoted as q_w^T in Table 12.

A similar procedure is used to calculate total heat flux for a 24-hr period from measured heat flux transducer data, q_{hfm}, and predictions based on steady-state analysis, q_{ss}. These are also denoted by the superscript "T" in Table 12.

"Total Heat Flux Comparisons" listed in Table 12 show measured heat flux as a percentage of predicted heat flux based on steady-state analysis.

As can be seen in the "Total Heat Flux Comparisons" column of Table 12, total heat flux measured using the calibrated hot box and the heat flux transducer is less than half the total heat flux predicted by steady-state analysis. This is the case for all three dynamic cycles applied to Wall C4. Values of q_w^T / q_{ss}^T, heat flux from calibrated hot box measurements divided by calculated heat flux, range from 30% for the NBS Test Cycle to 47% for the NBS-10 Test Cycle.

It is important to note that comparison of measured heat flux values for the test walls is limited to specimens and dynamic cycles evaluated in this program. Results are for diurnal test cycles and should not be arbitrarily assumed to represent annual heating and cooling loads. In addition, results

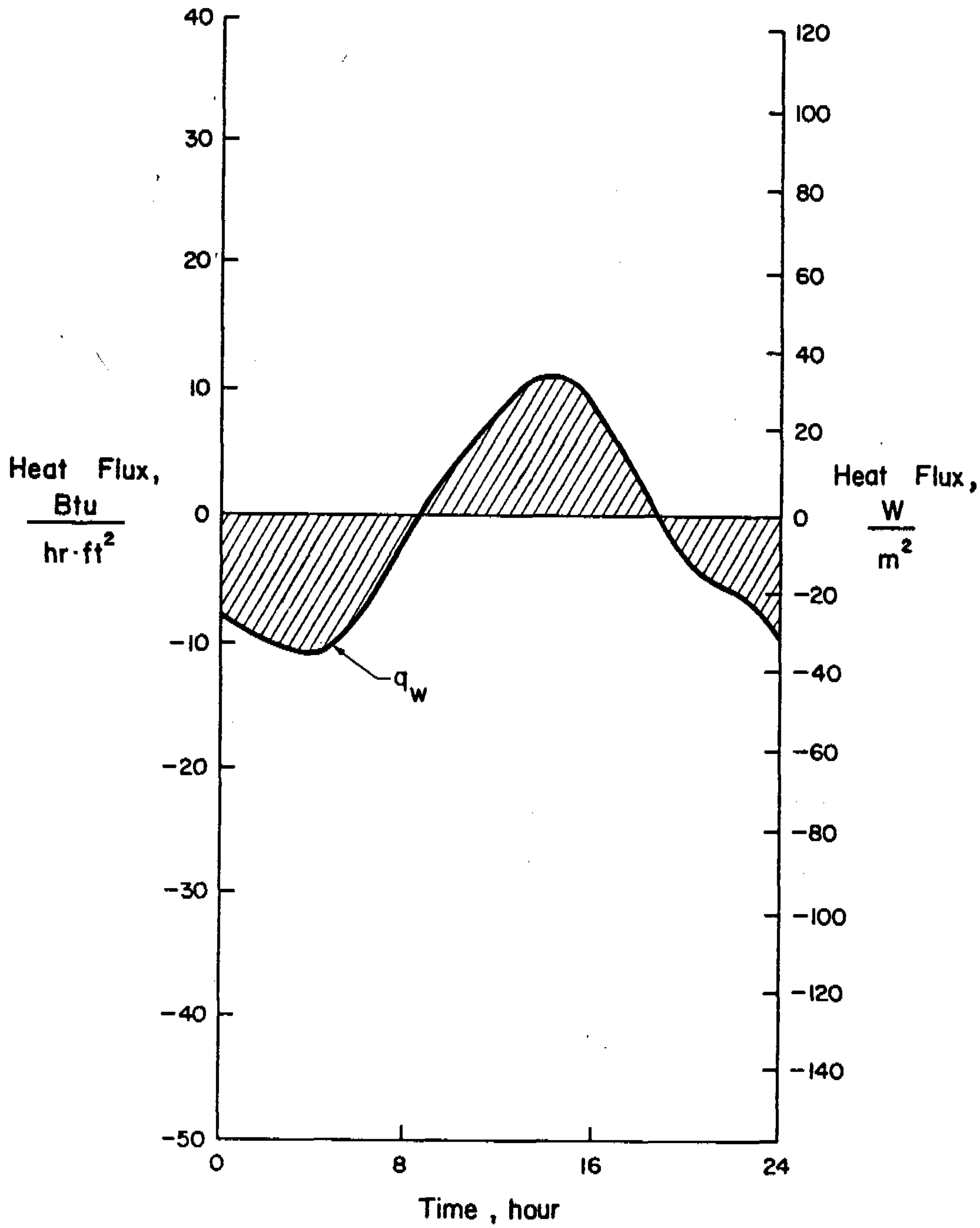


Fig. 14 Definition of Measured Total Heat Flux

TABLE 12 - TOTAL AND NET HEAT FLUX FOR WALL C4

Test Cycle	Total Heat Flux, Btu/ft^2 (W·hr/m^2)			Total Heat Flux Comparisons, %		Net Heat Flux, Btu/ft^2 (W·hr/m^2)			Net Heat Flux, Comparisons, %	
	Measured		Calculated	$\frac{q_w^T}{q_{ss}^T}$	$\frac{q_{hfm}^T}{q_{ss}^T}$	Measured		Calculated	$\frac{q_w^N}{q_{ss}^N}$	$\frac{q_{hfm}^N}{q_{ss}^N}$
	q_w^T	q_{hfm}^T	q_{ss}^T			q_w^N	q_{hfm}^N	q_{ss}^N		
NBS	20.5 (64.8)	14.1 (44.6)	69.6 (219.5)	30	20	-6.8 (-21.4)	-2.7 (-8.6)	-5.7 (-18.1)	118	48
NBS+10	30.1 (94.8)	25.7 (81.1)	67.0 (211.5)	45	38	30.1 (94.8)	25.7 (81.1)	22.9 (72.3)	131	112
NBS-10	34.6 (109.0)	29.1 (91.7)	73.4 (231.7)	47	40	-33.9 (-107.0)	-29.1 (-91.7)	-32.4 (-102.3)	105	90

are for individual opaque wall assemblies. As such, they are representative of only one component of the building envelope.

Net Heat Flux

Total heat flux is defined as the cumulative or integrated heat flux for a given period of time. Net heat flux is the average heat flux for a given period of time, multipled by the length of the time period. Total heat flux is equal to net heat flux for time periods with no reversals in heat flow through the specimen.

Net heat flux for a 24-hr periodic cycle is equal to the sum of hourly measured rates of heat flux. These values can be determined by totaling values of "q" from columns of Tables 7 through 9. Net heat flux values are denoted by the superscript "N" in Table 12.

The column labeled "Net Heat Flux Comparisons" lists measured heat flux as a percentage of predicted net heat flux based on steady-state analysis. Measured calibrated hot box net heat flux theoretically should be equal to net heat flux based on steady-state predictions.

Transient Tests

Time required for a wall to reach a steady-state condition can be determined from transient tests. This time is affected by both thermal resistance and heat storage capacity of the test wall.

Transient tests with a final wall mean temperature of about 32°F (0°C) were performed on Walls C3 and C4. A transient test was not performed on Wall S1. Appendix A contains transient test results for Wall C3. Transient test results for Walls C3 and C4 are compared in the section of this report entitled "Comparison of Test Results for Walls with Similar R-Values."

Test Procedures

Results of a transient test are determined from data collected in the period of time between two steady-state tests. After a wall has achieved a steady-state condition, denoted time 0, the outdoor chamber temperature setting is changed. The transient test continues until the wall reaches an equilibrium for the new outdoor chamber air temperature. The rate of heat flow through a test specimen is determined from hourly averages of data.

Test Results

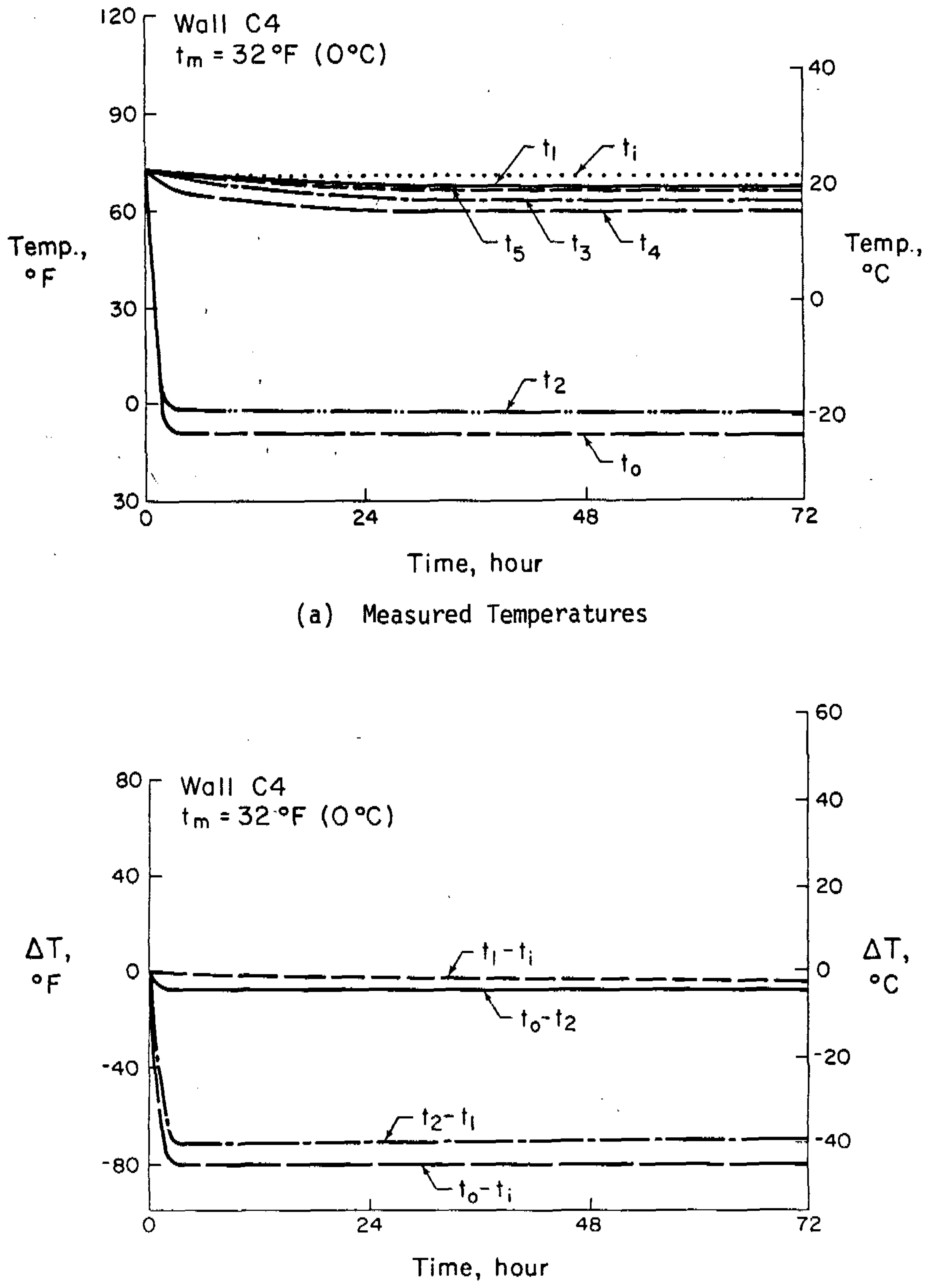
Results are illustrated in Fig. 15 and listed in Table 13 for a transient test with initial and final wall mean temperatures of 72°F (22°C) and 32°F (0°C), respectively. Table 6 in the "Dynamic Tests" section lists brief descriptions of symbols used in test data figures and tables.

Figure 15(a) presents measured air, surface, and internal wall temperatures. Air-to-air, surface-to-surface, and surface-to-air temperature differentials are illustrated in Fig. 15(b). Figure 15(c) presents heat flow measured by the calibrated hot box, q_w, and heat flow predicted by steady-state analysis, q_{ss}. Heat flow rates measured by heat flux transducers mounted on the indoor surface of Wall C4, q_{hfm}, and on the outdoor wall surface, q'_{hfm}, are also shown in Fig. 15(c). Values are shown as a function of time.

Heat flow predicted by steady-state analysis, q_{ss}, was calculated using Eq. 1 with measured indoor and outdoor wall surface temperatures and measured wall thermal resistance. Values of q_{ss} change dramatically during the first portion of a transient test because of changes in outdoor surface temperatures.

Table 13(a) lists measured temperatures and heat flux in U.S. units. Table 13(b) lists values in SI units.

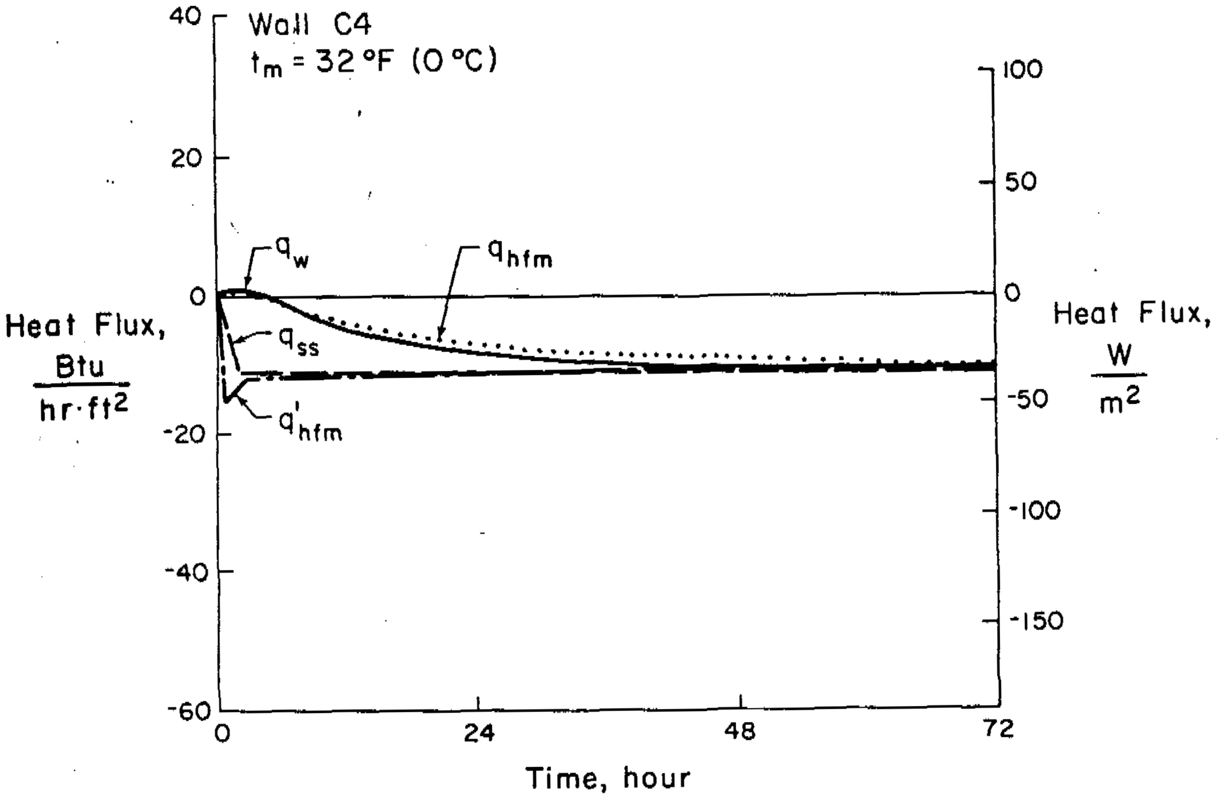
Table 14 lists time required to reach 99.5, 95, 90, and 63% of the final steady-state heat flux achieved during a transient test. Steady-state analysis



(a) Measured Temperatures

(b) Temperature Differentials

Fig. 15 Transient Test Results for Wall C4



(c) Heat Flux

Fig. 15 Transient Test Results for Wall C4

TABLE 13(a) - TRANSIENT TEST RESULTS FOR WALL C4

Time, hr	Measured Temperatures, °F							Measured Heat Flux, Btu/hr·ft^2			Calculated Heat Flux, Btu/hr·ft^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_4 Conc./ Insul.	t_3 Internal Conc.	t_5* Indoor Surf., Embed.	t_1 Indoor Surf., Taped	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
0	71.8	72.1	72.3	71.7	72.2	72.0	71.7	0.16	0.09	-0.11	0.02
1	28.6	35.2	70.3	71.5	72.2	71.9	71.7	0.61	0.10	-15.32	-5.37
2	-5.4	2.1	67.7	71.1	72.2	71.9	71.7	0.87	0.04	-13.21	-10.19
3	-9.2	-1.8	66.6	70.6	71.9	71.7	71.7	0.60	-0.28	-11.06	-10.73
4	-9.4	-2.0	65.9	70.1	71.6	71.5	71.6	-0.26	-0.72	-10.86	-10.73
5	-9.5	-2.1	65.4	69.6	71.3	71.2	71.6	-0.82	-1.24	-10.78	-10.71
6	-9.4	-2.2	64.9	69.2	70.9	70.9	71.5	-1.59	-1.68	-10.68	-10.67
7	-9.4	-2.2	64.5	68.8	70.6	70.5	71.5	-2.15	-2.16	-10.64	-10.62
8	-9.5	-2.3	64.0	68.3	70.3	70.4	71.4	-2.97	-2.60	-10.60	-10.62
9	-9.6	-2.4	63.7	67.9	70.0	70.2	71.3	-3.49	-3.10	-10.53	-10.60
10	-9.6	-2.4	63.3	67.5	69.8	70.0	71.3	-4.18	-3.49	-10.42	-10.57
11	-9.5	-2.4	62.9	67.2	69.5	69.8	71.2	-4.57	-3.89	-10.43	-10.55
12	-9.6	-2.5	62.6	66.9	69.3	69.6	71.2	-4.75	-4.20	-10.38	-10.53
13	-9.6	-2.5	62.3	66.6	69.1	69.5	71.1	-5.20	-4.57	-10.31	-10.51
14	-9.6	-2.6	62.0	66.3	68.8	69.3	71.1	-5.53	-4.91	-10.25	-10.49
15	-9.6	-2.6	61.7	66.1	68.6	69.1	71.0	-5.81	-5.18	-10.16	-10.47
16	-9.6	-2.7	61.5	65.8	68.4	69.0	71.0	-6.19	-5.44	-10.24	-10.46
17	-9.6	-2.7	61.2	65.6	68.3	68.8	71.0	-6.03	-5.76	-10.17	-10.44
18	-9.6	-2.7	61.0	65.4	68.1	68.7	70.9	-6.27	-5.96	-10.05	-10.42
19	-9.6	-2.7	60.8	65.2	68.0	68.6	70.9	-6.60	-6.27	-10.04	-10.40
20	-9.6	-2.7	60.6	65.0	67.8	68.5	70.9	-6.81	-6.47	-10.03	-10.39
21	-9.7	-2.8	60.4	64.9	67.7	68.4	70.9	-7.14	-6.71	-9.99	-10.38
22	-9.7	-2.8	60.3	64.7	67.6	68.2	70.8	-7.28	-6.87	-9.96	-10.37
23	-9.7	-2.8	60.1	64.5	67.4	68.2	70.8	-7.82	-7.04	-9.95	-10.36
24	-9.7	-2.8	60.0	64.4	67.4	68.1	70.8	-7.79	-7.16	-9.93	-10.35
26	-9.6	-2.8	59.7	64.1	67.2	67.9	70.7	-8.20	-7.50	-9.83	-10.32
28	-9.7	-2.8	59.5	63.9	67.0	67.8	70.7	-8.66	-7.71	-9.84	-10.31
30	-9.7	-2.9	59.3	63.8	66.8	67.7	70.7	-8.70	-8.06	-9.78	-10.29
32	-9.7	-2.9	59.1	63.6	66.7	67.5	70.6	-8.99	-8.22	-9.79	-10.28
34	-9.7	-2.9	59.0	63.4	66.6	67.4	70.6	-9.12	-8.46	-9.73	-10.27
36	-9.8	-2.9	58.8	63.2	66.4	67.4	70.6	-9.40	-8.62	-9.81	-10.26
38	-9.7	-2.9	58.7	63.1	66.4	67.3	70.6	-9.53	-8.74	-9.69	-10.24
40	-9.8	-2.9	58.7	63.1	66.3	67.2	70.5	-9.55	-8.92	-9.74	-10.24
42	-9.8	-2.9	58.5	62.9	66.2	67.1	70.5	-9.60	-8.89	-9.71	-10.23
44	-9.8	-2.9	58.5	62.9	66.1	67.1	70.5	-9.53	-9.04	-9.62	-10.22
46	-9.8	-2.9	58.4	62.8	66.1	67.1	70.5	-9.71	-9.14	-9.69	-10.22
48	-9.8	-3.0	58.3	62.8	66.1	67.0	70.5	-9.88	-9.22	-9.67	-10.22
50	-9.7	-3.0	58.3	62.7	66.0	67.0	70.5	-9.78	-9.22	-9.69	-10.21
52	-9.9	-3.0	58.2	62.6	66.0	67.0	70.5	-9.69	-9.31	-9.70	-10.22
54	-10.0	-3.3	58.0	62.5	65.6	66.6	70.4	-9.28	-9.29	-9.61	-10.21
56	-10.0	-3.2	58.1	62.5	65.7	66.7	70.4	-9.44	-9.39	-9.64	-10.21
58	-9.9	-3.0	58.1	62.6	65.5	66.8	70.5	-9.55	-9.40	-9.63	-10.20
60	-9.8	-3.0	58.1	62.5	65.9	66.9	70.5	-9.84	-9.49	-9.59	-10.20
62	-9.8	-3.0	58.1	62.5	65.8	66.9	70.5	-9.92	-9.59	-9.57	-10.20
64	-9.8	-3.0	58.0	62.5	65.8	66.9	70.5	-10.03	-9.58	-9.64	-10.20
66	-9.9	-3.0	58.1	62.5	65.9	66.9	70.5	-9.99	-9.56	-9.62	-10.20
68	-9.8	-3.0	58.1	62.4	65.9	66.9	70.5	-9.99	-9.71	-9.62	-10.21
70	-9.7	-3.0	58.0	62.4	65.8	66.8	70.5	-9.69	-9.68	-9.68	-10.20
72	-9.9	-3.2	58.0	62.4	65.8	66.8	70.5	-9.56	-9.70	-9.66	-10.22

*Data are averages of 8 thermocouples, not 16.

