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Surface Temperature Measurement Techniques for a Calibrated Hot Box Test Specimen

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SURFACE TEMPERATURE MEASUREMENT TECHNIQUES FOR A CALIBRATED HOT BOX TEST SPECIMEN

Final Report

by

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

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SURFACE TEMPERATURE MEASUREMENT TECHNIQUES FOR A CALIBRATED HOT BOX TEST SPECIMEN

by

Steven C. Larson and Martha G. Van Geem*

ABSTRACT

Heat flow through a 143 pcf (2290 kg/m^3) normal weight concrete wall was measured using the calibrated hot box facility at the Construction Technology Laboratories, a division of the Portland Cement Association. Two methods of measuring specimen surface temperatures were used to investigate thermal contact resistance between thermocouples and a normal weight concrete specimen. Thermocouples used to measure surface temperatures frequently are taped to the wall surfaces. In this test program, thermocouples were also embedded in wall surfaces.

The wall was subjected to steady-state, transient, and periodically varying temperature conditions. Steady-state results are used to determine concrete thermal conductivity and wall resistance. Data obtained during transient and periodic temperature variations are used to define dynamic thermal response of the wall.

Steady-state and dynamic test results using the two measurement techniques are compared. Steady-state properties determined from surface temperatures measured using taped thermocouples differ significantly from those determined from embedded thermocouple measurements. Concrete thermal conductivity derived from embedded thermocouple measurements was 32% greater than that based on taped thermocouple measurements. Measurements from embedded and taped thermocouples for a dynamic temperature cycle with a 56°F (31°C) amplitude in the outdoor temperature applied to the wall were also compared. Maximum differences in temperature measurements were 6.6°F (3.0°C) and 0.9°F (0.4°C) for the wall surfaces exposed to outdoor and indoor temperatures, respectively. The response characteristics used to compare periodic dynamic and transient thermal performance of alternative wall systems are the same for the two measurement techniques.

Differences between embedded and taped thermocouple measurements are attributed to thermal contact resistance. Based on results of the test program, it is recommended that thermocouples for measuring surface temperatures be embedded in surfaces of normal weight concrete walls to minimize the thermal contact resistance between thermocouples and the wall surface.

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SURFACE TEMPERATURE MEASUREMENT TECHNIQUES FOR A CALIBRATED HOT BOX TEST SPECIMEN

By

Steven C. Larson and Martha G. Van Geem*

INTRODUCTION

Tests were conducted to evaluate thermal performance of a 143 pcf (2290 kg/m^3) normal weight concrete wall using two methods of measuring surface temperatures. An 8-in. (200-mm) concrete wall was tested in the calibrated hot box facility of the Portland Cement Association's Construction Technology Laboratories (CTL). One set of thermocouples for measuring surface temperatures was embedded in the concrete surface. Another set was taped to the surface. Results using the two techniques are compared. Data obtained from this investigation can be used to evaluate contact thermal resistance between taped thermocouples and a normal weight concrete specimen.

BACKGROUND

Calibrated Hot Box Test Facility

A normal weight concrete wall with embedded and taped surface thermocouples was tested 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."(1)**

The following is a brief description of the calibrated hot box. Instrumentation and calibration details are described in Appendix A and Reference 2.