TABLE 13(b) - TRANSIENT TEST RESULTS FOR WALL C4, SI UNITS

Time, hr	Measured Temperatures, °C							Measured Heat Flux, W/m^2			Calculated Heat Flux, W/m^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_4 Conc./ Insul.	t_3 Internal Conc.	t_5* Indoor Surf., Embed.	t_1 Indoor Surf., Taped	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
0	22.1	22.3	22.4	22.1	22.4	22.2	22.1	0.5	0.3	-0.3	0.1
1	-1.9	1.8	21.3	21.9	22.3	22.2	22.1	1.9	0.3	-48.3	-16.9
2	-20.8	-16.6	19.8	21.7	22.3	22.2	22.1	2.8	0.1	-41.7	-32.2
3	-22.9	-18.8	19.2	21.5	22.2	22.1	22.1	1.9	-0.9	-34.9	-33.9
4	-23.0	-18.9	18.8	21.2	22.0	21.9	22.0	-0.8	-2.3	-34.3	-33.9
5	-23.0	-19.0	18.6	20.9	21.8	21.8	22.0	-2.6	-3.9	-34.0	-33.8
6	-23.0	-19.0	18.3	20.7	21.6	21.6	22.0	-5.0	-5.3	-33.7	-33.7
7	-23.0	-19.0	18.1	20.4	21.4	21.4	21.9	-6.8	-6.8	-33.6	-33.5
8	-23.0	-19.1	17.8	20.2	21.3	21.3	21.9	-9.4	-8.2	-33.4	-33.5
9	-23.1	-19.1	17.6	20.0	21.1	21.2	21.8	-11.0	-9.8	-33.2	-33.4
10	-23.1	-19.1	17.4	19.7	21.0	21.1	21.8	-13.2	-11.0	-32.9	-33.4
11	-23.1	-19.1	17.2	19.6	20.8	21.0	21.8	-14.4	-12.3	-32.9	-33.3
12	-23.1	-19.2	17.0	19.4	20.7	20.9	21.8	-15.0	-13.3	-32.8	-33.2
13	-23.1	-19.2	16.9	19.2	20.6	20.8	21.7	-16.4	-14.4	-32.5	-33.2
14	-23.1	-19.2	16.7	19.1	20.5	20.7	21.7	-17.4	-15.5	-32.4	-33.1
15	-23.1	-19.2	16.5	18.9	20.3	20.6	21.7	-18.3	-16.4	-32.0	-33.0
16	-23.1	-19.3	16.4	18.8	20.2	20.5	21.7	-19.5	-17.2	-32.3	-33.0
17	-23.1	-19.3	16.2	18.7	20.2	20.5	21.7	-19.0	-18.2	-32.1	-32.9
18	-23.1	-19.3	16.1	18.6	20.0	20.4	21.6	-19.8	-18.8	-31.7	-32.9
19	-23.1	-19.3	16.0	18.4	20.0	20.3	21.6	-20.8	-19.8	-31.7	-32.8
20	-23.1	-19.3	15.9	18.4	19.9	20.3	21.6	-21.5	-20.4	-31.6	-32.8
21	-23.1	-19.3	15.8	18.3	19.8	20.2	21.6	-22.5	-21.2	-31.5	-32.8
22	-23.2	-19.3	15.7	18.2	19.8	20.1	21.6	-23.0	-21.7	-31.4	-32.7
23	-23.2	-19.3	15.6	18.1	19.7	20.1	21.5	-24.7	-22.2	-31.4	-32.7
24	-23.1	-19.3	15.6	18.0	19.7	20.1	21.5	-24.6	-22.6	-31.3	-32.6
26	-23.1	-19.3	15.4	17.9	19.5	20.0	21.5	-25.9	-23.7	-31.0	-32.6
28	-23.1	-19.4	15.3	17.7	19.4	19.9	21.5	-27.3	-24.3	-31.0	-32.5
30	-23.1	-19.4	15.2	17.6	19.4	19.8	21.5	-27.5	-25.4	-30.9	-32.5
32	-23.2	-19.4	15.1	17.5	19.3	19.7	21.5	-28.4	-25.9	-30.9	-32.4
34	-23.2	-19.4	15.0	17.4	19.2	19.7	21.4	-28.8	-26.7	-30.7	-32.4
36	-23.2	-19.4	14.9	17.4	19.1	19.6	21.4	-29.7	-27.2	-30.9	-32.4
38	-23.2	-19.4	14.9	17.3	19.1	19.6	21.4	-30.1	-27.6	-30.6	-32.3
40	-23.2	-19.4	14.8	17.3	19.1	19.6	21.4	-30.1	-28.1	-30.7	-32.3
42	-23.2	-19.4	14.7	17.2	19.0	19.5	21.4	-30.3	-28.0	-30.6	-32.3
44	-23.2	-19.4	14.7	17.2	19.0	19.5	21.4	-30.1	-28.5	-30.3	-32.2
46	-23.2	-19.4	14.7	17.1	18.9	19.5	21.4	-30.6	-28.8	-30.6	-32.2
48	-23.2	-19.4	14.6	17.1	18.9	19.5	21.4	-31.2	-29.1	-30.5	-32.3
50	-23.2	-19.4	14.6	17.1	18.9	19.4	21.4	-30.8	-29.1	-30.6	-32.2
52	-23.3	-19.5	14.6	17.0	18.9	19.4	21.4	-30.6	-29.4	-30.6	-32.2
54	-23.3	-19.6	14.5	16.9	18.7	19.2	21.3	-29.3	-29.3	-30.3	-32.2
56	-23.4	-19.6	14.5	17.0	18.7	19.3	21.3	-29.8	-29.6	-30.4	-32.2
58	-23.3	-19.5	14.5	17.0	18.6	19.4	21.4	-30.1	-29.7	-30.4	-32.2
60	-23.2	-19.4	14.5	17.0	18.8	19.4	21.4	-31.0	-29.9	-30.3	-32.2
62	-23.2	-19.4	14.5	17.0	18.8	19.4	21.4	-31.3	-30.2	-30.2	-32.2
64	-23.2	-19.5	14.5	17.0	18.8	19.4	21.4	-31.7	-30.2	-30.4	-32.2
66	-23.3	-19.4	14.5	16.9	18.8	19.4	21.4	-31.5	-30.2	-30.3	-32.2
68	-23.2	-19.5	14.5	16.9	18.8	19.4	21.4	-31.5	-30.6	-30.4	-32.2
70	-23.2	-19.5	14.4	16.9	18.8	19.4	21.4	-30.6	-30.5	-30.6	-32.2
72	-23.3	-19.5	14.4	16.9	18.8	19.3	21.4	-30.2	-30.6	-30.5	-32.2

*Data are averages of 8 thermocouples, not 16.

TABLE 14 - SUMMARY OF TRANSIENT TEST RESULTS FOR WALL C4

Heat Flux	Measured				Calculated	
	Calib. Hot Box		HFM @ Indoor Surf.		Steady-State	
	q_w, Btu/hr·ft^2 (W/m^2)	Time to Reach q_w, hr	q_{hfm}, Btu/hr·ft^2 (W/m^2)	Time to Reach q_{hfm}, hr	q_{ss}, Btu/hr·ft^2 (W/m^2)	Time to Reach q_{ss}, hr
99.5% of Final Heat Flux	-9.9 (-31.4)	64	-9.7 (-30.6)	68	-10.2 (-32.1)	2
95% of Final Heat Flux	-9.5 (-30.0)	38	-9.3 (-29.2)	52	-9.7 (-30.6)	2
90% of Final Heat Flux	-9.0 (-28.4)	32	-8.8 (-27.6)	38	-9.2 (-29.0)	2
63% of Final Heat Flux	-6.3 (-19.8)	18	-6.0 (-19.1)	19	-6.4 (-20.3)	2

using measured wall surface temperatures predicted 95% of the final heat flux would be reached after 2 hours for Wall C4. Calibrated hot box test results show that 95% of the final heat flux is reached after 38 hours. The amount of time required for Wall C4 to reach 95% of the final heat flux was 19 times greater than steady-state predictions. Similarly, the amount of time required for Wall C4 to reach 63% of the final heat flux was 9 times greater than steady-state predictions. Massive walls, such as Wall C4 "damp out" effects of a sudden change in outdoor air temperature.

COMPARISON OF TEST RESULTS FOR WALLS WITH SIMILAR R-VALUES

In this section, results for Wall C4 are compared to those of two specimens previously tested in the calibrated hot box. Specimens used for comparison are Wall C3, low density concrete, and Wall S1, fiberglass board insulation. Each specimen has an R-value of about 7 hr•ft^2•°F/Btu (1.2 m^2•K/W). However, the specimens have different levels of thermal mass. Wall C4 has a relatively large thermal mass isolated from the outdoor environment by board insulation. Wall C3 consists of a low density concrete with a relatively high insulating value. Wall S1 consists of insulation alone with relatively low thermal mass. Results of steady-state, dynamic, and transient calibrated hot box tests are compared.

Calibrated hot box test results for Walls C3 and S1 are summarized in Appendix A. Each table or figure designation in Appendix A identifies the wall described and the type of data presented. Designation formats are

XX-Y

where

XX = designation of measured wall (C3 or S1)

Y = table or figure type as described in Table 15

TABLE 15 - APPENDIX A TABLE AND FIGURE DESCRIPTIONS

Appendix A Table or Figure No.	Description
Table XX-1*	Physical Properties of Wall at Time of Test
Table XX-2	Material Properties
Table XX-3	Design Heat Transmission Coefficients
Table XX-4	Steady-State Test Results
Figure XX-1	Transient Test Results
Table XX-5	Transient Test Results
Table XX-6	Summary of Transient Test Results
Figure XX-2	Dynamic Test Results (Periodic) for NBS Test Cycle
Table XX-7	Dynamic Test Results (Periodic) for NBS Test Cycle
Figure XX-3 and XX-4	Dynamic Test Results (Periodic) for Test Cycles Other Than the NBS Cycle.
Table XX-8 and XX-9	Dynamic Test Results (Periodic) for Test Cycles Other Than the NBS Cycle
Table XX-10	Summary of Dynamic Test Results (Periodic), Thermal Lag
Table XX-11	Summary of Dynamic Test Results (Periodic), Reduction in Amplitude
Table XX-12	Summary of Dynamic Test Results (Periodic), Energy Requirements

*Characters in the "XX" position are wall designations (C3 or S1).

Test Specimens

Wall C4 is described in the section of this report entitled "Concrete Wall with Board Insulation." Following are brief descriptions of wall construction and instrumentation for Walls C3 and S1.

Wall C3: Low Density Concrete

Wall C3 was a low density concrete wall with a unit weight of 46 pcf (740 kg/m^3) and an average measured thickness of 8.52 in. (216 mm). The wall had overall nominal dimensions of 103x103 in. (2.62x2.62 m). Calibrated hot box test results for Wall C3 are presented in Appendix A and have been previously published in References 6 and 8. Details of Wall C3 construction are given in Reference 6.

Wall C3 was cast horizontally in July 1981. The wall was cured in formwork for 14 days. After removing formwork, the wall was air cured in the laboratory at an air temperature of 73±5°F (23±3°C) and 45±15% RH for six months prior to testing. Wall C3 was tested in the calibrated hot box in February and March 1982.

Expanded perlite aggregate with a maximum size which passed through a No. 8 (2.36 mm) mesh was used in the concrete for Wall C3. Expanded perlite is produced by heating and thereby expanding perlite, a volcanic glass.

Wall C3 reinforcement consisted of a single layer of 0.24-in. (6-mm) diameter bars spaced 12-in. (300-mm) center-to-center in each direction. The reinforcement was placed at the approximate midthickness of the wall.

Control specimens were cast of the same concrete used in Wall C3. Table 16 shows physical properties of Wall C3 and control specimens. Thermal properties of concrete used for Wall C3 are presented in Table C3-2(a) of Appendix A.

Prior to testing, shrinkage cracks became visible on both sides of Wall C3. The faces of the wall were coated with a cementitious waterproofing material that sealed minor surface imperfections, including observed shrinkage cracks.

TABLE 16 - PHYSICAL PROPERTIES OF WALL C3(6)

Property	Measured Value
Unit Weight of Wall, pcf (kg/m^3)	46 (740)
Estimated Moisture Content of Wall, % ovendry weight	9.5
Average Thickness, in. (mm)	8.52 (216)
Area, ft^2 (m^2)	73.79 (6.86)
Concrete Compressive Strength, psi (MPa)	
moist cured*	750 (5.2)
air cured**	880 (6.1)
Concrete Splitting Tensile Strength, psi (MPa)	
moist cured*	140 (0.95)
air cured**	65 (0.45)

*Measured on 6x12-in. (150x300-mm) cylinders cured in molds for first 24 hours, then moist cured for 27 days.
**Measured on 6x12-in. (150x300-mm) cylinders cured in molds for first 14 days, then air cured for 204 days.

A textured, non-cementitious white paint was used as a finish coat to provide a uniform surface for both wall faces.

Thermocouples corresponding to ASTM Designation: E230, "Standard Temperature-Electromotive Force (EMF) Tables for Thermocouples,"[10] Type T, were used to measure temperatures. There were 16 in the air space of each chamber, 16 on each face of the test wall and 16 at the approximate midthickness of the wall. Thermocouples were uniformly distributed on a 20-3/5-in. (525-mm) square grid over the wall area.

Thermocouples measuring temperatures in the air space of each chamber were located approximately 3 in. (75 mm) from the face of the test wall.

Surface thermocouples were securely taped to the wall over a length of approximately 3-in. (75-mm). Tape that covered the sensors was painted the same color as the test wall surface.

Internal thermocouples were cast 4 in. (100 mm) from the formwork base. To secure their location, thermocouples were taped to reinforcement or suspended by wire between reinforcement. Thermocouple junctions were not placed in contact with the reinforcement. This was done for all internal thermocouples to avoid any influence on internal heat flow through reinforcement. Thermocouples were wired such that electrical averages of four thermocouple junctions located along horizontal lines across the grid were obtained.

Heat flux transducers measuring 4x4-in. (100x100-mm) were mounted near the center of the indoor and outdoor wall surfaces. The transducers were mechanically fastened to the wall surfaces to ensure contact throughout the calibrated hot box test program. To mount the heat flux transducers on the concrete surface, 3/8-in. (10-mm) holes were drilled at selected mounting locations. Wood dowels 3/8-in. (10-mm) in diameter were epoxied in place and sanded flush with the wall surface. Each heat flux transducer surface in con tact with the wall surface was coated with a thin layer of high conductivity silicon grease. The heat flux transducers were then mounted on Wall C3 using screws into the wood dowels. The silicon grease provided uniform contact between the heat flux transducers and wall surfaces.

Wall S1: Fiberglass Board Insulation

Wall S1 consists of specially fabricated 1-3/8-in. (35-mm) fiberglass board insulation. This specimen was used as a "standard" specimen in the calibration of CTL's calibrated hot box (see Appendix B). Calibrated hot box test results are given in Appendix A and Reference 9.

Wall S1 was originally constructed and tested in the calibrated hot box in 1979. Reference 11 contains descriptions of construction and 1979 calibrated hot box test results for Wall S1. The specimen was fabricated from specially manufactured fiberglass boards that had a uniform density of 8.17 pcf (131 kg/m^2) and nominal dimensions of 4x10 ft (1.2x3.0 m). Faces were sanded to obtain a uniform thickness of 1.38 in. (35 mm). Boards were glued together along tongue and groove vertical joints and then cut to 8.58 ft (2.62 m) square to form the test specimen. To prevent air infiltration during calibrated hot box testing, each face of the specimen was covered with 0.004-in. (0.1-mm) thick polyethylene film.

Wall S1 was retested in the calibrated hot box during September and October 1981. Prior to retesting, the polyethylene film on specimen surfaces was replaced with a fiber-reinforced foil material. The foil was bonded to the fiberglass with a spray adhesive over the entire area of each face of the specimen. The foil facing on each side of the specimen was painted with an off-white flat latex wall paint.

Modifications were made in the method of calculating the indoor (metering) chamber cooling energy in August 1981. Wall S1 retest data provided information used in the revised calibration procedure. Calibrated hot box test results for Wall S1 in Appendix A and Reference 9 are from the tests conducted in 1981.

Thermocouples corresponding to ASTM Designation: E230, "Standard Temperature-Electromotive Force (EMF) Tables for Thermocouples,"[10] Type T, were used to measure temperatures. There were 16 in the air space of each chamber and 16 on each face of the test specimen. Thermocouples were uniformly distributed on a 20-3/5-in. (525-mm) square grid over the specimen area.

Thermocouples measuring temperatures in the air space of each chamber were located approximately 3 in. (75 mm) from the face of the test specimen.

Surface thermocouples were securely taped to the specimen over a length of approximately 3 in. (75 mm). Tape that covered the sensors was painted the same color as the test specimen surface.

Heat flux transducers measuring 4x4-in. (100x100-mm) were also mounted on each face of the specimen. Heat flux transducers were coated with a thin layer of high conductivity silicon grease. Duct tape was used to secure heat flux transducers to the specimen. Duct tape was painted the same color as the test specimen surface.

Unit weight, average thickness, area, and moisture content of Walls C4, C3, and S1 at time of calibrated hot box tests are summarized in Table 17.

Steady-State Test Results

Results of steady-state tests for Walls C3 and S1 are summarized in Appendix A in Tables C3-4 and S1-4, respectively. Steady-state test procedures and descriptions of the contents of Tables C3-4 and S1-4 are in the section of this report entitled "Concrete Wall with Board Insulation."

TABLE 17 - PHYSICAL PROPERTIES OF WALLS AT TIME OF TEST

Wall Designation	Wall Description	Measured Property			
		Unit Weight, psf (kg/m^2)	Average Thickness, in. (mm)	Area, ft^2 (m^2)	Moisture* Content, %
C4	Concrete with Outside Insulation	98.5 (480)	8.90 (225)	73.75 (6.85)	0.8
C3	Low Density Concrete	32.7 (160)	8.52 (216)	73.79 (6.86)	9.5
S1**	Fiberglass Board	1.07 (5.22)	1.46 (37.1)	73.21 (6.80)	--

*Measured on concrete, after tests.
**Specimen was tested September through October 1981. Properties were measured January 1985.

Thermal Resistance

Total thermal resistance values, R_T, for Walls C4, C3, and S1 are summarized in Table 18 and Fig. 16. Measured total thermal resistances in Table 18 are calculated from calibrated hot box heat flux measurements and surface temperatures from taped thermocouples. Values include standard surface resistance coefficients equal to 0.68 hr•ft^2•°F/Btu (0.12 m^2•K/W) on the indoor side and 0.17 hr•ft^2•°F/Btu (0.03 m^2•K/W) on the outdoor side. These values are commonly used in design and are considered to represent still air on the indoor wall surface and an air flow of 15 mph (24 km/hr) on the outdoor wall surface.

Design thermal resistances for the three walls are also listed in Table 18. Design values include standard surface resistance coefficients and were calculated in accordance with procedures established by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers.(14) Resistances for construction materials were taken from the ASHRAE Handbook - 1981 Fundamentals.(14) Reinforcement in Walls C3 and C4 was not considered in design calculations because reinforcing bars in these walls are not parallel to the direction of heat flow.

For Walls C4 and S1, measured total thermal resistances are within 10% of the calculated design values. For Wall C3, the measured thermal resistance is 24% less than the calculated design value from Reference 14.

As stated in the "Steady-State Tests" portion of the "Concrete Wall with Board Insulation" section of this report, contact resistance introduced by using taped thermocouples is more significant for walls with high thermal conductivity, such as normal weight concrete. Contact resistances for Wall C3 made with low density concrete, and Wall S1, made with fiberglass board, are expected to be significantly less than the 12% measured for Wall C6, which was

TABLE 18 - TOTAL THERMAL RESISTANCE, R_T

Wall Designation	Wall Description	Calculated (Design) R_T $hr \cdot ft^2 \cdot °F/Btu$ ($m^2 \cdot K/W$)	Measured R_T* $hr \cdot ft^2 \cdot °F/Btu$ ($m^2 \cdot K/W$)	Wall Mean Temperature, °F (°C)
C4	Concrete with Outside Insulation	6.94** (1.22)	7.64+ (1.35)	72 (22)
		—	7.85 (1.38)	32 (0)
		—	7.49 (1.32)	101 (38)
C3	Low Density Concrete	8.8** (1.56)	6.75+ (1.19)	72 (22)
		—	7.02 (1.24)	53 (11)
		—	6.53 (1.15)	89 (32)
		—	6.31 (1.11)	100 (38)
S1	Fiberglass Board	6.35** (1.12)	7.76+ (1.19)	72 (22)
		6.61*** (1.16)	—	72 (22)
		—	7.10 (1.25)	32 (0)
		—	6.50 (1.14)	103 (40)

*Total thermal resistance, R_T, for steady-state tests was calculated using design surface resistance coefficients, heat flux measured by the calibrated hot box, and surface temperatures from taped thermocouples.
**Calculated using properties from ASHRAE Handbook - 1981 Fundamentals.(14)
***Calculated using properties measured by Owens-Corning Fiberglass Corporation.
+Interpolated from calibrated hot box test results.

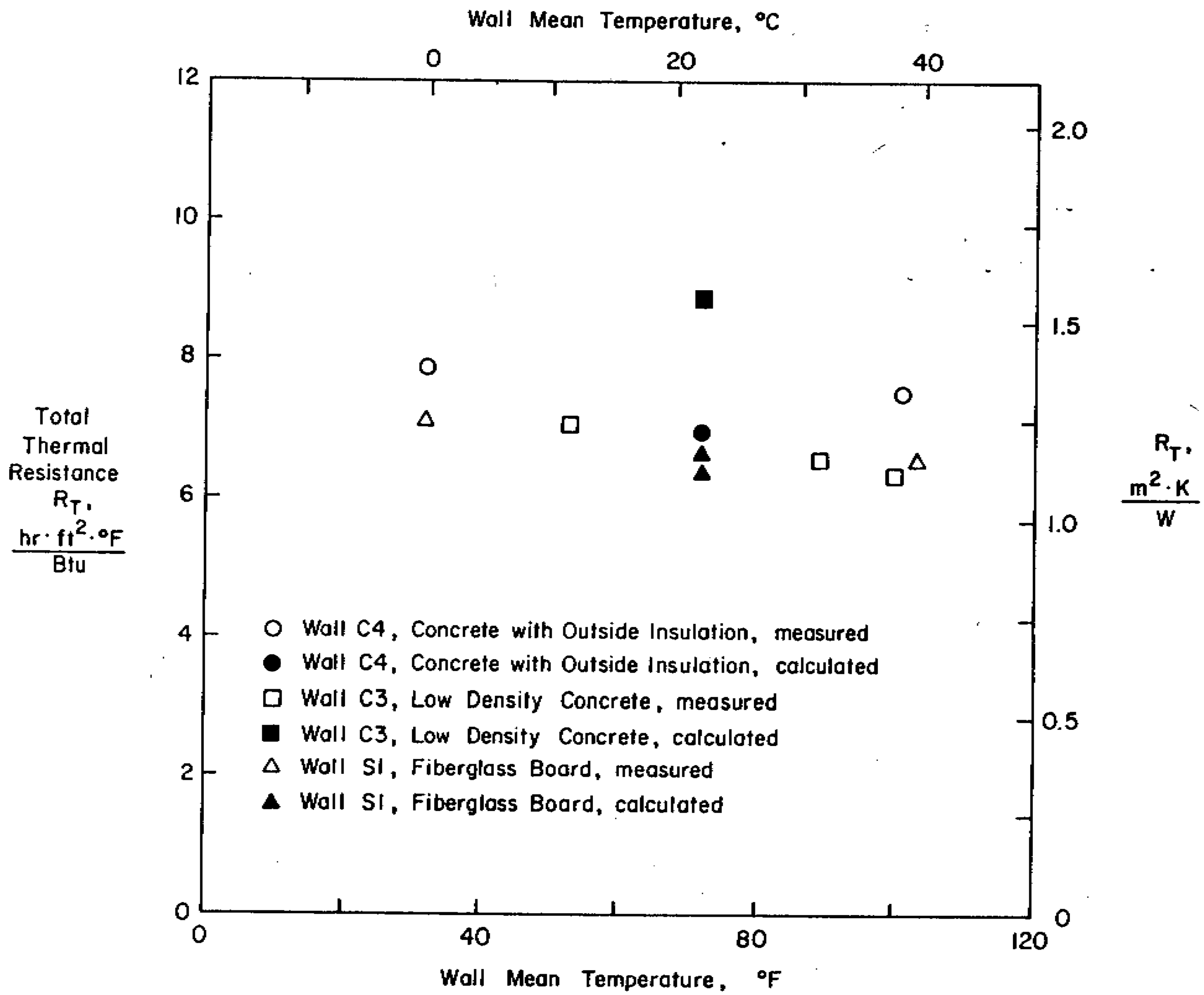


Fig. 16 Measured and Calculated Total Thermal Resistance

constructed with normal weight concrete.[12] The difference in Wall C4 resistances determined using taped and embedded thermocouples was 2%.

Steady-State Temperature Profiles

Figure 17 illustrates temperature profiles from steady-state calibrated hot box tests performed on Walls C4, C3, and S1. Wall mean temperatures are approximately 100°F (38°C). Figure 8(b) is repeated here as Figure 17(a) for comparison purposes.

Notation used to designate average measured temperatures is repeated here for convenience.

t_o = outdoor air temperature

t_2 = wall surface temperature, outdoor side

t_4 = internal wall temperature at interface of concrete and insulation (Wall C4 only)

t_3 = internal wall temperature at approximate midthickness of concrete (Walls C4 and C3 only)

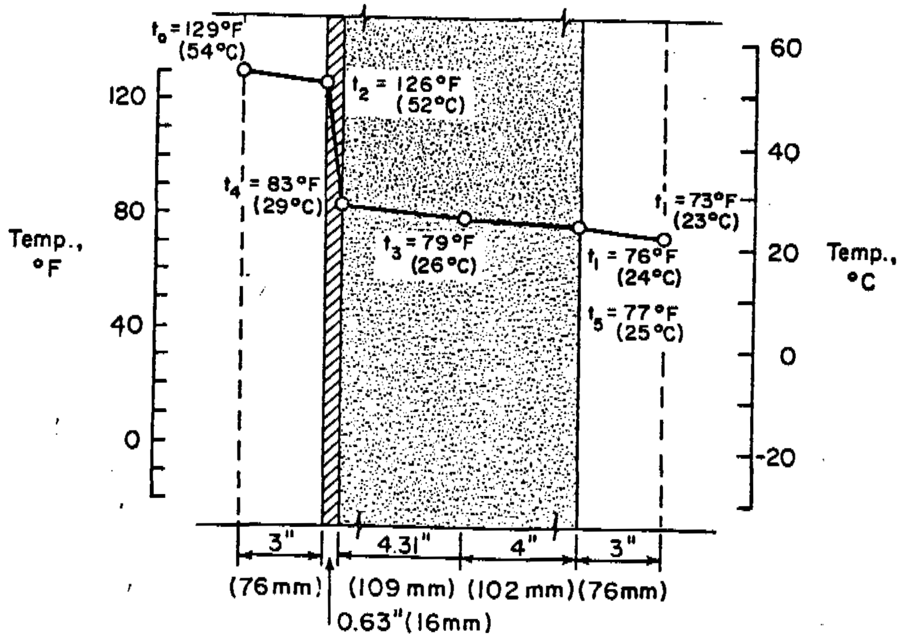
t_5 = wall surface temperature, indoor side (embedded thermocouples, Wall C4 only)

t_1 = wall surface temperature, indoor side (taped thermocouples)

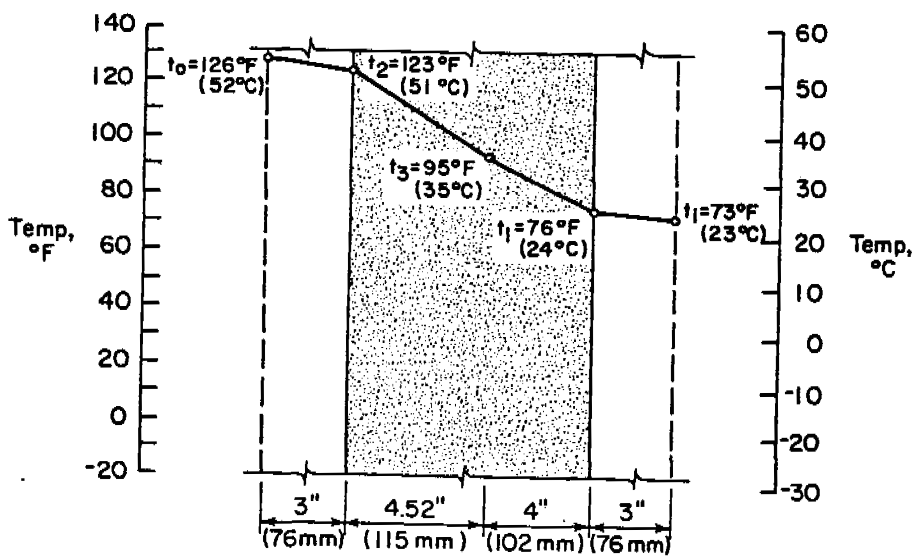
t_i = indoor air temperature

As can be seen in Figs. 17(a) and (b), the temperature profile lines through Wall C3 and the concrete portion of Wall C4 are nearly straight. Small deviations may be due to slight repositioning of the internal thermocouples during construction, or variations in concrete thermal conductivity with temperature.

Relative thermal resistances of wall components can be determined from slopes of temperature profile lines in Fig. 17. Materials with higher thermal

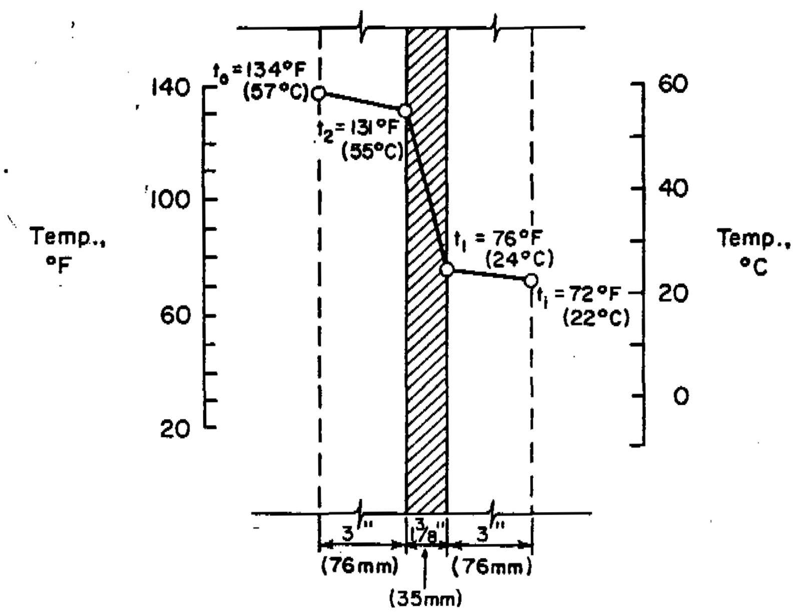


(a) Wall C4



(b) Wall C3

Fig. 17 Steady-State Temperature Profiles Across Walls C4, C3, and S1



(c) Wall S1

Fig. 17 Steady-State Temperature Profiles Across Walls C4, C3, and S1 resistances have steeper slopes. This is due to walls having similar total thermal resistances and air-to-air temperature differentials. Wall S1 and the insulation portion of Wall C4 have relatively steep temperature profiles since these materials have high thermal resistances. The concrete portion of Wall C4 has a relatively flat temperature profile, which implies a low thermal resistance. Figures 17(a) and (b) show that the low density concrete composing Wall C3 has a higher thermal resistance than the normal weight concrete portion of Wall C4. The slope of the temperature profile through concrete is greater for Wall C3 than for Wall C4.

The air-to-surface temperature differentials for the three walls are uniformly 3 to 4°F (2°C). Air-to-surface temperature differentials are expected to be similar since the three walls have similar thermal conductances.

Dynamic Test Results

Calibrated hot box results for the one dynamic cycle applied to all three walls, the NBS cycle described previously, are compared in the following sections. Overall dynamic performance of the three walls is also compared.

Table 19 lists dynamic temperature cycles applied to Walls C4, C3, and S1.

Appendix A contains dynamic test results for Walls C3 and S1. Dynamic test results for Wall C4, dynamic test procedures, and descriptions of Tables and Figures in Appendix A are given in the section of this report entitled "Concrete Wall with Board Insulation".

Heat Flux Comparisons

Heat flux measured by the calibrated hot box, q_w, is illustrated in Fig. 18 for the NBS Test Cycle applied to Walls C4, C3, and S1. Steady-state heat flux curves for the three walls are similar because resistances and wall surface temperatures are similar. For this reason, Fig. 18 shows a single

TABLE 19 - CALIBRATED HOT BOX DYNAMIC TEMPERATURE CYCLES APPLIED TO WALLS C4, C3, AND S1

Test Cycle Designation	Cycle Applied to Walls	Cycle Description
NBS	C3, C4, S1	Used by NBS in evaluation of an experimental masonry building.[15] See text.
Modified Phoenix August	S1	Average 30-year sol-air temperature conditions for Phoenix and Tucson, Arizona on August 21.[3] Indoor and outdoor temperatures decreased 7°F (4°C).
NBS+10	C3, C4	Similar to NBS cycle, but outdoor temperatures increased by 10°F (6°C).
NBS-10	C3, C4	Similar to NBS cycle, but outdoor temperatures decreased by 10°F (6°C).

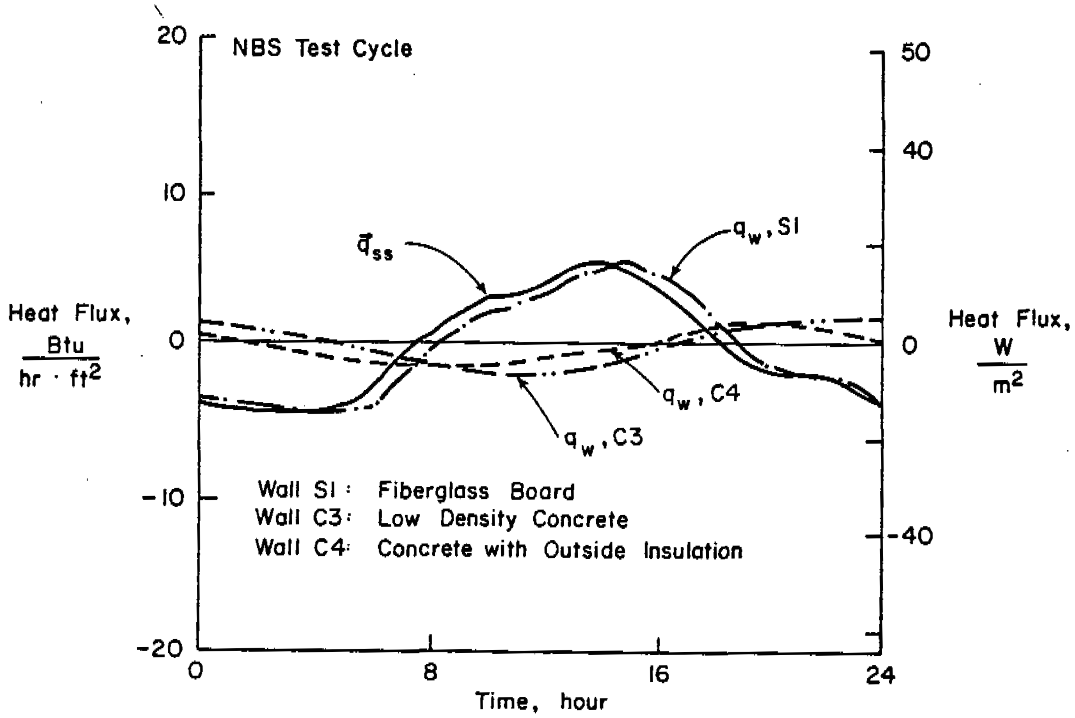


Fig. 18 Heat Flux for the NBS Test Cycle Applied to Walls C4, C3, and S1

curve representing average steady-state heat flux, $\bar{q}_{ss}$. Values for this curve were calculated using Eq. (1) for data from each wall assembly. Hourly values for the three walls were then averaged to obtain $\bar{q}_{ss}$.

The measured heat flux, q_w, for fiberglass board, Wall S1, follows the $\bar{q}_{ss}$ curve with a delay of less than one hour and a negligible decrease in amplitude. Measured heat flux curves, q_w, for massive Walls C4 and C3 show significantly reduced and delayed peaks compared to the calculated heat flux, $\bar{q}_{ss}$. Wall C4, insulated normal weight concrete, has the smallest heat flow amplitude. Wall C3, low density concrete, has the longest delay in peak heat flow. Measured peak heat flows are significantly reduced and delayed for the NBS Test Cycle applied to Walls C3 and C4 when compared to results for Wall S1.

Thermal Lag and Reduction in Amplitude

Thermal lag is the time delay in peak heat flow through a wall when compared to the predicted occurrence of peak heat flow based on steady-state analysis. Thermal lag is of interest because the time of occurrence of peak heat flows will have an effect on overall response of the building envelope. If the envelope can be effectively used to delay the occurrence of peak loads, it may be possible to improve overall energy efficiency. The "lag effect" is also of interest for passive solar applications.

Reduction in amplitude is the percent reduction in actual peak heat flow when compared to peak heat flow calculated using steady-state theory. Actual maximum heat flow through a wall is important in determining the peak energy load for a building envelope. Using actual peak heat flow rather than heat flow based on steady-state theory will reduce anticipated peak energy demands.

Thermal lag and reduction in amplitude are dependent on both thermal resistance, R, and heat storage capacity:

$$\rho c L$$

where

ρcL = heat storage capacity per unit area, Btu/ft^2•°F(J/m^2•K)

ρ = wall density, pcf (kg/m^3)

c = wall specific heat, Btu/lb•°F (J/kg•K)

L = wall thickness, ft (m)

Mass per unit area, ρL, is the predominant factor in determining heat storage capacity of most building materials.

For homogeneous walls, thermal lag and reduction in amplitude have been shown to increase with an increase in[17]

$$M = \left(\frac{L^2/\alpha}{P}\right)^{1/2} \tag{4}$$

where

L = wall thickness, ft (m)

α = thermal diffusivity, $k/\rho c$, ft^2/hr (m^2/s)

k = thermal conductivity of wall, Btu/hr•ft•°F (W/m•K)

ρ = wall density, pcf (kg/m^3)

c = wall specific heat, Btu/lb•°F (J/kg•K)

P = period of dynamic cycle, hr

Successive daily temperature conditions are assumed to be constant for calibrated hot box tests. The same 24-hr dynamic cycle is repeated for several days. The mean daily temperature does not change from day to day. For this case, dynamic temperature cycles have a period, P, of 24 hours.

Equation (4) may be rearranged to show that M, and therefore thermal lag and reduction in amplitude, is dependent on thermal resistance, R, and heat storage capacity, ρcL, as follows:

$$M = \left(\frac{L^2}{P} \cdot \frac{\rho c}{k}\right)^{1/2} = \left(\frac{(L/k) \cdot L\rho c}{P}\right)^{1/2} = \left(\frac{(R) \cdot (\rho cL)}{P}\right)^{1/2} \tag{5}$$

where

R = thermal resistance of wall, $hr \cdot ft^2 \cdot °F/Btu$ ($m^2 \cdot K/W$)

ρcL = heat storage capacity of wall per unit surface area, $Btu/°F \cdot ft^2$ ($W \cdot hr/K \cdot m^2$)

P = period of dynamic cycle, hr

Changes in R affect the dynamic parameters of thermal lag and reduction in amplitude, as well as alter the maximum heat flux predicted by steady-state analysis. Changes in heat storage capacity affect only the dynamic parameters of thermal lag and reduction in amplitude.

The principles discussed in the last three paragraphs are valid for multi-layered wall assemblies even though Eqs. (4) and (5) are derived for homogeneous walls only. Childs, in Reference 17, suggests using the sum of M values for each wall layer as an approximate method of predicting lag and reduction in amplitude for the entire wall.

Table 20 lists material properties used to calculate M values for individual layers of Walls C4, C3, and S1. All properties for Walls C4 and C3 were determined from measurements performed at CTL with the following exceptions. The specific heat of the insulation for Wall C4 was taken from Reference 14. Thermal resistance of the insulation for Wall C4 was taken from manufacturer's specifications.[13] All properties for Wall S1, except specific heat, were measured by Owens-Corning Fiberglass Corporation and are listed in Table S1-2 of Appendix A. Specific heat of Wall S1 was taken from Reference 14.

The last two columns of Table 20 list heat storage capacity, ρcL, and M values, $(\rho cL \cdot R/24)^{1/2}$, for each layer of the walls.

Table 21 lists M values, time constants, thermal lag, and percent reduction in amplitude for the NBS Test Cycle applied to Walls C4, C3, and S1. Values of M for individual wall layers are summed to determine total wall M values. Equation (2) was used to calculate time constants from wall material properties

TABLE 20 - CALCULATION OF M VALUES FOR INDIVIDUAL WALL LAYERS

Wall Designation	Wall Layer	R Thermal Resistance, $hr \cdot ft^2 \cdot °F/Btu$ ($m^2 \cdot K/W$)	ρ Unit Weight, pcf (kg/m^3)	c Specific Heat, $Btu/lb \cdot °F$ ($J/kg \cdot K$)	L Thickness, ft (m)	ρcL Storage Capacity, $Btu/°F \cdot ft^2$ ($W \cdot hr/K \cdot m^2$)	M $(\rho cL \cdot R/24)^{1/2}$
C4	Normal Weight Concrete	0.71* (0.13)	144+ (2310)	0.19++ (810)	0.69+ (0.21)	18.9 (107)	0.75
	Polyisocyanurate Board	5.4** (0.95)	2.2+ (35)	0.22+++ (920)	0.058+ (0.018)	0.028 (0.16)	0.08
C3	Low Density Concrete	5.92* (1.04)	46.0+ (740)	0.18++ (750)	0.71+ (0.22)	5.85 (33.2)	1.20
S1	Fiberglass Board	5.76*** (1.01)	8.42*** (135)	0.23+++ (960)	0.12*** (0.037)	0.23 (1.3)	0.23

*Measured at CTL using calibrated hot box, ASTM Designation: C976
**At time of manufacture per manufacturer's specification, from Reference 13
***Measured by Owens-Corning Fiberglas Corporation
+Measured at CTL
++Measured at CTL using a method similar to U.S. Army Corps of Engineers Test Method CRD-C124-73
+++From Reference 14

TABLE 21 - DYNAMIC PARAMETERS FOR NBS TEST CYCLE APPLIED TO WALLS C4, C3, AND S1

Wall Designation	Wall Description	Wall Properties			
		Calculated M	Calculated Time Constant, hrs	Measured Thermal Lag, hrs	Measured Reduction in Amplitude, %
C4	Concrete with Outside Insulation	0.83	1.6	5.0	71
C3	Low Density Concrete	1.20	3.6	8.5	61
S1	Fiberglass Board	0.23	0.13	0.5	1

listed in Table 20. Thermal lag and percent reduction in amplitude for the walls were measured using the calibrated hot box.

Measured thermal lag and measured reduction in amplitude for the NBS Test Cycle are larger for walls with high thermal mass. Thermal lag for Walls C4 and C3, the walls with high heat storage capacities, were 5 and 8.5 hours, respectively. These values may be compared to a thermal lag of 0.5 hours for Wall S1, fiberglass board. Reductions in amplitudes for Walls C4 and C3 were 71 and 61%, respectively, compared to 1% for Wall S1. The heat flow through Wall S1 is essentially the same as the heat flow predicted by steady-state analysis for the three walls. The large thermal storage capacity of Walls C4 and C3 significantly reduces and delays peak heat flows compared to a wall with similar total thermal resistance but with negligible thermal mass.

In Fig. 19 calculated values of M are plotted versus measured thermal lags for the NBS Cycle applied to Walls C4, C3, and S1. The relationship between M and thermal lag is linear for these walls. An increase in M results in an increase in thermal lag, as expected.

The largest thermal lags occur for Wall C3. This wall consists of a single material, low density concrete, that has a combination of relatively high thermal storage capacity and a high thermal resistance. This provides optimal conditions for producing large thermal lags, as predicted by the parameter M.

Figure 20 shows calculated values of M plotted versus measured reduction in amplitude for the NBS cycle applied to Walls C4, C3, and S1. Wall C4 has the largest reduction in amplitude value of the three walls. Wall C4 has a large thermal storage capacity in the concrete portion of the wall. The concrete is isolated from the outdoor environment by the board insulation on the outside of the wall. As a result, the concrete maintains a relatively constant temperature throughout the dynamic cycle.

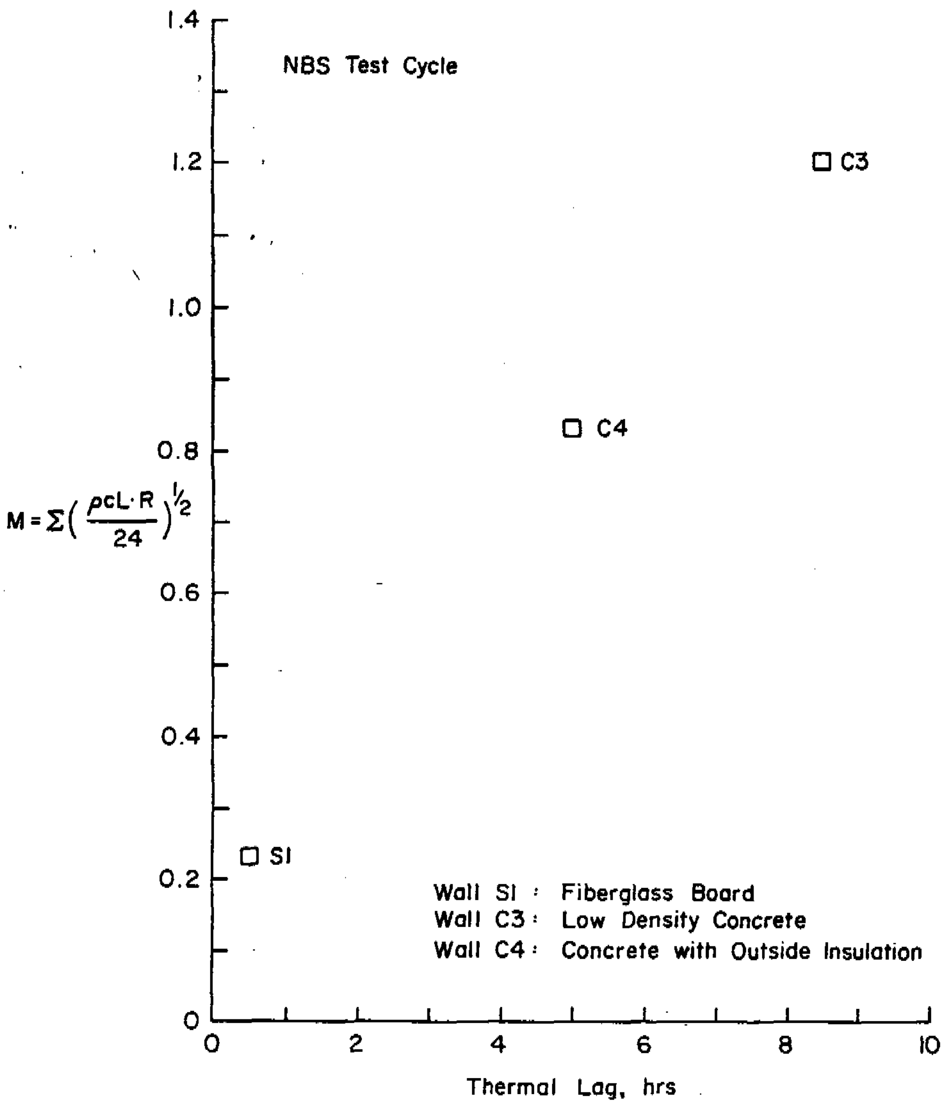


Fig. 19 Relationship Between Calculated M Values and Measured Thermal Lags

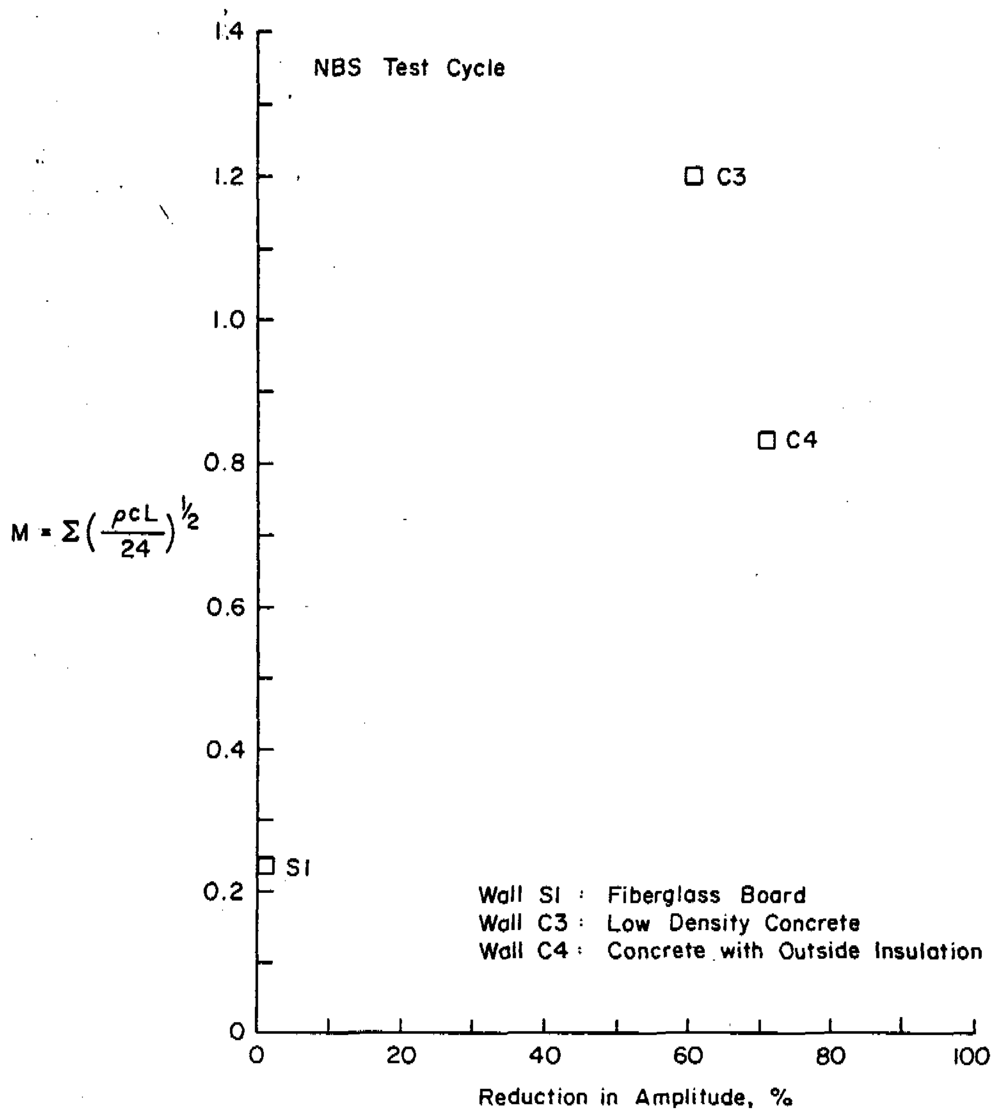


Fig. 20 Relationship Between Calculated M Values and Measured Reduction in Amplitude

Using the parameter M as a predictor of reduction in amplitude, Wall C4 is expected to have a smaller reduction in amplitude than Wall C3 because Wall C4 has a smaller M value. Table 21 and Fig. 20 show the reverse is true. Reduction in amplitude for Wall C4 is 10% greater than that for Wall C3.

Values of M for individual layers of Wall C4 were summed to determine the total wall M value. The M value determined using this technique is not a good predictor of reduction in amplitude for Wall C4 because the relative placement of insulation and concrete are not considered.

Table 22 shows thermal lags and reductions in amplitude for each dynamic test cycle applied to Walls C4, C3, and S1. For all test cycles applied to the walls, thermal lag from calibrated hot box measurements averages 5.5 hours for Wall C4, 8.5 hours for Wall C3, and 0.5 hours for Wall S1. Thermal lag values for each wall are constant regardless of the 24-hr temperature cycle applied to the wall.

Reduction in amplitude values from calibrated hot box tests average 70% for Wall C4, 61% for Wall C3, and 3% for Wall S1 for all test cycles applied to the walls. Reduction in amplitude values are dependent on the temperature cycle applied to the walls. Reduction in amplitude values for massive walls are larger for outdoor air temperature cycles which fluctuate above and below indoor air temperatures, causing reversals in heat flow through the wall. During reversals in heat flow, the amplitude of the actual heat flow through the wall is not as large as that predicted by steady-state analysis because steady-state equilibrium is never achieved within the wall.

It should be noted that Wall S1 is not typical of actual construction because it does not contain structural framing members. An insulated wood frame wall will have larger thermal lag and greater reduction in amplitude than Wall S1.[8,9]

TABLE 22 - DYNAMIC PARAMETERS FOR ALL CYCLES APPLIED TO WALLS C4, C3, AND S1

Wall Designation	Wall Description	Dynamic Cycle	Dynamic Parameter	
			Measured Thermal Lag, hr	Measured Reduction in Amplitude, %
C4	Concrete with Outside Insulation	NBS	5	71
		NBS+10	6	74
		NBS-10	5.5	65
		Avg.	5.5	70
C3	Low Density Concrete	NBS	8.5	61
		NBS+10	8.5	62
		NBS-10	8.5	61
		Avg.	8.5	61
S1	Fiberglass Board	NBS	0.5	1
		Mod. Phoenix August	0.5	5
		Avg.	0.5	3

Total Heat Flux

Definitions of total heat flux are given in the "Total Heat Flux" portion of the "Test Results" section of this report. Measured total heat flux, q_w^T, is determined from calibrated hot box test results. Calculated total heat flux, q_{ss}^T, is determined from steady-state analysis. Total heat flux, q_w^T or q_{ss}^T, is equal to the sum of the absolute values of hourly heat flux through a wall for a 24-hr period.

Measured and calculated total heat flux for the NBS Test Cycle applied to Walls C4, C3, and S1 are summarized in Table 23. Results for calculated total heat flux, q_{ss}^T, are similar for the three walls. Values are within 5% of the average for the three walls.

Measured total heat flux as a percentage of calculated total heat flux for the NBS Test Cycle is shown in Table 23 in the column entitled "Total Heat Flux Comparison." Measured total heat flux, q_w^T, is less than calculated total heat flux, q_{ss}^T, for each wall. Measured total heat flux for walls with high heat storage capacity, Walls C4 and C3, are 30 and 39%, respectively, of calculated total heat flux. For the fiberglass board, Wall S1, measured total heat flux is 96% of calculated total heat flux.

Table 24 shows average values of measured total heat flux as a percentage of calculated total heat flux for all test cycles applied to the walls. Values range from 30 to 47% for Wall C4, from 39 to 55% for Wall C3, and from 96 to 99% for Wall S1. The ratio of total measured heat flux to steady-state heat flux predictions depends on the outdoor air temperature cycle applied to the wall. Particularly for massive walls, greater reductions in actual heat flux over steady-state predictions occur for temperature cycles which produce heat flow reversals through the wall.

TABLE 23 - TOTAL HEAT FLUX FOR THE NBS TEST CYCLE APPLIED TO WALLS C4, C3, AND S1

Wall Designation	Wall Description	Measured Total Heat Flux q_w^T, Btu/ft^2 (W•hr/m^2)	Calculated Total Heat Flux q_{ss}^T, Btu/ft^2 (W•hr/m^2)	Total Heat Flux Comparison, q_w^T/q_{ss}^T %
C4	Concrete with Outside Insulation	20.5 (64.8)	69.6 (219.5)	30
C3	Low Density Concrete	27.8 (87.7)	71.1 (224.4)	39
S1	Fiberglass Board	72.6 (228.9)	75.3 (237.7)	96

TABLE 24 - TOTAL HEAT FLUX COMPARISONS FOR ALL CYCLES APPLIED TO WALLS C4, C3, AND S1

Wall Designation	Wall Description	Dynamic Cycle	Total Heat Flux Comparison, q_w^T/q_{ss}^T, %
C4	Concrete with Outside Insulation	NBS	30
		NBS+10	45
		NBS-10	47
		Avg.	41
C3	Low Density Concrete	NBS	39
		NBS+10	43
		NBS-10	55
		Avg.	46
S1	Fiberglass Board	NBS	96
		Mod. Phoenix August	99
		Avg.	98

It should be noted again that comparison of measured energy values for test walls is limited to specimens and dynamic cycles evaluated in this test program. Results are for diurnal test cycles and should not be arbitrarily assumed to represent annual heating and cooling loads.

Transient Test Results

Appendix A contains transient test results for Wall C3. A transient test was not performed on Wall S1. Transient test results for Wall C4, transient test procedures, and descriptions of Tables and Figures in Appendix A are given in the section of this report entitled "Concrete Wall with Board Insulation." Transient test results for Walls C4 and C3 are compared in this section.

Figure 21 shows measured heat flux from calibrated hot box tests, q_w, and calculated heat flux using steady-state theory, q_{ss}, for each transient test. Heat flux predicted by steady-state analysis, q_{ss}, was calculated using Eq. 1 with measured indoor and outdoor wall surface temperatures and measured wall thermal resistance.

Initial mean temperatures of Walls C4 and C3, respectively, were 72°F (22°C) and 73°F (23°C). Final mean temperatures of Walls C4 and C3, respectively, were 32°F (0°C) and 31°F (-1°C). Transient tests were continued until steady-state conditions were achieved.

Measured results show that Wall C4, concrete with outside insulation, and Wall C3, low density concrete, prolonged the consequences of a sudden change in outdoor air temperature, when compared to steady-state theory.

Table 25 summarizes times required to reach 99.5, 95, 90, and 63% of the final steady-state heat flux achieved during transient tests for Walls C3 and C4. Steady-state analysis predicted 95% of the final heat flux would be reached after 2 and 5 hours for Walls C4 and C3, respectively. Calibrated hot box test results show that 95% of the final heat flux is reached after 38 and

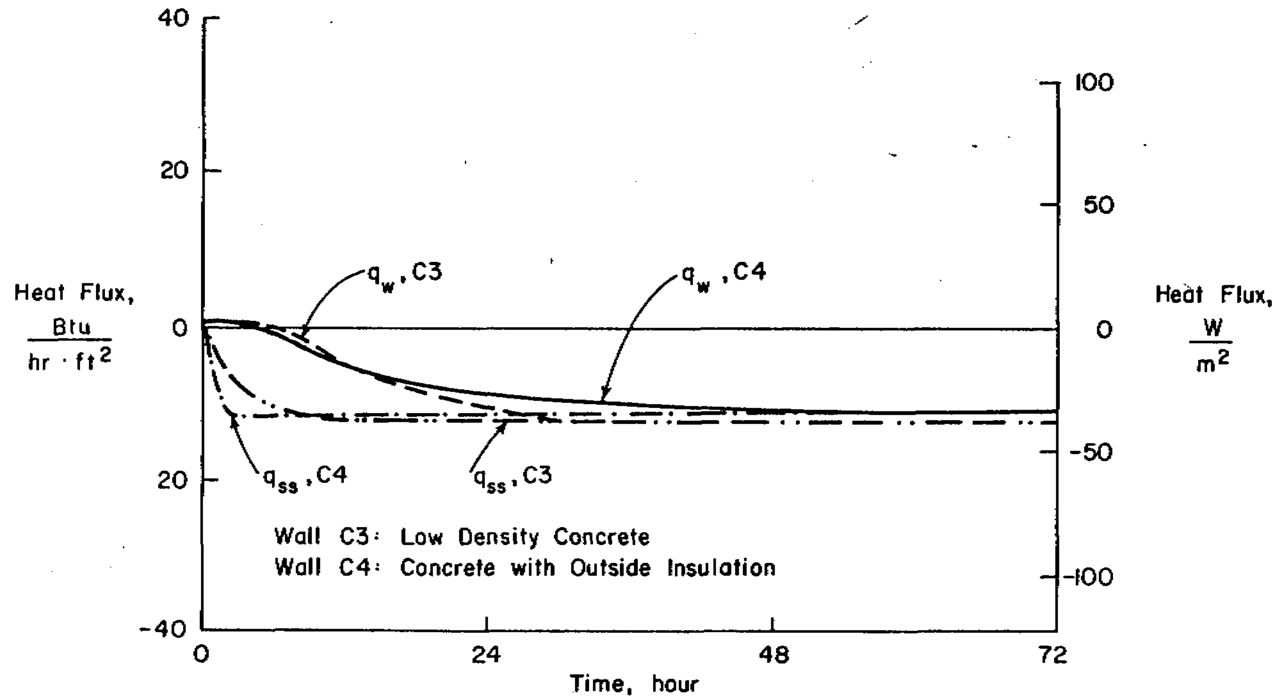


Fig. 21 Transient Test Results for Walls C4 and C3

TABLE 25 - COMPARISON OF TRANSIENT TEST RESULTS FOR WALLS C4 AND C3

Heat Flux	Measured, Calibrated Hot Box				Calculated, Steady-State			
	Wall C4		Wall C3		Wall C4		Wall C3	
	q_w, Btu/hr·ft^2 (W/m^2)	Time to Reach q_w, hr	q_w, Btu/hr·ft^2 (W/m^2)	Time to Reach q_w, hr	q_{ss}, Btu/hr·ft^2 (W/m^2)	Time to Reach q_{ss}, hr	q_{ss}, Btu/hr·ft^2 (W/m^2)	Time to Reach q_{ss}, hr
99.5% of Final Heat Flux	-9.9 (-31.4)	64	-12.0 (-37.7)	57	-10.2 (-32.1)	2	-11.1 (-35.1)	9
95% of Final Heat Flux	-9.5 (-30.0)	38	-11.4 (-36.0)	47	-9.7 (-30.6)	2	-10.6 (-33.6)	5
90% of Final Heat Flux	-9.0 (-28.4)	32	-10.8 (-34.1)	33	-9.2 (-29.0)	2	-10.1 (-31.8)	4
63% of Final Heat Flux	-6.3 (-19.8)	18	-7.6 (-23.9)	18	-6.4 (-20.3)	2	-7.0 (-22.2)	2

47 hours for Walls C4 and C3, respectively. The amount of time required for Walls C4 and C3, respectively, to reach 95% of the final heat flux was 19 and 9.4 times greater than steady-state predictions. Similarly, the amount of time required for both Walls C4 and C3 to reach 63% of the final heat flux was 9 times greater than steady-state predictions. Massive walls, such as Walls C4 and C3, "damp out" effects of a sudden change in outdoor air temperatures.

Although Wall C4 has smaller calculated M and time constant values than Wall C3, Wall C4 took more time to reach the final steady-state heat flux. This is because calculations for M values and time constants do not take into account the relative placement of insulation and mass within a wall.

SUMMARY AND CONCLUSIONS

This report presents results of an experimental investigation of heat transmission characteristics of a normal weight concrete wall with insulation on the outdoor surface, designated Wall C4. Tests were conducted in a calibrated hot box under steady-state, dynamic, and transient temperature conditions. Results are compared to calibrated hot box test results of Wall C3, low-density concrete, and Wall S1, fiberglass insulation board. The three specimens had comparable thermal resistance values and varying levels of thermal storage capacity.

The following conclusions are based on results obtained in this investigation.

1. Measured total thermal resistances, R_T, for Wall C4 determined from readings of thermocouples taped to and embedded in the indoor concrete surface were 7.64 and 7.49 hr•ft^2•°F/Btu (1.35 and 1.32 m^2•K/W), respectively. Values include standard surface film resistances and were determined for a specimen mean temperature of 72°F (22°C). Measured

total resistance determined from taped thermocouple readings were within 2% of that determined from embedded thermocouple readings.

2. Design total thermal resistance for Wall C4 was 7% lower than calibrated hot box test results determined using embedded thermocouple measurements.
3. As indicated by thermal lag, heat storage capacity of Wall C4 under dynamic test conditions delayed heat flow through the wall when compared to steady-state predictions. Average thermal lag for 3 test cycles applied to Wall C4 was 5.5 hours.
4. As indicated by the damping effect, heat storage capacity of Wall C4 under dynamic test conditions reduced peak heat flows through the specimen when compared to steady-state predictions. Reduction in amplitude values range from 65 to 74% for Wall C4.
5. For the three diurnal temperature cycles applied to Wall C4, total heat flux values for a 24-hr period were less than would be predicted by steady-state analysis. Total measured heat flux for the diurnal cycles ranged from 30 to 47% of heat flux predicted by steady-state analysis. These reductions in total heat flux are attributed to wall thermal storage capacity.
6. Transient test results indicate that thermal storage capacity of Wall C4 delays heat flow through the specimen when compared to steady-state analysis. The amount of time required for Wall C4 to reach 95% of the final heat flux was 19 times greater than that predicted by steady-state calculations using measured surface tempeatures and measured wall resistance.
7. Measured total thermal resistances, including standard surface film resistances, for Walls C4, C3, and S1 at mean temperatures of 72°F

(22°C) were 7.6, 6.8, and 6.8 hr•ft^2•°F/Btu (1.4,1.2, and 1.2 m^2•K/W), respectively.

8. Dynamic test results for the three specimens indicate that the massive walls, C4 and C3, have larger thermal lags than the fiberglass board, S1. This is a consequence of the heat storage capacities of the massive walls. For the NBS Test Cycle, Walls C4, C3, and S1 had measured thermal lags of 5, 8.5, and 0.5 hours, respectively.

9. Dynamic test results for the three specimens indicate that the massive walls, C4 and C3, have larger reduction in amplitude values than the fiberglass board, S1. This is a consequence of the thermal storage capacities of the massive walls and the reversals of heat flow through the walls caused by the applied temperature cycle. For the NBS Test Cycle, Walls C4, C3, and S1 had measured reduction in amplitude values of 71, 61, and 1%, respectively.

10. The massive walls, C4 and C3, have lower measured total heat flux values as a percentage of calculated total heat flux than the fiberglass board, S1. This is a result of the thermal storage capacities of the massive walls and the reversals of heat flow through the walls caused by the applied temperature cycles. For the NBS Test Cycle, Walls C4, C3, and S1 had ratios of measured total heat flux to calculated total heat flux of 30, 39, and 96%, respectively.

11. Configuration of insulation and mass within Walls C4 and C3 influenced dynamic test results. Wall C4 consisted of a large heat storage component isolated from the outdoor environment by insulation. Wall C3 consisted of a single wall component combining heat storage capacity and thermal resistance. Wall C3 had longer thermal lags than Wall C4. Wall C4 had larger reduction in amplitude values and lower ratios of measured total heat flux to calculated total heat flux.

Results described in this report provide data on thermal response of walls subjected to steady-state and diurnal sol-air temperature cycles. A complete analysis of building energy requirements must include consideration of the entire building envelope, building orientation, building operation, and yearly weather conditions. Data developed in this experimental program provide a quantitative basis for modeling the building envelope, which is part of the overall energy analysis process.

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Mr. J. A. Chavez and Mr. P. P. Hordorwich constructed Walls C4 and S1 and prepared specimens for calibrated hot box tests.

Mr. J. T. Julien, Research Engineer, Fire Research Section, monitored calibrated hot box tests of Wall S1 under the direction of Dr. A. E. Fiorato, Director of the Structural Evaluation and Fire Research Department.

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Mrs. E. Ringquist provided editorial assistance in preparation of the manuscript. The manuscript was typed by personnel of the Portland Cement Association's Word Processing Department. Mr. R. Kuhart and Mr. C. Steer drafted the figures.

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APPENDIX A - TEST DATA FOR WALLS C3 and S1

TABLE A1 - APPENDIX A TABLE AND FIGURE DESCRIPTIONS

Appendix A Table or Figure No.	Description
Table XX-1*	Physical Properties of Wall at Time of Test
Table XX-2	Material Properties
Table XX-3	Design Heat Transmission Coefficients
Table XX-4	Steady-State Test Results
Figure XX-1	Transient Test Results
Table XX-5	Transient Test Results
Table XX-6	Summary of Transient Test Results
Figure XX-2	Dynamic Test Results (Periodic) for NBS Test Cycle
Table XX-7	Dynamic Test Results (Periodic) for NBS Test Cycle
Figure XX-3 and XX-4	Dynamic Test Results (Periodic) for Test Cycles Other Than the NBS Cycle.
Table XX-8 and XX-9	Dynamic Test Results (Periodic) for Test Cycles Other Than the NBS Cycle
Table XX-10	Summary of Dynamic Test Results (Periodic), Thermal Lag
Table XX-11	Summary of Dynamic Test Results (Periodic), Reduction in Amplitude
Table XX-12	Summary of Dynamic Test Results (Periodic), Energy Requirements

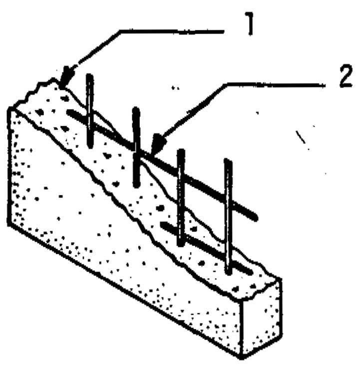
*Characters in the "XX" position are wall designations (C3 or S1).

WALL C3: LOW DENSITY CONCRETE

DESCRIPTION: Low density concrete wall with reinforcement at approximate midthickness.

REFERENCE: Van Geem, M. G. and Fiorato, A. E., "Heat Transfer Characteristics of Low Density Concrete Wall," Construction Technology Laboratories, Portland Cement Association, Skokie, 1983, 89 pages.

COMPOSITION:



1. Low Density Concrete
   - Portland Cement
   - Perlite Aggregate*
     - Loose unit weight of 7.9 pcf (126 kg/m^3)
   - Measured Air Content: not available

2. Reinforcement
   - Single layer of 6-mm diameter bars
     - Spaced 12 in. (305 mm) center-to-center

TABLE C3-1 - PHYSICAL PROPERTIES OF WALL AT TIME OF TEST

Property	Measured Value
Weight, psf (kg/m^2)	32.7 (160)
Average Thickness, in. (mm)	8.52 (216)
Area, ft^2 (m^2)	73.79 (6.86)
Estimated Moisture Content, % by ovendry weight	9.5

*Perlite only, no sand was used as aggregate.

TABLE C3-2(a) - MATERIAL PROPERTIES, LOW DENSITY CONCRETE

Property	Test Method	Specimen Condition	Mean Temperature, °F (°C)	Measured Value
Unit Weight, pcf (kg/m^3)	--	ovendry	--	42 (670)
Specific Heat, Btu/lb·°F (J/kg·K)	Similar to CRD-C124-73	saturated	73 (23)	0.444 (1860)
Specific Heat, Btu/lb·°F (J/kg·K)	Calculated	air dry*	73 (23)	0.179 (750)
Thermal Conductivity, Btu·in/hr·ft^2·°F (W/m·K)	Hot Wire	air dry**	--	3.05 (0.440)
Thermal Conductivity, Btu·in/hr·ft^2·°F (W/m·K)	ASTM C 177	ovendry	70 (21)	1.44 (0.207)
Thermal Conductivity, Btu·in/hr·ft^2·°F (W/m·K)	ASTM C 976	air dry*	70 (21)	1.44 (0.207)
Thermal Diffusivity, ft^2/hr (mm^2/s)	CRD-C36-73	saturated	--	0.00849 (0.219)
Compressive Strength, psi (MPa)	ASTM C 39	air dry	--	880 (6.1)
Splitting Tensile Strength, psi (MPa)	ASTM C 496	air dry	--	65 (0.45)

*9.5% moisture content relative to ovendry weight
**17.3% moisture content relative to ovendry weight

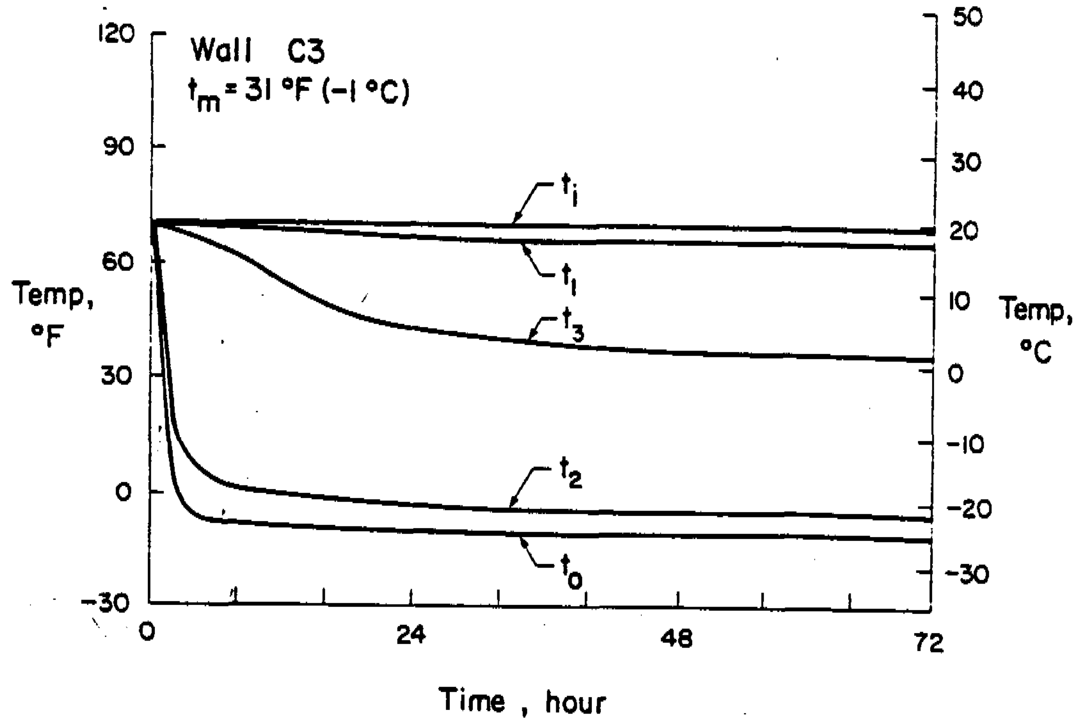
TABLE C3-3 - DESIGN HEAT TRANSMISSION COEFFICIENTS

Component	R, Thermal Resistance $hr \cdot ft^2 \cdot °F/Btu$ $(m^2 \cdot K/W)$
1. Outside Air Film	0.17 (0.03)
2. 8-in. (203-mm) Low Density Concrete	8.02* (1.41)
3. Inside Air Film	0.68 (0.12)
Total R	8.87 (1.56)
Total U	0.11 (0.64)

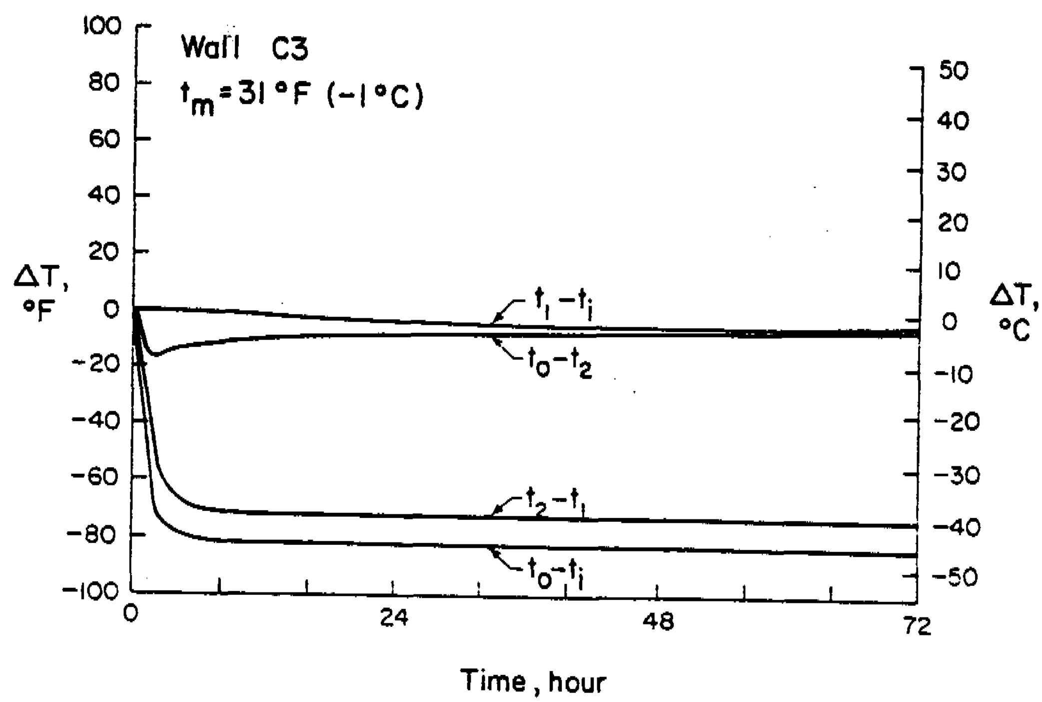
*Source: ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc., Atlanta, 1981, Chapter 23.

TABLE C3-4 - STEADY-STATE TEST RESULTS

Nominal Test Condition	q Heat Flux, Btu/hr·ft² (W/m²)	R_T, hr·ft²·°F/Btu (m²·K/W)	U, Btu/hr·ft²·°F (W/m²·K)	Measured Temperatures, °F (°C)					Relative Humidity		Laboratory Air Temperature	
				t_o Outdoor Air	t_2 Outdoor Surface	t_3 Internal	t_1 Indoor Surface	t_i Indoor Air	Indoor Chamber, %	Outdoor Chamber, %	Max. °F (°C)	Min. °F (°C)
t_m = 53°F (11°C)	-5.69 (-17.9)	7.02 (1.24)	0.14 (0.81)	32 (0)	35 (2)	55 (13)	70 (21)	72 (22)	24	22	72 (22)	70 (21)
t_m = 89°F (32°C)	5.13 (16.2)	6.53 (1.15)	0.15 (0.87)	105 (41)	104 (40)	86 (30)	75 (24)	73 (23)	26	25	72 (22)	70 (21)
t_m = 100°F (38°C)	8.64 (27.3)	6.31 (1.11)	0.16 (0.90)	126 (52)	123 (51)	95 (35)	76 (24)	73 (23)	24	28	72 (22)	68 (20)
Design Values	-	8.87 (1.56)	0.11 (0.64)	-	-	-	-	-	-	-	-	-

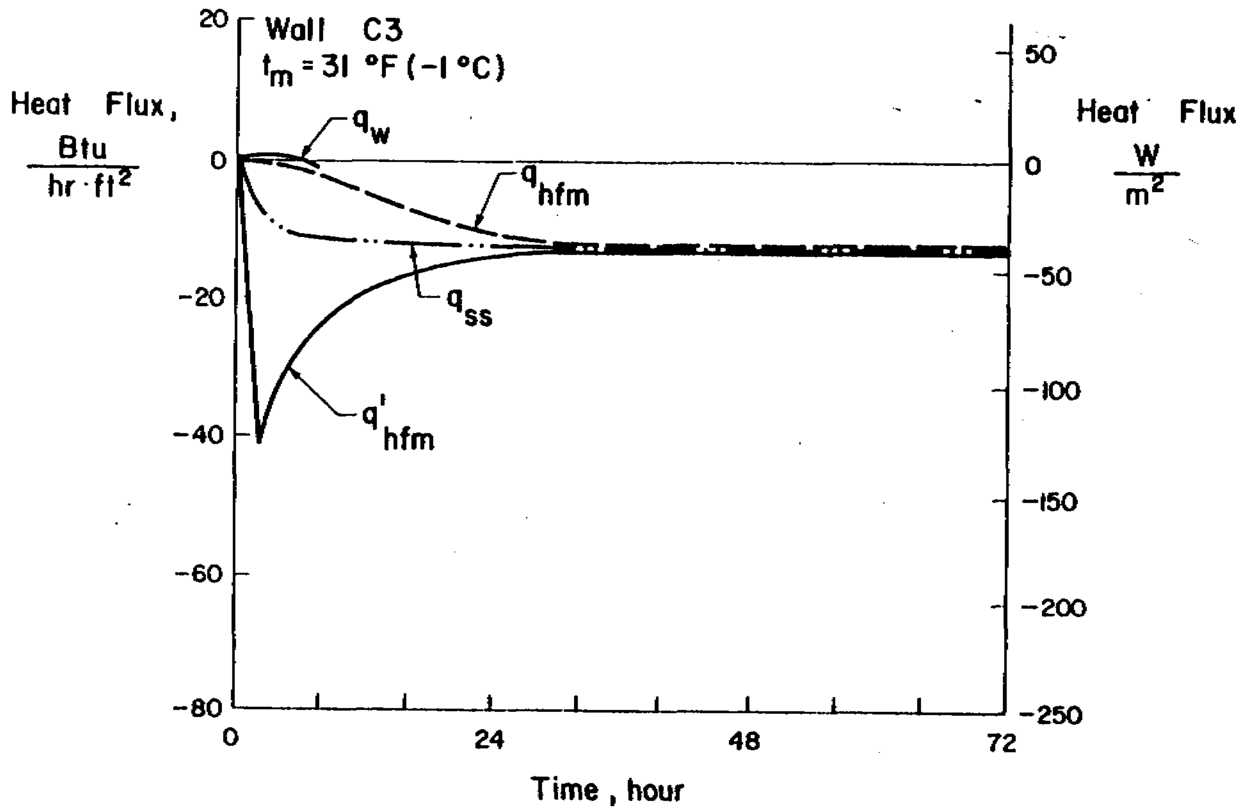


(a) Measured Temperatures



(b) Temperature Differentials

Fig. C3-1 Wall C3 Transient Test Results



(c) Heat Flux

Fig. C3-1 Wall C3 Transient Test Results

TABLE C3-5(a) - TRANSIENT TEST RESULTS

Time, hr	Measured Temperatures, °F					Measured Heat Flux, Btu/hr·ft^2			Calculated Heat Flux, Btu/hr·ft^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_3 Internal	t_1 Indoor Surf.	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
0	72.0	72.7	71.8	72.7	72.4	-0.1	-0.1	-0.0	0.0
1	39.9	52.4	71.7	72.7	72.4	0.6	-0.1	-26.9	-3.4
2	3.3	20.0	71.6	72.7	72.4	0.6	-0.0	-41.7	-8.4
3	-4.7	9.4	70.7	72.7	72.4	0.6	-0.0	-34.3	-10.0
4	-6.3	6.0	69.1	72.6	72.5	0.9	-0.1	-29.0	-10.5
5	-7.3	4.1	67.0	72.6	72.4	0.3	-0.3	-25.6	-10.7
6	-8.0	2.7	64.8	72.4	72.3	-0.3	-0.7	-23.9	-10.9
7	-8.4	1.8	62.8	72.1	72.3	-0.5	-1.2	-22.4	-11.0
8	-8.8	0.9	60.8	71.9	72.3	-1.1	-1.8	-20.9	-11.1
9	-9.1	0.3	58.9	71.6	72.2	-2.2	-2.4	-20.3	-11.1
10	-9.4	-0.2	57.2	71.3	72.2	-3.0	-3.1	-19.3	-11.1
11	-9.5	-0.7	55.7	71.0	72.1	-3.4	-3.8	-18.6	-11.1
12	-9.7	-1.1	54.2	70.7	72.1	-4.5	-4.4	-17.5	-11.1
13	-9.9	-1.5	52.8	70.3	72.0	-4.9	-4.9	-17.3	-11.1
14	-10.1	-1.9	51.5	70.2	71.9	-5.5	-5.5	-17.1	-11.2
15	-10.2	-2.2	50.3	69.9	71.9	-5.8	-6.0	-16.4	-11.2
16	-10.4	-2.4	49.1	69.8	71.8	-6.7	-6.5	-16.0	-11.2
17	-10.6	-2.6	47.8	69.6	71.4	-7.2	-6.9	-15.8	-11.2
18	-10.7	-3.0	46.9	69.4	71.5	-7.7	-7.3	-15.3	-11.2
19	-10.6	-3.2	46.3	69.1	71.6	-7.5	-7.6	-15.1	-11.2
20	-10.7	-3.3	45.5	69.0	71.6	-7.8	-8.0	-14.8	-11.2
21	-10.8	-3.5	44.9	68.9	71.6	-8.5	-8.3	-14.6	-11.2
22	-10.9	-3.7	44.1	68.8	71.5	-8.8	-8.6	-14.4	-11.1
23	-10.9	-3.8	43.6	68.7	71.6	-8.8	-8.9	-14.2	-11.2
24	-10.9	-4.0	43.0	68.6	71.6	-9.1	-9.2	-13.7	-11.2
26	-11.0	-4.2	42.0	68.4	71.6	-9.7	-9.7	-13.6	-11.2
28	-11.0	-4.3	41.2	68.3	71.6	-10.0	-10.0	-13.0	-11.2
30	-11.2	-4.5	40.4	68.1	71.4	-10.3	-10.3	-12.9	-11.2
32	-11.1	-4.7	39.9	68.0	71.6	-10.5	-10.6	-12.7	-11.2
34	-11.2	-4.8	39.3	67.9	71.5	-10.8	-10.8	-12.5	-11.2
36	-11.2	-4.9	38.7	67.8	71.5	-11.0	-10.9	-12.6	-11.2
38	-11.3	-4.9	38.6	67.8	71.5	-11.2	-11.1	-12.2	-11.2
40	-11.2	-4.9	38.3	67.7	71.5	-11.3	-11.2	-12.2	-11.2
42	-11.3	-5.0	38.0	67.6	71.4	-11.0	-11.3	-12.0	-11.2
44	-11.3	-5.1	37.8	67.5	71.4	-11.1	-11.4	-11.7	-11.2
46	-11.2	-5.1	37.6	67.4	71.4	-11.3*	-11.7	-12.1	-11.1
48	-11.3	-5.1	37.5	67.5	71.4	-11.3	-11.6	-11.9	-11.2
50	-11.3	-5.2	37.3	67.4	71.4	-11.6	-11.7	-11.7	-11.2
52	-11.4	-5.3	37.2	67.4	71.4	-11.0	-11.7	-12.0	-11.2
54	-11.5	-5.3	37.1	67.4	71.4	-11.5	-11.7	-11.7	-11.2
56	-11.5	-5.3	37.0	67.5	71.4	-11.5	-11.8	-11.6	-11.2
58	-11.5	-5.4	37.0	67.5	71.5	-11.6	-11.8	-11.7	-11.2
60	-11.5	-5.3	36.9	67.5	71.3	-12.1	-11.8	-11.7	-11.2
62	-11.5	-5.4	36.8	67.5	71.5	-11.7	-11.8	-11.7	-11.2
64	-11.5	-5.4	36.8	67.5	71.4	-12.0	-11.8	-11.6	-11.2
66	-11.5	-5.4	36.8	67.5	71.5	-11.8	-11.9	-11.5	-11.2
68	-11.5	-5.4	36.7	67.5	71.3	-11.9	-11.9	-11.6	-11.2
70	-11.5	-5.4	36.6	67.5	71.4	-12.0	-11.9	-11.7	-11.2
72	-11.5	-5.4	36.6	67.5	71.4	-11.9	-12.0	-11.7	-11.2

*Calibrated hot box data for this hour derived from linear interpolation of data from hours 44 to 47.

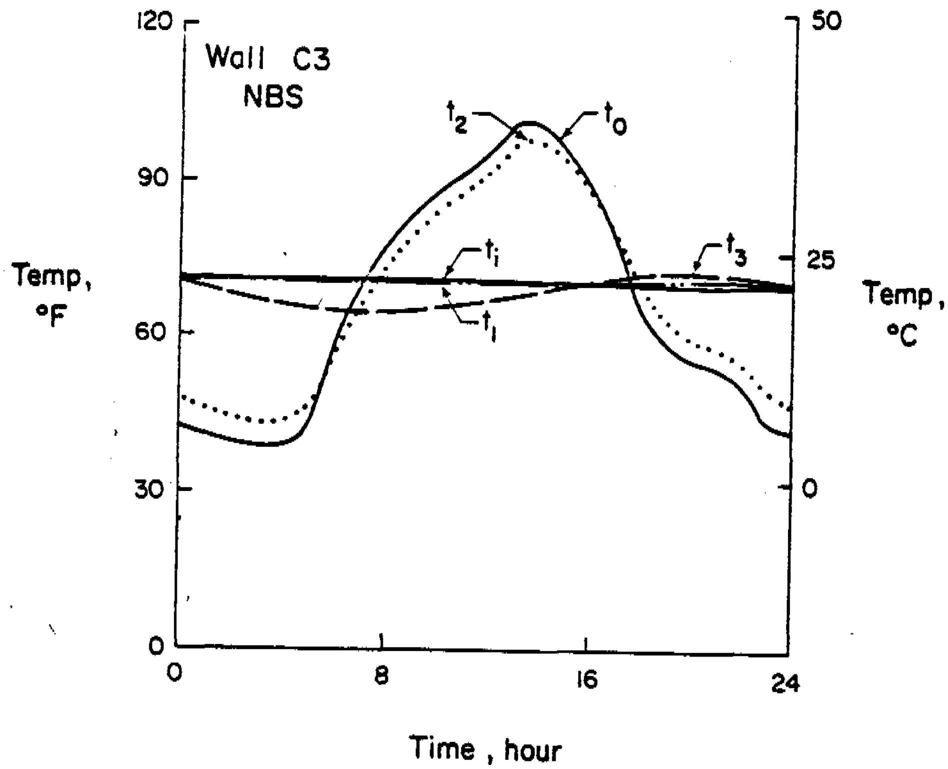
TABLE C3-5(b) - TRANSIENT TEST RESULTS, SI UNITS

Time, hr	Measured Temperatures, °C					Measured Heat Flux, W/m^2			Calculated Heat Flux, W/m^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_3 Internal	t_1 Indoor Surf.	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
0	22.3	22.6	22.1	22.6	22.4	-0.5	-0.3	-0.1	0.0
1	4.4	11.4	22.1	22.6	22.5	1.9	-0.2	-84.8	-10.6
2	-16.0	-6.7	22.0	22.6	22.4	1.7	-0.1	-131.5	-26.6
3	-20.4	-12.6	21.5	22.6	22.4	1.9	-0.1	-108.1	-31.4
4	-21.3	-14.4	20.6	22.6	22.5	2.7	-0.4	-91.5	-33.0
5	-21.8	-15.5	19.4	22.5	22.5	0.9	-1.0	-80.7	-33.7
6	-22.2	-16.3	18.2	22.4	22.4	-0.9	-2.1	-75.5	-34.3
7	-22.4	-16.8	17.1	22.3	22.4	-1.5	-3.9	-70.8	-34.7
8	-22.7	-17.3	16.0	22.1	22.4	-3.6	-5.8	-65.8	-34.9
9	-22.9	-17.6	15.0	22.0	22.3	-6.9	-7.6	-63.9	-35.1
10	-23.0	-17.9	14.0	21.8	22.3	-9.6	-9.9	-60.8	-35.0
11	-23.1	-18.2	13.2	21.7	22.3	-10.8	-12.0	-58.6	-35.0
12	-23.2	-18.4	12.3	21.5	22.3	-14.3	-13.8	-55.2	-35.1
13	-23.3	-18.6	11.6	21.3	22.2	-15.5	-15.5	-54.7	-35.1
14	-23.4	-18.8	10.9	21.2	22.2	-17.2	-17.3	-53.8	-35.2
15	-23.4	-19.0	10.2	21.1	22.2	-18.3	-18.9	-51.8	-35.2
16	-23.5	-19.1	9.5	21.0	22.1	-21.0	-20.5	-50.6	-35.3
17	-23.7	-19.2	8.8	20.9	21.9	-22.8	-21.8	-49.9	-35.3
18	-23.7	-19.4	8.3	20.8	22.0	-24.2	-23.1	-48.3	-35.4
19	-23.7	-19.6	7.9	20.6	22.0	-23.8	-24.1	-47.7	-35.4
20	-23.7	-19.6	7.5	20.6	22.0	-24.5	-25.3	-46.7	-35.4
21	-23.8	-19.7	7.2	20.5	22.0	-26.7	-26.1	-46.2	-35.4
22	-23.8	-19.8	6.7	20.4	22.0	-27.8	-27.2	-45.3	-35.1
23	-23.8	-19.9	6.4	20.4	22.0	-27.7	-28.0	-44.6	-35.2
24	-23.8	-20.0	6.1	20.3	22.0	-28.7	-28.9	-43.2	-35.2
26	-23.9	-20.1	5.6	20.2	22.0	-30.5	-30.5	-42.8	-35.2
28	-23.9	-20.2	5.1	20.1	22.0	-31.5	-31.4	-41.1	-35.2
30	-24.0	-20.3	4.7	20.1	21.9	-32.5	-32.3	-40.8	-35.2
32	-24.0	-20.4	4.4	20.0	22.0	-33.0	-33.4	-40.2	-35.3
34	-24.0	-20.4	4.1	20.0	21.9	-34.2	-34.1	-39.4	-35.3
36	-24.0	-20.5	3.7	19.9	22.0	-34.7	-34.3	-39.7	-35.3
38	-24.1	-20.5	3.6	19.9	21.9	-35.2	-35.0	-38.4	-35.3
40	-24.0	-20.5	3.5	19.8	21.9	-35.6	-35.5	-38.4	-35.2
42	-24.0	-20.6	3.3	19.8	21.9	-34.7	-35.6	-37.8	-35.2
44	-24.1	-20.6	3.2	19.7	21.9	-35.0	-36.0	-37.0	-35.2
46	-24.0	-20.6	3.1	19.7	21.9	-35.7*	-36.9	-38.0	-35.1
48	-24.1	-20.6	3.0	19.7	21.9	-35.6	-36.6	-37.6	-35.2
50	-24.1	-20.7	2.9	19.7	21.9	-36.5	-36.8	-37.0	-35.2
52	-24.1	-20.7	2.9	19.7	21.9	-34.8	-36.9	-37.7	-35.3
54	-24.1	-20.7	2.8	19.7	21.9	-36.1	-37.0	-36.9	-35.3
56	-24.2	-20.7	2.8	19.7	21.9	-36.3	-37.3	-36.7	-35.3
58	-24.2	-20.8	2.8	19.7	22.0	-36.5	-37.3	-37.0	-35.4
60	-24.1	-20.7	2.7	19.7	21.9	-38.3	-37.3	-36.8	-35.3
62	-24.2	-20.8	2.7	19.7	21.9	-37.0	-37.3	-36.9	-35.3
64	-24.2	-20.8	2.6	19.7	21.9	-37.9	-37.4	-36.6	-35.3
66	-24.2	-20.8	2.6	19.7	22.0	-37.1	-37.5	-36.4	-35.3
68	-24.2	-20.8	2.6	19.7	21.9	-37.7	-37.4	-36.6	-35.3
70	-24.2	-20.8	2.6	19.7	21.9	-38.0	-37.5	-36.9	-35.4
72	-24.2	-20.8	2.6	19.7	21.9	-37.4	-37.8	-36.8	-35.4

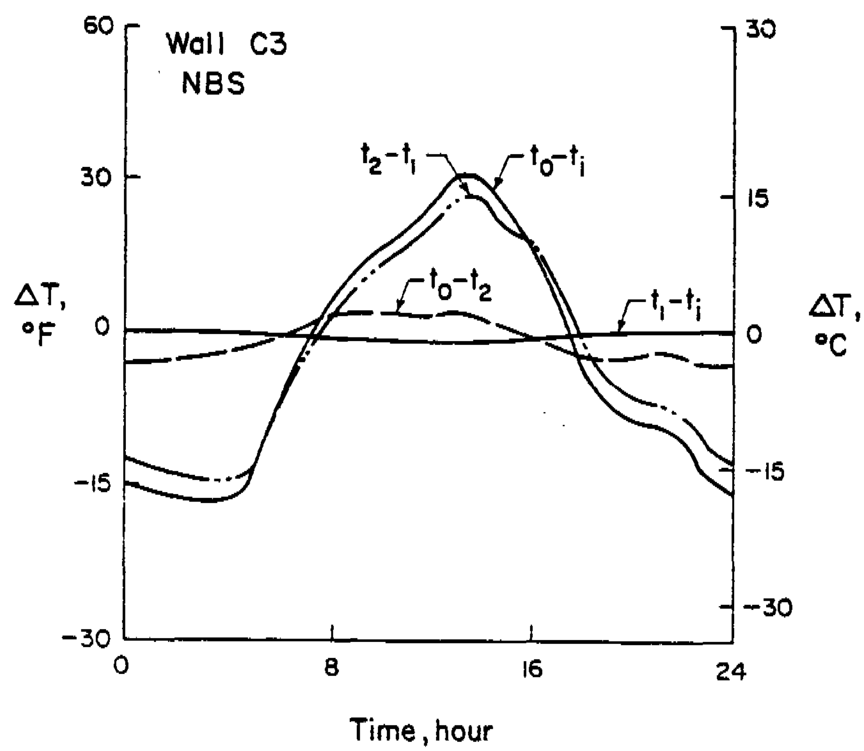
*Calibrated hot box data for this hour derived from linear interpolation of data from hours 44 to 47.

TABLE C3-6 - SUMMARY OF TRANSIENT TEST RESULTS

Heat Flux	Measured				Calculated	
	Calib. Hot Box		HFM @ Indoor Surf.		Steady-State	
	q_w, Btu/hr·ft^2 (W/m^2)	Time to Reach q_w, hr	q_{hfm}, Btu/hr·ft^2 (W/m^2)	Time to Reach q_{hfm}, hr	q_{ss}, Btu/hr·ft^2 (W/m^2)	Time to Reach q_{ss}, hr
99.5% of Final Heat Flux	-12.0 (-37.7)	57	-11.9 (-37.4)	65	-11.1 (-35.1)	9
95% of Final Heat Flux	-11.4 (-36.0)	47	-11.3 (-35.7)	43	-10.6 (-33.6)	5
90% of Final Heat Flux	-10.8 (-34.1)	33	-10.7 (-33.9)	34	-10.1 (-31.8)	4

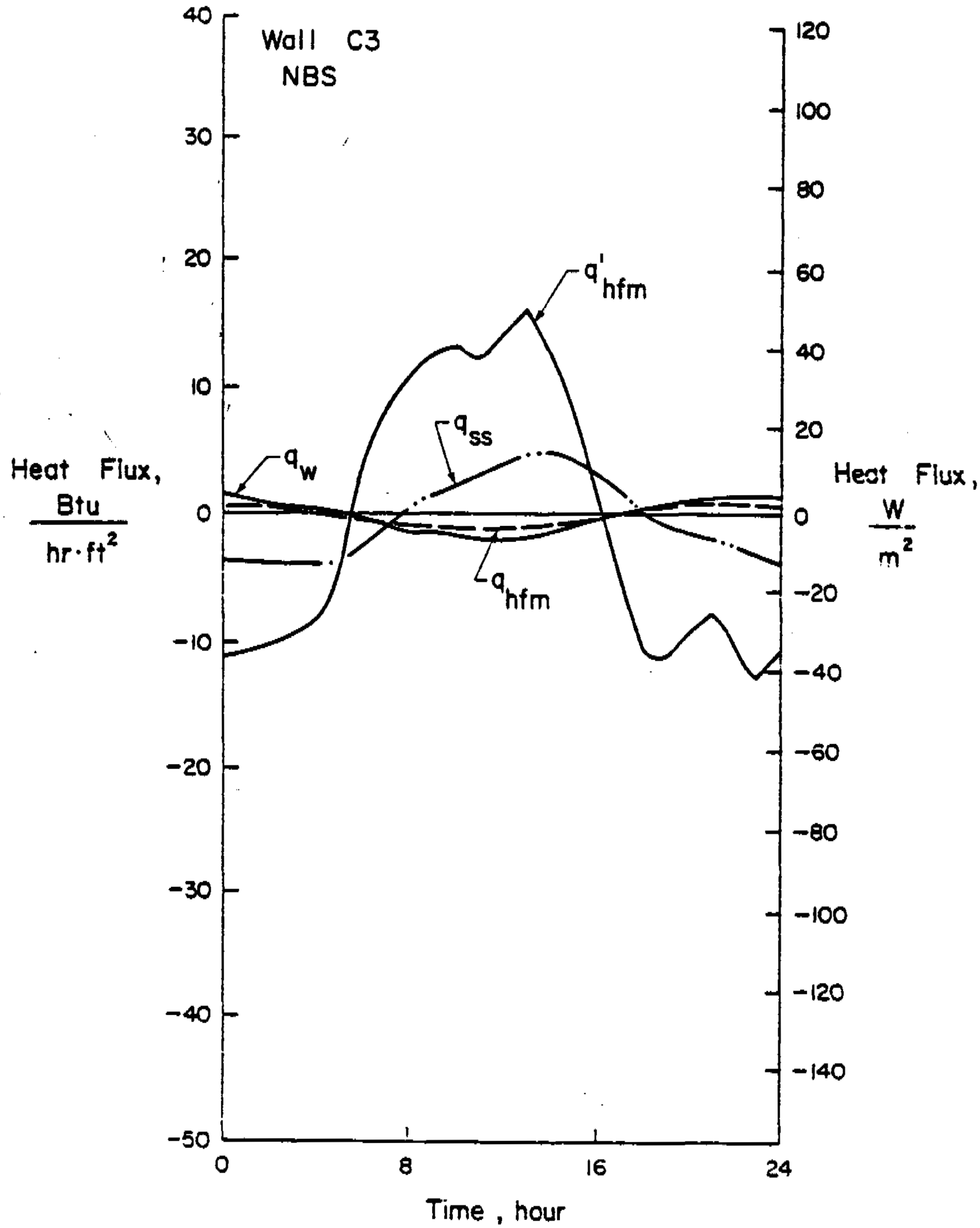


(a) Measured Temperatures



(b) Temperature Differentials

Fig. C3-2 Wall C3 Dynamic Test Results for NBS Test Cycle



(c) Heat Flux

Fig. C3-2 Wall C3 Dynamic Test Results for NBS Test Cycle

TABLE C3-7(a) - DYNAMIC TEST RESULTS (PERIODIC), NBS TEST CYCLE

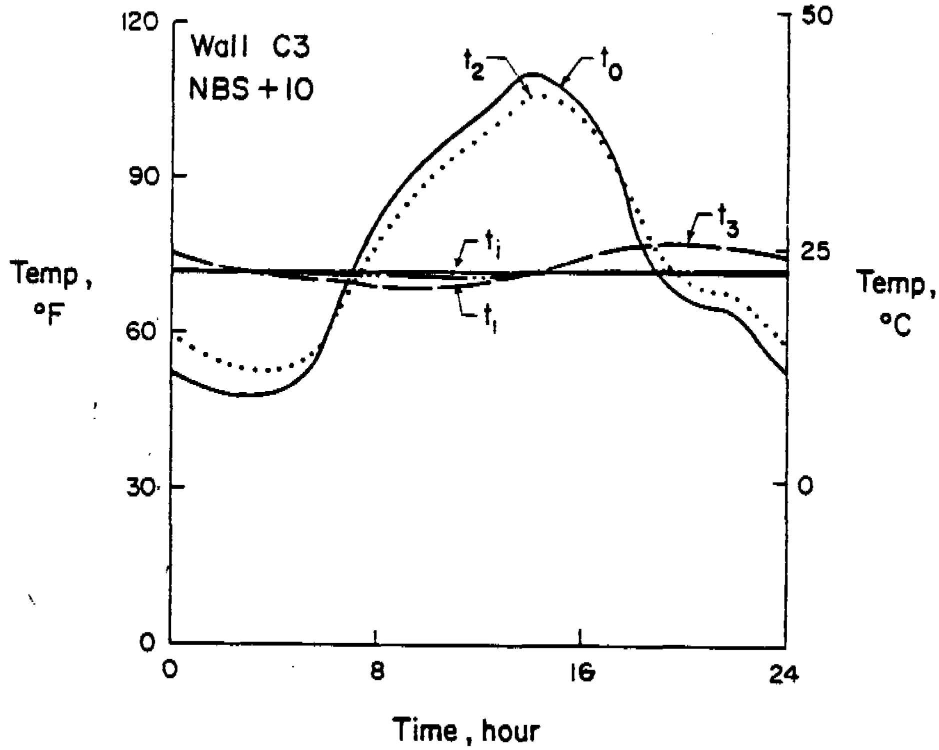
Time, hr	Measured Temperatures, °F					Measured Heat Flux, Btu/hr·ft^2			Calculated Heat Flux, Btu/hr·ft^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_3 Internal	t_1 Indoor Surf.	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	41.6	46.9	70.9	72.8	72.4	0.93	0.43	-11.16	-4.26
2	40.2	45.2	70.0	72.7	72.4	0.51	0.23	-10.81	-4.49
3	39.8	44.6	69.1	72.6	72.4	0.32	-0.03	-9.91	-4.58
4	39.7	44.2	68.2	72.4	72.3	0.19	-0.29	-9.17	-4.63
5	44.1	46.7	67.4	72.3	72.3	-0.28	-0.58	-5.06	-4.21
6	58.1	57.0	66.6	72.2	72.3	-0.93	-0.88	4.47	-2.50
7	68.0	65.7	66.1	72.1	72.3	-1.39	-1.13	8.07	-1.06
8	77.7	74.4	66.0	72.0	72.3	-1.90	-1.46	10.86	0.42
9	84.5	80.6	66.1	71.9	72.3	-1.80	-1.64	12.58	1.48
10	90.0	85.9	66.6	71.8	72.2	-2.08	-1.78	13.23	2.41
11	92.1	88.5	67.4	71.8	72.2	-2.08	-1.76	11.84	2.87
12	97.3	92.8	68.3	71.8	72.2	-2.27	-1.73	14.19	3.65
13	103.4	98.4	69.3	71.9	72.2	-2.08	-1.58	16.25	4.63
14	103.2	99.5	70.4	72.0	72.3	-1.62	-1.36	12.65	4.81
15	98.3	96.5	71.5	72.1	72.2	-1.25	-1.09	7.39	4.21
16	91.0	91.0	72.7	72.3	72.3	-0.93	-0.77	1.98	3.24
17	79.1	82.0	73.6	72.4	72.4	-0.32	-0.39	-5.62	1.62
18	66.5	71.2	74.2	72.6	72.4	0.37	-0.08	-11.28	-0.23
19	59.5	64.4	74.4	72.8	72.4	0.83	0.22	-11.80	-1.39
20	56.7	61.0	74.2	72.9	72.5	1.06	0.49	-10.03	-1.99
21	56.2	59.9	73.7	72.9	72.5	1.02	0.68	-8.12	-2.17
22	52.2	57.0	73.2	72.9	72.5	1.06	0.72	-10.25	-2.64
23	44.8	50.8	72.5	72.9	72.5	1.34	0.67	-13.30	-3.65
24	43.3	48.7	71.7	72.9	72.4	1.25	0.57	-11.52	-4.02
Mean	67.8	68.9	70.2	72.4	72.3	-0.42	-0.52	-0.60	-0.52

Calibrated Hot Box Relative Humidity:
Indoor Chamber - 24%
Outdoor Chamber - 24%

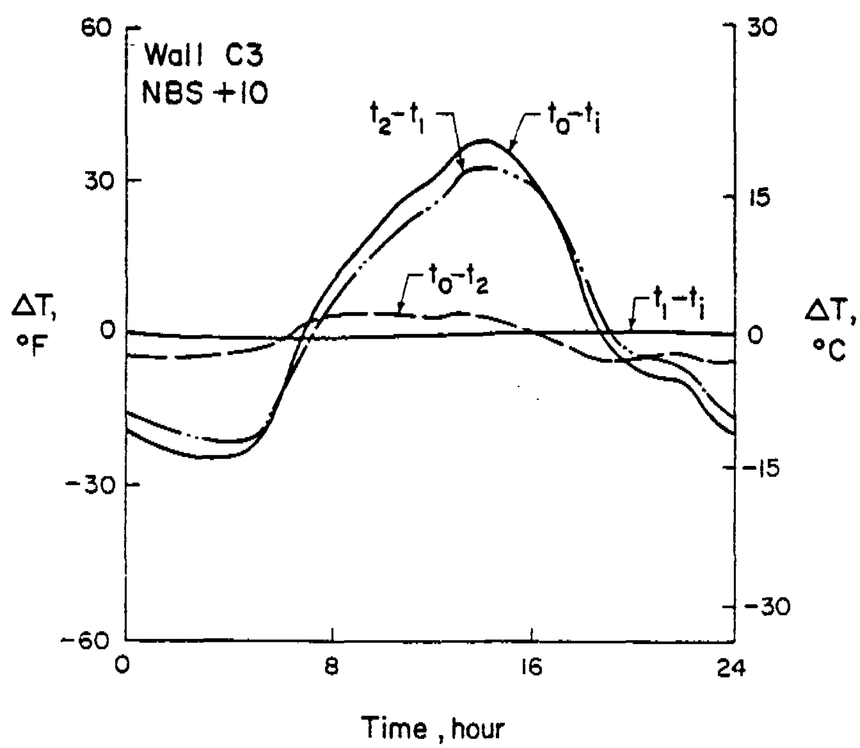
Laboratory Air Temperature:
Max. - 72°F (22°C)
Min. - 68°F (20°C)

TABLE C3-7(b) - DYNAMIC TEST RESULTS (PERIODIC), NBS TEST CYCLE, SI UNITS

Time, hr	Measured Temperatures, °C					Measured Heat Flux, W/m^2			Calculated Heat Flux, W/m^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_3 Internal	t_1 Indoor Surf.	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	5.3	8.3	21.6	22.7	22.5	2.92	1.35	-35.21	-13.42
2	4.5	7.4	21.1	22.6	22.4	1.60	0.72	-34.11	-14.15
3	4.4	7.0	20.6	22.5	22.4	1.02	-0.10	-31.27	-14.44
4	4.3	6.8	20.1	22.5	22.4	0.58	-0.92	-28.93	-14.59
5	6.7	8.1	19.7	22.4	22.4	-0.88	-1.83	-15.89	-13.27
6	14.5	13.9	19.2	22.3	22.4	-2.92	-2.77	14.10	-7.88
7	20.0	18.7	18.9	22.3	22.4	-4.38	-3.57	25.47	-3.36
8	25.4	22.5	18.9	22.2	22.4	-5.98	-4.61	34.25	1.31
9	29.2	27.0	19.0	22.2	22.3	-5.69	-5.17	39.68	4.67
10	32.2	30.0	19.2	22.1	22.3	-6.56	-5.60	41.73	7.59
11	33.4	31.4	19.7	22.1	22.3	-6.56	-5.57	37.37	9.04
12	36.3	33.8	20.2	22.1	22.3	-7.15	-5.44	44.77	11.52
13	39.7	36.9	20.7	22.2	22.3	-6.56	-4.97	51.26	14.59
14	39.5	37.5	21.3	22.2	22.4	-5.11	-4.28	39.92	15.17
15	36.9	35.8	21.9	22.3	22.3	-3.94	-3.43	23.30	13.27
16	32.8	32.8	22.6	22.4	22.4	-2.92	-2.42	6.25	10.21
17	26.2	27.8	23.1	22.5	22.4	-1.02	-1.24	-17.73	5.11
18	19.1	21.8	23.4	22.6	22.5	1.17	-0.25	-35.60	-0.73
19	15.3	18.0	23.5	22.6	22.5	2.63	0.71	-37.17	-4.38
20	13.7	16.1	23.4	22.7	22.5	3.36	1.55	-31.66	-6.27
21	13.5	15.5	23.2	22.7	22.5	3.21	2.13	-25.61	-6.86
22	11.2	13.9	22.9	22.7	22.5	3.36	2.28	-32.28	-8.32
23	7.1	10.4	22.5	22.7	22.5	4.23	2.12	-41.97	-11.52
24	6.3	9.3	22.1	22.7	22.5	3.94	1.80	-36.35	-12.69
Mean	19.9	20.5	21.2	22.4	22.4	-1.32	-1.65	-1.90	-1.64

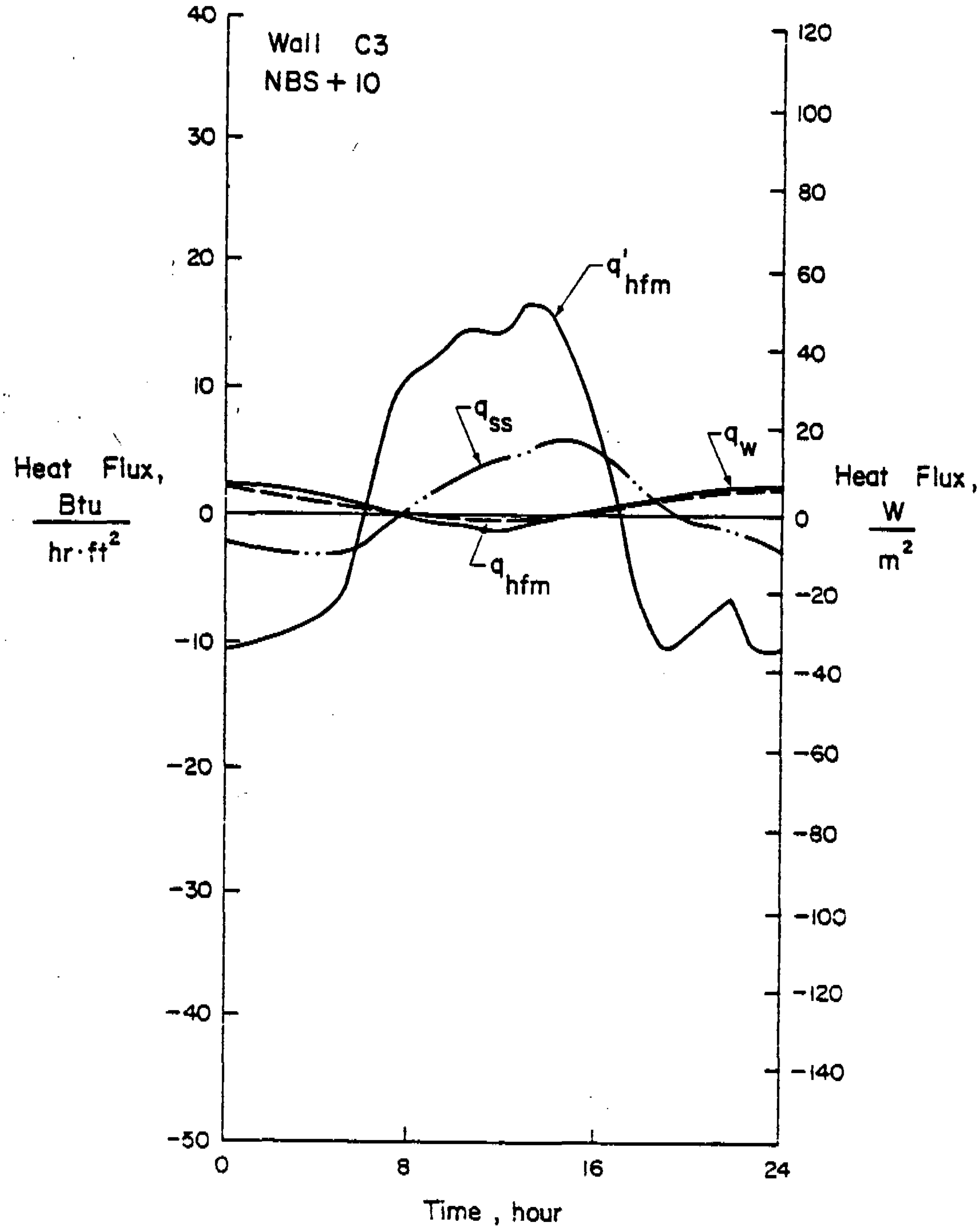


(a) Measured Temperatures



(b) Temperature Differentials

Fig. C3-3 Wall C3 Dynamic Test Results for NBS +10 Test Cycle



(c) Heat Flux

Fig. C3-3 Wall C3 Dynamic Test Results for NBS +10 Test Cycle

TABLE C3-8(a) - DYNAMIC TEST RESULTS (PERIODIC), NBS+10 TEST CYCLE

Time, hr	Measured Temperatures, °F					Measured Heat Flux, Btu/hr·ft^2			Calculated Heat Flux, Btu/hr·ft^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_3 Internal	t_1 Indoor Surf.	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	52.1	56.8	75.3	73.5	72.7	2.41	1.82	-10.46	-2.78
2	50.2	54.8	74.4	73.4	72.7	2.17	1.67	-10.06	-3.10
3*	49.1	53.5	73.5	73.3	72.7	1.71	1.41	-9.43	-3.28
4	49.3	53.2	72.7	73.2	72.6	1.39	1.18	-8.05	-3.33
5	50.3	53.7	71.8	73.1	72.6	1.06	0.89	-6.81	-3.19
6	59.3	59.4	71.0	72.9	72.6	0.65	0.59	0.87	-2.27
7	72.9	70.3	70.3	72.8	72.6	0.09	0.31	8.68	-0.46
8	81.9	78.5	69.3	72.6	72.4	-0.46	-0.20	11.31	0.97
9	88.5	84.6	69.4	72.5	72.4	-0.74	-0.43	12.58	2.08
10	95.4	90.7	69.8	72.3	72.4	-0.79	-0.56	14.76	3.15
11*	99.7	95.3	70.2	72.3	72.3	-1.11	-0.71	14.43	4.02
12	102.6	98.2	71.3	72.4	72.4	-1.11	-0.60	14.10	4.49
13	108.6	103.3	72.2	72.4	72.3	-0.93	-0.49	17.11	5.41
14	112.0	107.2	73.3	72.5	72.4	-0.56	-0.33	16.59	6.11
15	110.0	106.6	74.5	72.6	72.5	-0.28	-0.09	12.24	5.97
16	105.8	103.7	75.6	72.7	72.5	0.19	0.25	7.99	5.46
17	97.3	97.4	76.7	72.9	72.5	0.42	0.59	1.49	4.26
18*	82.8	86.1	77.5	73.1	72.6	1.02	0.93	-7.49	2.27
19	71.9	76.4	78.0	73.3	72.7	1.34	1.22	-10.91	0.56
20	67.3	71.4	78.2	73.5	72.7	1.90	1.62	-9.84	-0.37
21	65.7	69.0	77.9	73.6	72.8	2.27	1.81	-7.86	-0.79
22	65.0	68.0	77.3	73.6	72.8	2.27	1.94	-6.59	-0.93
23	58.1	63.0	76.7	73.6	72.7	2.41	2.04	-11.01	-1.80
24	54.6	59.1	76.0	73.6	72.7	2.41	1.92	-10.66	-2.41
Mean	77.1	77.5	73.9	73.0	72.5	0.74	0.70	0.96	0.83

*Data for these hours are 2-day averages, not 3-day averages, of test results.

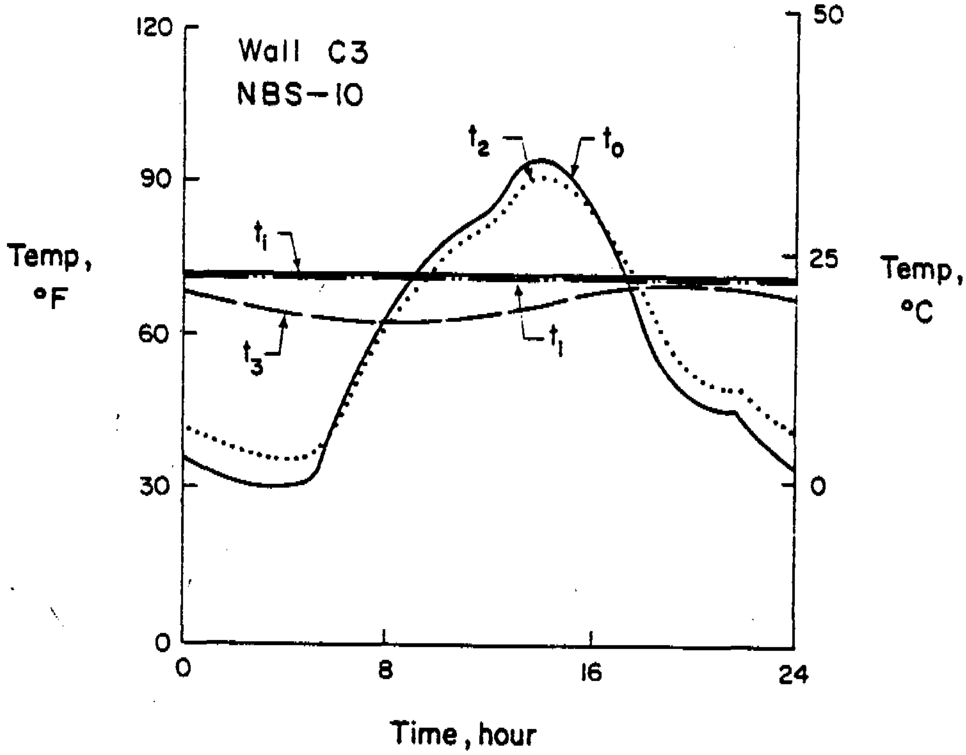
Calibrated Hot Box Relative Humidity:
Indoor Chamber - 25%
Outdoor Chamber - 24%

Laboratory Air Temperature:
Max. - 72°F (22°C)
Min. - 70°F (21°C)

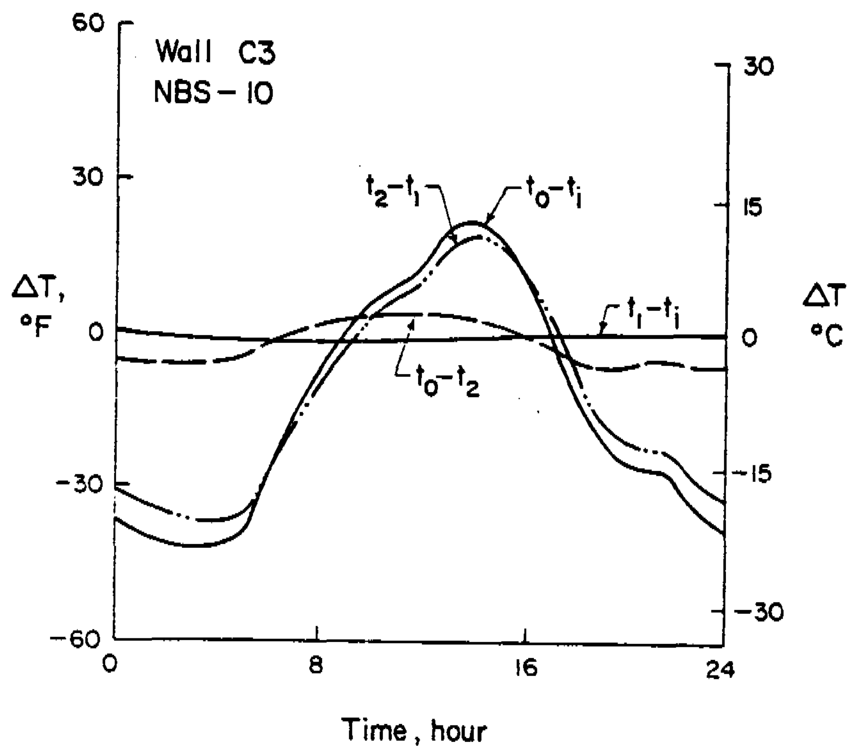
TABLE C3-8(b) - DYNAMIC TEST RESULTS (PERIODIC), NBS+10 TEST CYCLE, SI UNITS

Time, hr	Measured Temperatures, °C					Measured Heat Flux, W/m^2			Calculated Heat Flux, W/m^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_3 Internal	t_1 Indoor Surf.	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	11.2	13.8	24.0	23.0	22.6	7.59	5.73	-32.99	-8.75
2	10.1	12.7	23.6	23.0	22.6	6.86	5.26	-31.72	-9.77
3*	9.5	12.0	23.1	23.0	22.6	5.40	4.45	-29.76	-10.36
4	9.6	11.8	22.6	22.9	22.5	4.38	3.73	-25.41	-10.50
5	10.1	12.0	22.1	22.8	22.6	3.36	2.80	-21.49	-10.07
6	15.2	15.2	21.7	22.7	22.5	2.04	1.86	2.74	-7.15
7	22.7	21.3	21.3	22.7	22.5	0.29	0.99	27.38	-1.46
8	27.7	25.8	20.7	22.5	22.5	-1.46	-0.62	35.67	3.06
9	31.4	29.2	20.8	21.5	22.4	-2.33	-1.36	39.70	6.56
10	35.2	32.6	21.0	21.4	22.4	-2.48	-1.78	46.58	9.92
11*	37.6	35.2	21.2	22.4	22.4	-3.50	-2.23	45.51	12.69
12	39.2	36.8	21.8	22.4	22.4	-3.50	-1.90	44.46	14.15
13	42.5	39.6	22.3	22.5	22.4	-2.92	-1.54	53.97	17.07
14	44.5	41.8	22.9	22.5	22.5	-1.75	-1.04	52.34	19.26
15	43.3	41.4	23.6	22.6	22.5	-0.88	-0.30	38.61	18.82
16	41.0	39.8	24.2	22.6	22.5	0.58	0.80	25.21	17.21
17	36.3	36.4	24.8	22.7	22.5	1.31	1.85	4.69	13.42
18*	28.2	30.1	25.3	22.8	22.6	3.21	2.92	-23.63	7.15
19	22.2	24.7	25.5	22.9	22.6	4.23	3.85	-34.42	1.75
20	19.6	21.9	25.7	23.0	22.6	5.98	5.11	-31.04	-1.17
21	18.7	20.6	25.5	23.1	22.7	7.15	5.72	-24.81	-2.48
22	18.3	20.0	25.2	23.1	22.6	7.15	6.11	-20.80	-2.92
23	14.5	17.2	24.8	23.1	22.6	7.59	6.43	-34.74	-5.69
24	12.5	15.1	24.5	23.1	22.6	7.59	6.05	-33.62	-7.59
Mean	25.1	25.3	23.3	22.8	22.5	2.33	2.20	3.01	2.63

*Data for these hours are 2-day averages, not 3-day averages, of test results.

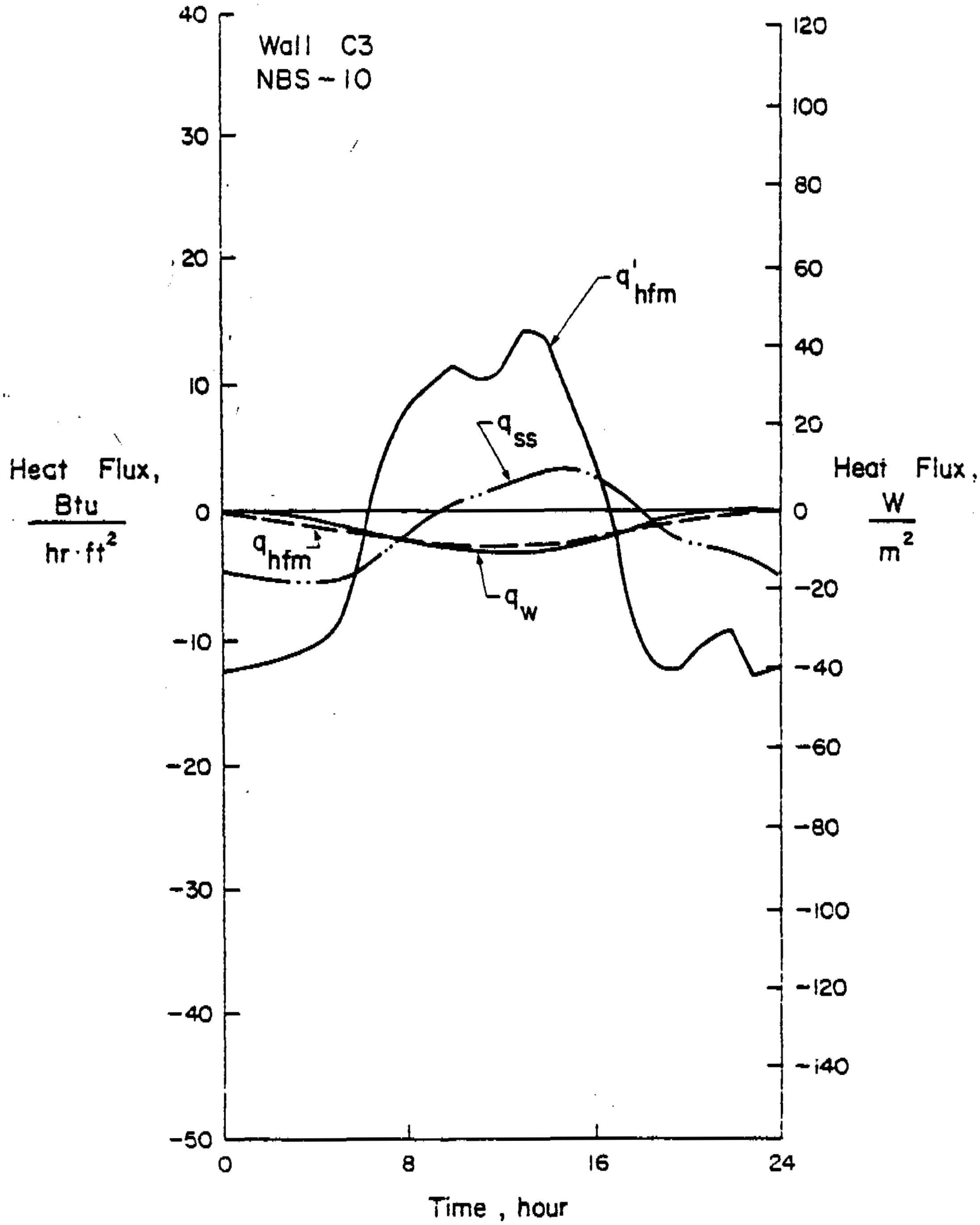


(a) Measured Temperatures



(b) Temperature Differentials

Fig. C3-4 Wall C3 Dynamic Test Results for NBS -10 Test Cycle



(c) Heat Flux

Fig. C3-4 Wall C3 Dynamic Test Results for NBS -10 Test Cycle

TABLE C3-9(a) - DYNAMIC TEST RESULTS (PERIODIC), NBS-10 TEST CYCLE

Time, hr	Measured Temperatures, °F					Measured Heat Flux, Btu/hr·ft^2			Calculated Heat Flux, Btu/hr·ft^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_3 Internal	t_1 Indoor Surf.	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	33.6	39.5	67.5	72.2	72.2	-0.28	-0.78	-12.68	-5.37
2	31.4	37.2	66.7	72.1	72.2	-0.56	-0.96	-12.59	-5.69
3	30.4	36.0	65.8	72.0	72.2	-0.69	-1.19	-11.80	-5.83
4	30.3	35.5	64.9	71.9	72.1	-1.02	-1.44	-10.85	-5.87
5	31.3	35.9	64.0	71.8	72.1	-1.48	-1.69	-9.35	-5.78
6	40.9	42.2	63.2	71.7	72.1	-2.04	-1.99	-1.82	-4.81
7	53.9	52.7	62.5	71.5	72.1	-2.36	-2.30	5.12	-3.10
8	63.2	60.9	62.1	71.4	72.0	-2.68	-2.58	8.07	-1.76
9	70.1	67.3	62.1	71.3	72.0	-3.15	-2.83	9.47	-0.69
10	77.5	74.0	62.6	71.3	72.1	-3.28	-2.96	11.45	0.46
11	81.1	78.0	63.2	71.2	72.1	-3.47	-3.06	10.65	1.11
12	84.3	80.9	64.0	71.3	72.1	-3.52	-3.05	10.81	1.67
13	91.3	86.7	64.8	71.3	72.1	-3.56	-2.96	14.40	2.64
14	94.5	90.5	65.9	71.4	72.1	-3.42	-2.79	13.31	3.28
15	92.6	90.0	66.9	71.5	72.1	-2.82	-2.56	9.34	3.19
16	87.1	86.2	68.1	71.6	72.1	-2.45	-2.29	4.37	2.50
17	79.1	80.3	69.2	71.7	72.2	-1.90	-1.96	-1.20	1.48
18	64.7	69.3	70.0	71.9	72.2	-1.39	-1.63	-10.18	-0.46
19	54.5	60.0	70.4	72.1	72.2	-0.88	-1.25	-12.92	-2.04
20	48.5	54.1	70.5	72.2	72.2	-0.51	-0.96	-12.84	-3.01
21	46.8	51.7	70.2	72.3	72.2	-0.28	-0.76	-10.67	-3.42
22	46.2	50.7	69.6	72.3	72.2	-0.09	-0.63	-9.32	-3.61
23	39.2	45.6	68.9	72.3	72.2	-0.05	-0.59	-13.37	-4.39
24	35.7	41.6	68.3	72.3	72.2	-0.19	-0.67	-13.03	-5.00
Mean	58.7	60.3	66.3	71.8	72.1	-1.75	-1.83	-1.90	-1.85

Calibrated Hot Box Relative Humidity:
Indoor Chamber - 24%
Outdoor Chamber - 25%

Laboratory Air Temperature:
Max. - 73°F (23°C)
Min. - 69°F (21°C)

TABLE C3-9(b) - DYNAMIC TEST RESULTS (PERIODIC), NBS-10 TEST CYCLE, SI UNITS

Time, hr	Measured Temperatures, °C					Measured Heat Flux, W/m^2			Calculated Heat Flux, W/m^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_3 Internal	t_1 Indoor Surf.	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	0.9	4.1	19.7	22.3	22.3	-0.88	-2.47	-40.01	-16.92
2	-0.3	2.9	19.3	22.3	22.3	-1.75	-3.04	-39.72	-17.94
3	-0.9	2.2	18.8	22.2	22.3	-2.19	-3.75	-37.23	-18.38
4	-0.9	2.0	18.3	22.2	22.3	-3.21	-4.55	-34.23	-18.53
5	-0.4	2.2	17.8	22.1	22.3	-4.67	-5.33	-29.49	-18.23
6	4.9	5.7	17.3	22.0	22.3	-6.42	-6.28	-5.75	-15.17
7	12.2	11.5	17.0	22.0	22.3	-7.44	-7.25	16.14	-9.77
8	17.3	16.1	16.7	21.9	22.2	-8.46	-8.13	25.47	-5.54
9	21.2	19.6	16.7	21.8	22.2	-9.92	-8.92	29.88	-2.19
10	25.3	23.3	17.0	21.8	22.3	-10.36	-9.33	36.12	1.46
11	27.3	25.5	17.3	21.8	22.3	-10.94	-9.66	33.59	3.50
12	29.0	27.2	17.8	21.8	22.3	-11.09	-9.63	34.10	5.25
13	33.0	30.4	18.2	21.8	22.3	-11.23	-9.33	45.43	8.32
14	34.7	32.5	18.8	21.9	22.3	-10.80	-8.80	42.00	10.36
15	33.6	32.2	19.4	21.9	22.3	-8.90	-8.08	29.48	10.07
16	30.6	30.1	20.0	22.0	22.3	-7.73	-7.22	13.78	7.88
17	26.2	26.9	20.6	22.1	22.3	-5.98	-6.17	-3.78	4.67
18	18.2	20.7	21.1	22.2	22.3	-4.38	-5.13	-32.13	-1.46
19	12.5	15.5	21.3	22.3	22.3	-2.77	-3.95	-40.75	-6.42
20	9.2	12.3	21.4	22.3	22.4	-1.60	-3.02	-40.50	-9.48
21	8.2	10.9	21.2	22.4	22.3	-0.88	-2.39	-33.67	-10.80
22	7.9	10.4	20.9	22.4	22.4	-0.29	-1.98	-29.39	-11.38
23	4.0	7.5	20.5	22.4	22.3	-0.15	-1.86	-42.19	-13.86
24	2.0	5.3	20.2	22.4	22.4	-0.58	-2.12	-41.12	-15.75
Mean	14.8	15.7	19.1	22.1	22.3	-5.53	-5.77	-6.00	-5.85

TABLE C3-10 - SUMMARY OF DYNAMIC TEST RESULTS (PERIODIC), THERMAL LAG

Test Cycle	Thermal Lag, hrs								Calc. Time Constant, hrs
	Measured								
	Calibrated Hot Box					Heat Flow Meter			
	t_o vs t_1		q_{ss} vs q_w		Avg.	q_{ss} vs q_{hfm}		Avg.	
	@ Max.	@ Min.	@ Max.	@ Min.		@ Max.	@ Min.		
NBS	9	7	9	8	8.5	8	6.5	7.5	3.6
NBS+10	8	8	10	8	8.5	9	7	8	3.6
NBS-10	8.5	7	9	9	8.5	9	7.5	8.5	3.6

TABLE C3-11 - SUMMARY OF DYNAMIC TEST RESULTS (PERIODIC), REDUCTION IN AMPLITUDE

Test Cycle	Measured, %					
	Calibrated Hot Box			Heat Flow Meter		
	@ Max.	@ Min.	Avg.	@ Max.	@ Min.	Avg.
NBS	67	55	61	77	69	73
NBS+10	68	56	62	75	66	71
NBS-10	67	55	61	76	69	73

TABLE C3-12 - SUMMARY OF DYNAMIC TEST RESULTS (PERIODIC), ENERGY REQUIREMENTS

Test Cycle	Total Energy Btu/ft^2 (W·hr/m^2)			Total Energy Comparisons, %		Net Energy Btu/ft^2 (W·hr/m^2)			Net Energy Comparisons, %	
	Measured		Calculated	$\frac{q_w^T}{q_{ss}^T}$	$\frac{q_{hfm}^T}{q_{ss}^T}$	Measured		Calculated	$\frac{q_w^N}{q_{ss}^N}$	$\frac{q_{hfm}^N}{q_{ss}^N}$
	q_w^T	q_{hfm}^T	q_{ss}^T			q_w^N	q_{hfm}^N	q_{ss}^N		
NBS	27.8 (87.7)	20.6 (65.0)	71.1 (224.4)	39	29	-10.0 (-31.7)	-12.5 (-39.5)	-12.5 (-39.4)	80	100
NBS+10	29.6 (93.5)	23.6 (74.5)	69.4 (219.0)	43	34	17.7 (55.9)	16.8 (53.0)	20.0 (63.2)	88	84
NBS-10	42.0 (132.6)	43.9 (138.4)	77.1 (243.3)	55	57	-42.0 (-132.6)	-43.9 (-138.4)	-44.5 (-140.3)	95	99

WALL S1: 1-3/8-in. (35-mm) FIBERGLASS BOARD INSULATION

DESCRIPTION: 1-3/8-in. (35-mm) fiberglass board insulation with foil facing.

REFERENCE: Fiorato, A. E., "Laboratory Tests of Thermal Performance of Exterior Walls," Proceedings of the ASHRAE/DOE-ORNL Conference on Thermal Performance of the Exterior Envelopes of Buildings, Orlando, Florida, Dec. 1979, ASHRAE SP28, Atlanta, 1981, pp. 221-236.

COMPOSITION:

1. 1-3/8-in. (35-mm) Fiberglass Board Insulation
2. Fiber-Reinforced Foil Facing (each face), painted off-white

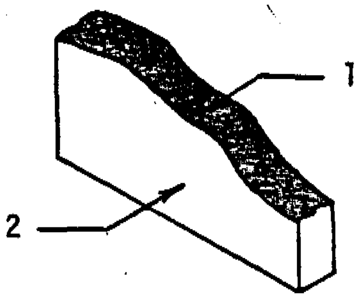


TABLE S1-1 - PHYSICAL PROPERTIES OF WALL AT TIME OF TEST*

Property	Measured Value
Unit weight, psf (kg/m^2)	1.07 (5.22)
Average Thickness, in. (mm)	1.46 (37.1)
Area, ft^2 (m^2)	73.21 (6.80)

*Wall was tested September through October 1981. Properties were measured January 1985.

TABLE S1-2 - MATERIAL PROPERTIES, FIBERGLASS

Property	Test Method	Specimen Condition	Mean Temperature, °F (°C)	Measured Value
Thickness*, in. (mm)	--	--	--	1.40 (35.6)
Unit Weight*, pcf (kg/m^3)	--	--	--	8.42 (135)
Thermal Conductivity*, $Btu \cdot in./hr \cdot ft^2 \cdot °F$ ($W/m \cdot K$)	ASTM C518	air dry	75 (24)	0.243 (0.0350)

*Properties determined by Owens-Corning Fiberglas Corporation.

TABLE S1-3 - DESIGN HEAT TRANSMISSION COEFFICIENTS

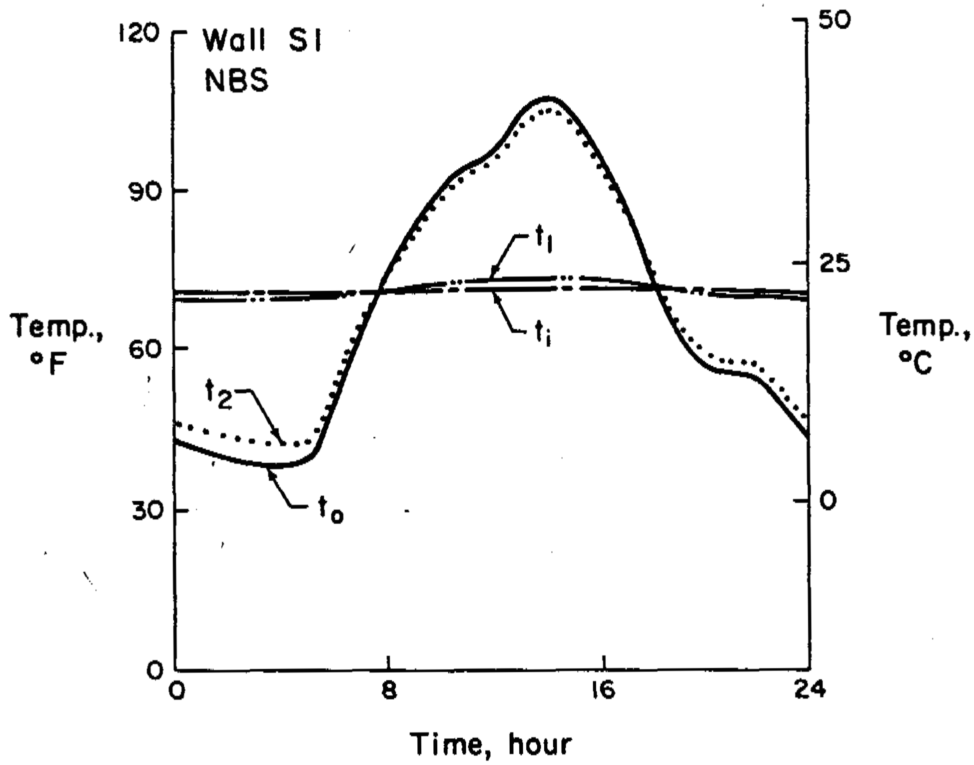
Component	R, Thermal Resistance hr•ft²•°F/Btu (m²•K/W)
1. Outside Air Film	0.17* (0.03)
2. 1-3/8-in. (35-mm) Fiberglass Board Insulation	5.50* (0.97)
3. Inside Air Film	0.68* (0.12)
Total R	6.35 (1.12)
Total U	0.16 (0.89)

*Source: ASHRAE Handbook-1981 Fundamentals, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, 1981, Chapter 23.

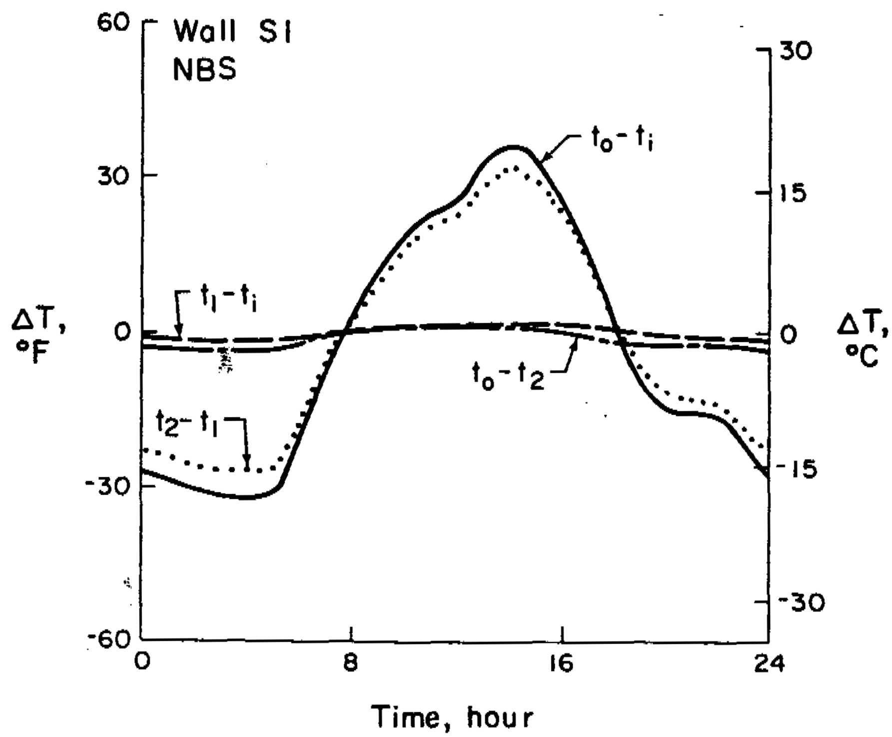
TABLE S1-4 - STEADY-STATE TEST RESULTS

Nominal Test Condition	q Heat Flux, Btu/hr·ft^2 (W/m^2)	R_T,* hr·ft^2·°F/Btu (m^2·K/W)	U,* Btu/hr·ft^2·°F (W/m^2·K)	Measured Temperatures, °F (°C)						Relative Humidity		Laboratory Air Temperature	
				t_o Outdoor Air	t_2 Outdoor Surface	t_3** Internal	t_4** Internal	t_1 Indoor Surface	t_i Indoor Air	Indoor Chamber, %	Outdoor Chamber, %	Max. °F (°C)	Min. °F (°C)
t_m = 32°F (0°C)	-11.1 (-35.1)	7.10 (1.25)	0.14 (0.80)	-10 (-23)	-3 (-19)	-	-	67 (19)	70 (21)	48	22	74 (23)	72 (22)
t_m = 103°F (40°C)	9.7 (30.6)	6.50 (1.14)	0.15 (0.87)	134 (57)	131 (55)	-	-	76 (24)	72 (22)	49	26	69 (21)	67 (19)
Design values (Predicted)+	-	6.61 (1.16)	0.15 (0.86)	-	-	-	-	-	-	-	-	-	-
Design values (ASHRAE)++	-	6.35 (1.12)	0.16 (0.89)	-	-	-	-	-	-	-	-	-	-

*Total thermal resistance, R_T, and transmittance, U, for steady-state tests were calculated using the design surface resistance coefficients from Table S1-3 and measured values of heat flux.
**Internal thermocouples were not used on this wall assembly.
+Calculated from properties measured by Owens-Corning Fiberglass Corporation and listed in Table S1-2.
++From Table S1-3.

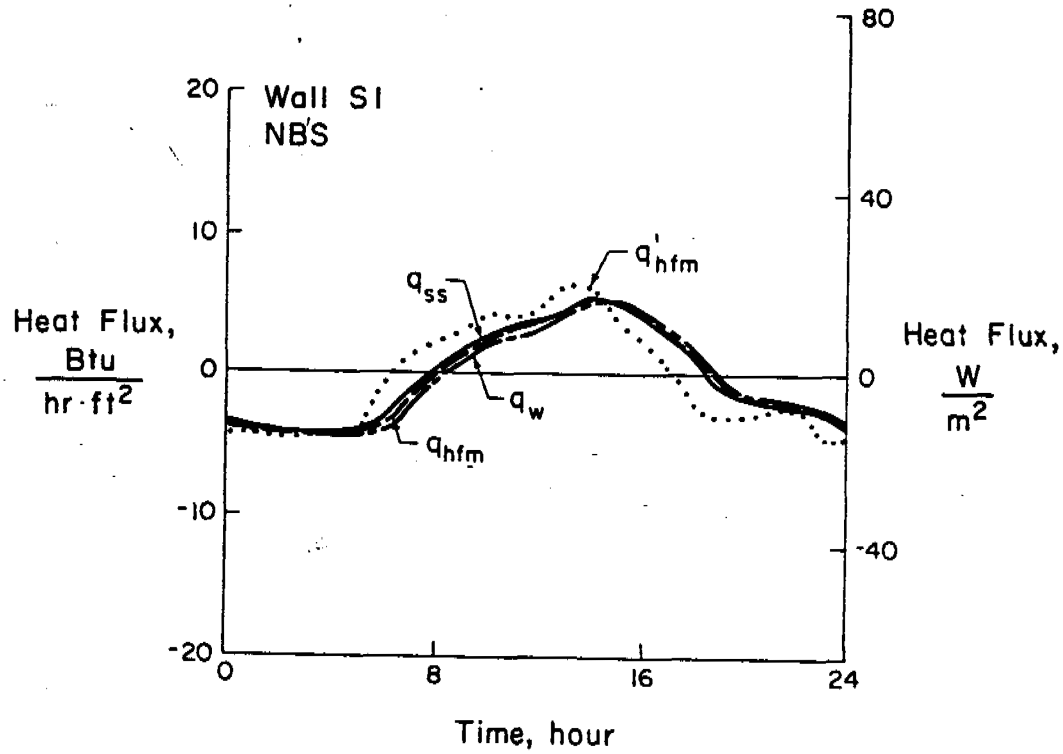


(a) Measured Temperatures



(b) Temperature Differentials

Fig. S1-2 Wall S1 Dynamic Test Results for NBS Test Cycle



(c) Heat Flux

Fig. S1-2 Wall S1 Dynamic Test Results for NBS Test Cycle

TABLE S1-7(a) - DYNAMIC TEST RESULTS (PERIODIC), NBS TEST CYCLE

Time, hr	Measured Temperatures, °F						Measured Heat Flux, Btu/hr·ft^2			Calculated Heat Flux, Btu/hr·ft^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_3^* Inter-nal	t_4^* Inter-nal	t_1 Indoor Surf.	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	42.2	45.3			69.6	70.7	-3.84	-4.00	-4.33	-4.03
2	40.4	43.7			69.5	70.8	-4.30	-4.28	-4.66	-4.28
3	39.3	42.6			69.5	70.8	-4.51	-4.48	-4.60	-4.47
4	39.2	42.4			69.5	70.7	-4.71	-4.46	-4.51	-4.50
5	39.5	42.7			69.4	70.7	-4.30	-4.47	-4.32	-4.43
6	49.6	51.0			69.8	70.8	-4.14	-3.79	-0.71	-3.14
7	64.5	64.9			70.8	71.0	-2.31	-1.57	1.44	-1.00
8	73.9	73.8			71.4	71.1	-0.50	-0.01	2.08	0.41
9	81.6	81.1			71.9	71.2	0.61	1.16	2.91	1.57
10	90.0	88.9			72.4	71.3	2.02	2.44	4.19	2.84
11	94.0	93.0			72.8	71.4	2.52	3.26	3.86	3.47
12	96.7	95.4			73.0	71.5	3.09	3.64	4.43	3.85
13	103.5	101.5			73.4	71.5	4.23	4.46	6.35	4.86
14	107.9	106.1			73.7	71.5	4.76	5.41	6.07	5.64
15	104.2	103.2			73.7	71.6	5.29	5.23	3.83	5.10
16	97.5	96.9			73.2	71.5	4.35	4.32	2.38	4.10
17	88.2	88.5			72.7	71.5	3.35	3.09	0.33	2.72
18	74.2	75.8			71.9	71.3	1.65	1.31	-2.63	0.66
19	62.9	64.9			71.0	71.1	-0.10	-0.67	-3.15	-1.03
20	57.1	59.2			70.6	71.0	-1.53	-1.74	-3.08	-1.92
21	55.4	57.3			70.4	70.9	-1.93	-2.20	-2.58	-2.20
22	55.3	57.3			70.4	71.0	-2.22	-2.28	-2.40	-2.20
23	48.7	51.8			70.2	70.9	-2.67	-2.71	-4.82	-3.07
24	43.2	46.4			69.6	70.7	-3.63	-3.74	-4.52	-3.85
Mean	68.7	69.7			71.3	71.1	-0.37	-0.25	-0.35	-0.20

*Internal thermocouples were not used on this wall assembly.

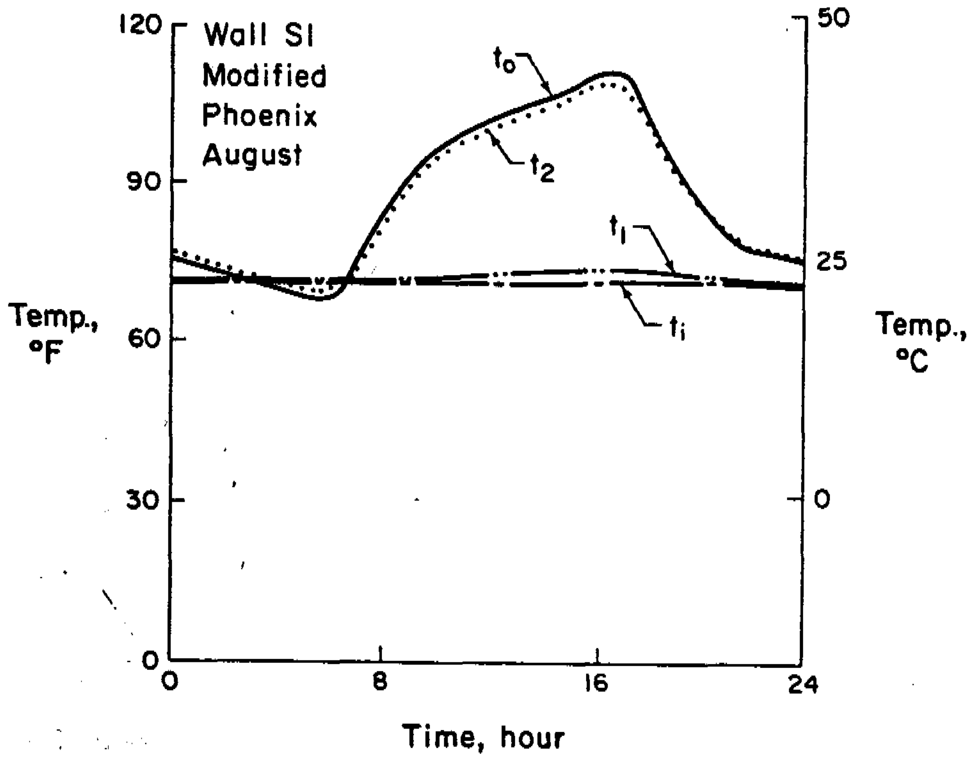
Calibrated Hot Box Relative Humidity:
Indoor Chamber - 44%
Outdoor Chamber - 20%

Laboratory Air Temperature:
Max. - 74°F (23°C)
Min. - 70°F (21°C)

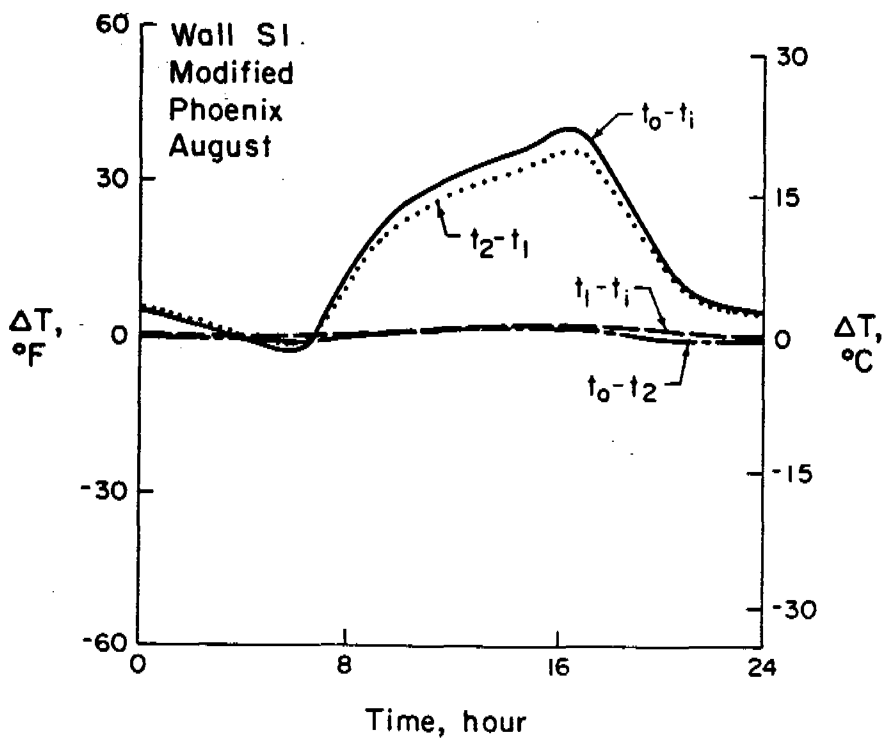
TABLE S1-7(b) - DYNAMIC TEST RESULTS (PERIODIC), NBS TEST CYCLE, SI UNITS

Time, hr	Measured Temperatures, °C						Measured Heat Flux, W/m^2			Calculated Heat Flux, W/m^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_3^* Inter-nal	t_4^* Inter-nal	t_1 Indoor Surf.	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	5.6	7.3			20.9	21.5	-12.13	-12.61	-13.65	-12.71
2	4.7	6.4			20.8	21.5	-13.57	-13.50	-14.71	-13.50
3	4.1	5.9			20.8	21.6	-14.24	-14.14	-14.52	-14.10
4	4.0	5.8			20.8	21.5	-14.86	-14.08	-14.22	-14.20
5	4.2	6.1			20.8	21.5	-13.56	-14.09	-13.63	-13.97
6	9.8	11.8			21.0	21.5	-13.06	-11.94	-2.24	-9.91
7	18.1	19.1			21.6	21.7	-7.27	-4.94	4.54	-3.15
8	23.3	23.9			21.9	21.7	-1.57	-0.02	6.56	1.29
9	27.6	27.8			22.2	21.8	1.92	3.67	9.17	4.95
10	32.2	31.6			22.5	21.8	6.38	7.68	13.21	8.96
11	34.5	33.9			22.7	21.9	7.94	10.29	12.18	10.95
12	35.9	35.2			22.8	21.9	9.76	11.47	13.98	12.15
13	39.7	38.6			23.0	21.9	13.34	14.07	20.02	15.33
14	42.1	41.2			23.2	22.0	15.02	17.06	19.14	17.79
15	40.1	39.6			23.2	22.0	16.69	16.51	12.09	16.09
16	36.4	36.1			22.9	22.0	13.73	13.62	7.51	12.93
17	31.2	31.4			22.6	21.9	10.58	9.75	1.03	8.58
18	23.4	24.3			22.2	21.8	5.21	4.12	-8.30	2.08
19	17.2	18.3			21.7	21.7	-0.30	-2.13	-9.94	-3.25
20	13.9	15.1			21.4	21.7	-4.81	-5.48	-9.70	-6.06
21	13.0	14.1			21.3	21.6	-6.08	-6.95	-8.14	-6.94
22	13.0	14.1			21.3	21.7	-7.00	-7.20	-7.59	-6.94
23	9.3	11.0			21.2	21.6	-8.43	-8.55	-15.22	-9.68
24	6.2	8.0			20.9	21.5	-11.46	-11.80	-14.27	-12.15
Mean	20.4	21.0			21.8	21.7	-1.16	-0.80	-1.11	-0.64

*Internal thermocouples were not used on this wall assembly.

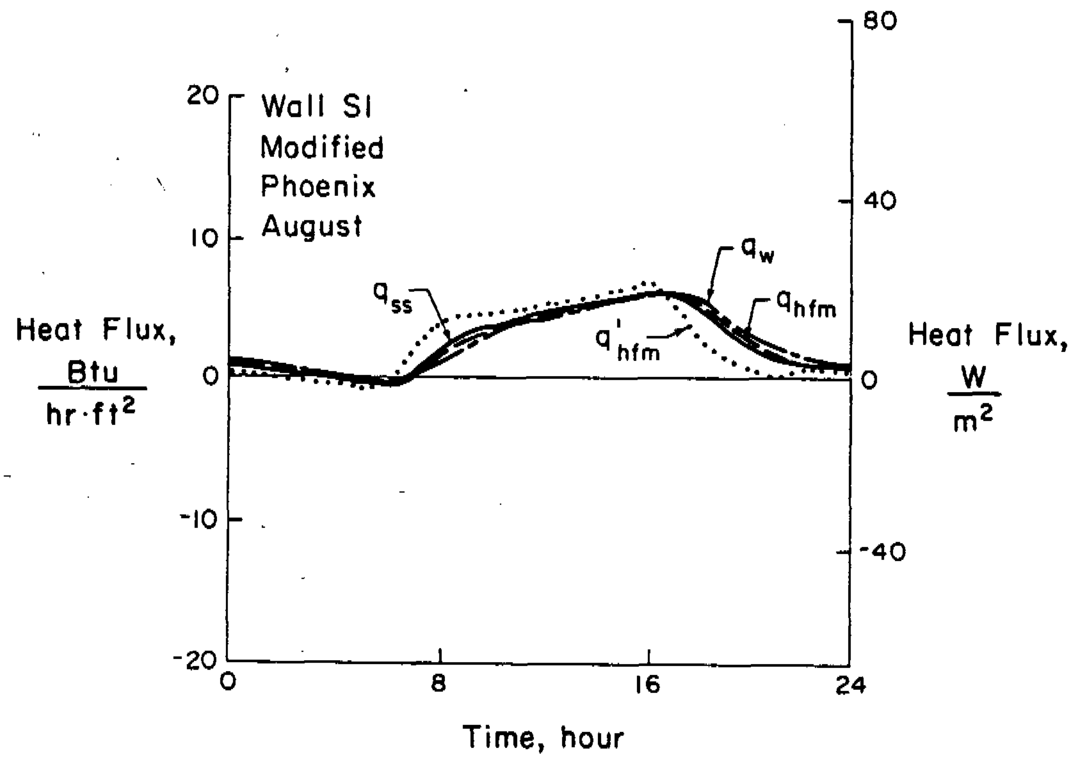


(a) Measured Temperatures



(b) Temperature Differentials

Fig. S1-3 Wall S1 Dynamic Test Results for Modified Phoenix August Test Cycle



(c) Heat Flux

Fig. S1-3 Wall S1 Dynamic Test Results for Modified Phoenix August Test Cycle

TABLE S1-8(a) - DYNAMIC TEST RESULTS (PERIODIC), MODIFIED PHOENIX AUGUST TEST CYCLE*

Time, hr	Measured Temperatures, °F						Measured Heat Flux, Btu/hr·ft^2			Calculated Heat Flux, Btu/hr·ft^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_3** Inter-nal	t_4** Inter-nal	t_1 Indoor Surf.	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	74.3	74.9			71.2	70.7	0.99	0.64	0.13	0.63
2	72.9	73.5			71.0	70.6	0.83	0.45	-0.04	0.43
3	71.1	71.9			71.0	70.6	0.38	0.18	-0.36	0.15
4	69.8	70.7			70.9	70.6	-0.10	-0.05	-0.46	-0.03
5	68.2	69.2			70.8	70.6	-0.16	-0.25	-0.74	-0.27
6	67.8	68.7			70.8	70.6	-0.16	-0.44	-0.45	-0.35
7	73.2	73.3			71.0	70.6	0.08	0.01	1.56	0.39
8	83.2	82.4			71.5	70.7	1.05	1.33	3.76	1.86
9	91.7	90.5			72.2	70.9	2.12	2.67	4.56	3.15
10	96.3	95.0			72.5	71.0	3.56	3.57	4.55	3.87
11	99.3	97.9			72.7	71.0	3.91	4.09	4.81	4.36
12	102.0	100.4			72.9	71.0	4.15	4.49	5.12	4.76
13	104.0	102.4			73.0	71.1	4.93	4.86	5.35	5.09
14	106.0	104.3			73.2	71.1	4.87	5.16	5.69	5.41
15	108.5	106.6			73.4	71.2	5.48	5.50	6.23	5.78
16	111.3	109.3			73.6	71.3	6.01	5.99	6.75	6.21
17	110.8	109.2			73.7	71.3	6.05	6.15	5.67$^+$	6.18
18	103.5	102.7			73.3	71.2	5.61	5.40	2.97	5.09
19	93.8	93.6			72.7	71.1	4.24	3.93	1.38	3.59
20	86.3	86.5			72.2	71.0	3.17	2.71	0.68	2.45
21	80.0	80.4			71.8	70.9	2.14	1.66	0.13	1.47
22	77.8	78.2			71.5	70.9	1.52	1.15	0.58	1.14
23	76.6	77.1			71.5	70.9	1.25	0.91	0.52	0.95
24	75.7	76.2			71.4	70.8	1.10	0.79	0.41	0.82
Mean	87.7	87.3			72.1	70.9	2.63	2.54	2.45	2.63

*Average indoor and outdoor air temperatures approximately 7°F (4°C) less than for Phoenix August Test Cycle.
**Internal thermocouples were not used on this wall assembly.
$^+$One day of data, not average of three days.

Calibrated Hot Box Relative Humidity:
Indoor Chamber - 41%
Outdoor Chamber - 20%

Laboratory Air Temperature:
Max. - 74°F (23°C)
Min. - 70°F (21°C)

TABLE S1-8(b) - DYNAMIC TEST RESULTS (PERIODIC), MODIFIED PHOENIX AUGUST TEST CYCLE,* SI UNITS

Time, hr	Measured Temperatures, °C						Measured Heat Flux, W/m^2			Calculated Heat Flux, W/m^2
	t_o Outdoor Air	t_2 Outdoor Surf.	t_3** Inter-nal	t_4** Inter-nal	t_1 Indoor Surf.	t_i Indoor Air	q_w Calib. Hot Box	q_{hfm} HFM @ Indoor Surf.	q'_{hfm} HFM @ Outdoor Surf.	q_{ss} Steady-State
1	23.5	23.8			21.8	21.5	3.13	2.01	0.40	1.99
2	22.7	23.1			21.7	21.4	2.63	1.41	-0.13	1.36
3	21.7	22.2			21.6	21.4	1.20	0.57	-1.12	0.47
4	21.0	21.5			21.6	21.5	-0.30	-0.16	-1.45	-0.09
5	20.1	20.7			21.6	21.5	-0.49	-0.79	-2.34	-0.85
6	19.9	20.4			21.5	21.5	-0.52	-1.38	-1.40	-1.10
7	22.9	22.9			21.6	21.5	0.26	0.03	4.91	1.23
8	28.5	28.0			21.9	21.5	3.30	4.19	11.87	5.87
9	33.2	32.5			22.3	21.6	6.70	8.43	14.39	9.94
10	35.7	35.0			22.5	21.6	11.25	11.26	14.35	12.21
11	37.4	36.6			22.6	21.7	12.32	12.90	15.17	13.75
12	38.9	38.0			22.7	21.7	13.09	14.16	16.17	15.02
13	40.0	39.1			22.8	21.7	15.56	15.35	16.89	16.06
14	41.1	40.2			22.9	21.7	15.36	16.27	17.96	17.07
15	42.5	41.5			23.0	21.8	17.28	17.36	19.66	18.23
16	44.1	42.9			23.1	21.8	18.96	18.91	21.29	19.59
17	43.8	42.9			23.2	21.8	19.08	19.41	17.88+	19.50
18	39.7	39.3			23.0	21.8	17.70	17.03	9.37	16.06
19	34.3	34.2			22.6	21.7	13.37	12.40	4.34	11.32
20	30.2	30.3			22.3	21.7	10.01	8.55	2.15	7.73
21	26.6	26.9			22.1	21.6	6.74	5.24	0.40	4.64
22	25.5	25.7			22.0	21.6	4.79	3.63	1.81	3.60
23	24.8	25.0			21.9	21.6	3.96	2.88	1.64	3.00
24	24.3	24.5			21.9	21.6	3.47	2.49	1.30	2.59
Mean	30.9	30.7			22.3	21.6	8.29	8.01	7.73	8.30

*Average indoor and outdoor air temperatures approximately 7°F (4°C) less than for Phoenix August Test Cycle.
**Internal thermocouples were not used on this wall assembly.
+One day of data, not average of three days.

TABLE S1-10 - SUMMARY OF DYNAMIC TEST RESULTS (PERIODIC), THERMAL LAG

Test Cycle	Thermal Lag, hrs								Calc. Time Constant,* hrs
	Measured								
	Calibrated Hot Box					Heat Flow Meter			
	t_o vs t_1		q_{ss} vs q_w		Avg.	q_{ss} vs q_{hfm}		Avg.	
	@ Max.	@ Min.	@ Max.	@ Min.		@ Max.	@ Min.		
NBS	0	1	1	0	0.5	0	0	0	0.13
Modified Phoenix August	1	0	0	0	0.5	0.5	0	0.5	0.13

*Calculated from properties measured by Owens-Corning Fiberglas Corporation and listed in Table S1-2.

TABLE S1-11 - SUMMARY OF DYNAMIC TEST RESULTS (PERIODIC), REDUCTION IN AMPLITUDE

Test Cycle	Measured, %					
	Calibrated Hot Box			Heat Flow Meter		
	@ Max.	@ Min.	Avg.	@ Max.	@ Min.	Avg.
NBS	3	-1	1	3	2	3
Modified Phoenix August	4	6	5	-1	0	0

Q_c = heat removed by indoor chamber cooling

Q_h = heat supplied by indoor electrical resistance heaters

Q_{fan} = heat supplied by indoor circulation fan

Q_ℓ = heat loss/gain from laboratory

Q_f = heat loss/gain from flanking path around specimen

The directions of arrows in Fig. B1 indicate positive heat flow.

Since net energy into the control volume of the indoor chamber equals zero, heat transfer through the test wall can be expressed by the following energy balance equation:

$$Q_w = Q_c - Q_h - Q_{fan} - Q_\ell - Q_f \tag{B1}$$

The need for cooling in the indoor chamber results from requirements for dynamic tests. In cases where outdoor temperatures exceed indoor temperatures, cooling capacity is required to maintain indoor temperature control.

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.

Steady-state calibrated hot box tests on two "standard" calibration specimens were used to refine calculations of heat removed by indoor chamber cooling, Q_c, and flanking losses, Q_f. The first calibration specimen, S1, has a relatively low thermal resistance of 6.8 hr•ft^2•°F/Btu (1.2 m^2•K/W). It consists of 1-3/8-in. (35-mm) thick fiberglass and was specially fabricated to insure uniformity.

The second calibration wall, S2, has a relatively high thermal resistance of 16.8 hr•ft^2•°F/Btu (3.0 m^2•K/W). Material for specimen S2 was selected as part of the ASTM Committee C16 Hot Box Round Robin program. It consists of expanded polystyrene board that is specially produced and cut to insure uniformity. Board faces are coated to provide surfaces suitable for attachment of instrumentation.

Heat removed by indoor chamber cooling, Q_c, was calculated from refrigerant enthalpy and mass flow rate, assuming an ideal basic vapor compression refrigeration cycle. Results from steady-state calibrated hot box tests on the two "standard" calibration specimens were used to adjust for inefficiencies in the actual refrigeration cycle.

Losses from the indoor chamber to the laboratory, Q_ℓ, were calculated from thermal properties of component materials making up walls and ceilings of the indoor chamber and temperature conditions on the inner and outer surfaces of the indoor chamber. Heat flux transducers mounted on the inside surface of the indoor chamber were used to check calculations. Indoor chamber air and laboratory air temperatures were generally maintained at the same nominal value, 72°F (22°C), to minimize laboratory losses. Thus, the value of Q_ℓ is small relative to other terms of the energy balance equation.

A watt-hour transducer was used to measure heat supplied to the indoor chamber by heaters and a fan, $Q_h + Q_{fan}$.

Heat loss or gain from flanking around the test specimen, Q_f, was determined from steady-state tests of the "standard" calibration walls. Since thermal conductance of each standard calibration wall is known, Q_w for a given steady-state test can be calculated using the following equation:

$$Q_w = A \cdot C \cdot (t_2 - t_1) \tag{B2}$$

where

Q_w = heat transfer through test wall, Btu/hr (W•hr/hr)

A = area of wall surface normal to heat flow, ft^2 (m^2)

C = average thermal conductance, Btu/hr•ft^2•°F (W/m^2•K)

t_2 = average temperature of outside wall surface, °F (°C)

t_1 = average temperature of inside wall surface, °F (°C)

Thus, Q_f was determined from Eq. (B1) using calculated values of Q_w, Q_c, and Q_ℓ, and measured values of Q_h and Q_{fan}.

For both standard calibration walls, values of Q_f were observed to follow the empirical relationship:

$$Q_f = 0.802\ (t_2 - t_1) \quad \text{U.S. units} \tag{B3}$$

$$Q_f = 0.131\ (t_2 - t_1) \quad \text{(SI units)}$$

where

Q_f = heat loss or gain from flanking around test specimen, Btu/hr (W•hr/hr)

t_2 = average temperature of outside wall surface, °F (°C)

t_1 = average temperature of inside wall surface, °F (°C)

Since Q_f is the residual from Eq. (B1), it may include other undetermined losses from the indoor chamber.

A round robin to include both calibrated (ASTM Designation: C976) and guarded (ASTM Designation: C236) hot boxes has been organized under ASTM Subcommittee C16.30 which, when completed, will provide information on the precision of the calibrated hot box test method.