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

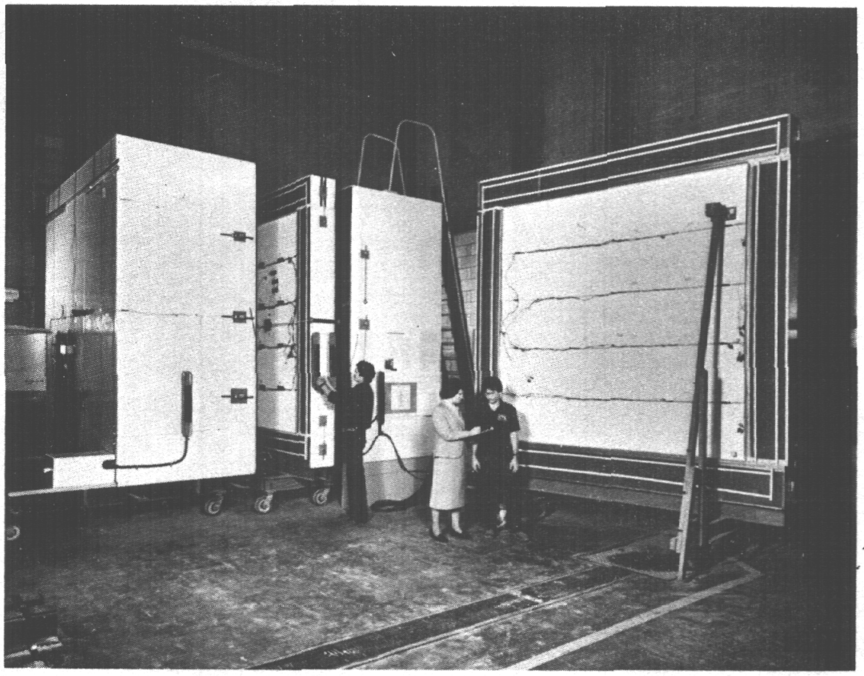


Fig. 1 Calibrated Hot Box Test Facility

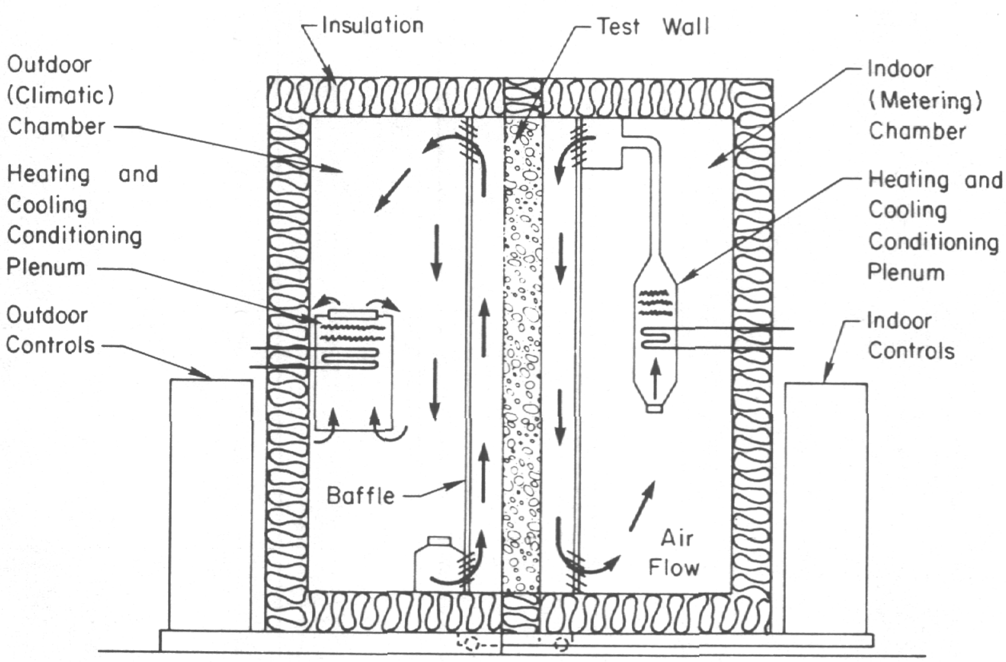


Fig. 2 Schematic of Calibrated Hot Box

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 insulated 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 specimen is in a vertical position in CTL's calibrated hot box. Therefore, heat flows horizontally through the wall. Required specimen dimensions are 103+1/8,-0 by 103+1/8,-0 in. (2.62+0.003,-0 by 2.62+0.003,-0 m). The facility was designed to accommodate walls with thermal resistance values ranging from 1.5 to 20 hr•ft^2•°F/Btu (0.26 to 3.52 m^2•K/W).

The outdoor (climatic) chamber can be held at a constant temperature or cycled within the range -15 to 130°F (-26 to 54°C). Temperature cycles can be programmed 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). CTL's calibrated hot box is not capable of maintaining a pressure differential across a specimen. The pressure in both chambers is atmospheric.

Contact Resistance

Thermocouples taped to normal weight concrete surfaces may not measure "true" surface temperatures because of contact thermal resistance. This thermal contact resistance is due to the influence of any thin air gap between the thermocouple wire and the normal weight concrete at their point of contact. Thermal contact resistance is more significant for materials with smaller thermal resistances. For normal weight concrete, contact resistance may be of the same order of magnitude as the resistance of the concrete.[3]

Inaccuracies in surface measurements due to thermal contact resistance can result in inordinately high values of surface-to-surface temperature differentials during steady-state tests. Thus, resulting thermal conductivity values are less than the actual thermal conductivity of the wall.

Reference 3 summarizes thermal conductivity measurements on three concretes. Walls designated C1, C2, and C3 had unit weights of 144, 102, and 46 pcf (2310, 1630, and 740 kg/m^2), respectively. Conductivities were measured on the three concretes using the calibrated hot box (ASTM Designation: C976[(1)]), the guarded hot plate (ASTM Designation: C177[(1)]), and the hot wire method. Calibrated hot box and hot wire tests were performed at CTL. Guarded hot plate tests were performed at Dynatech R/D Company.

Thermal conductivity results for 144 pcf (2310 kg/m^3) normal weight and 102 pcf (1630 kg/m^3) structural lightweight concrete walls tested in the calibrated hot box were lower than results determined using the guarded hot plate or the hot wire method. These results are indicative of the influence of thermal contact resistance on determination of thermal conductivity for Walls C1 and C2. This influence is negligible for the 46 pcf (740 kg/m^3) low density concrete from Wall C3.[(3)]

For calibrated hot box tests, thermocouple wires were taped to the walls in accordance with ASTM Designation: C976-82, Section 5.7.1, which states that requirements of the standard are presumed to be met if wire is "taped, cemented or otherwise held in thermal contact with the surface using materials of emittance close to that of the surface."[(1)] For guarded hot plate tests thermocouples were embedded into surfaces of each concrete specimen. For hot wire tests, concrete specimens were cast with a thermocouple embedded along their central axis.[(3)]

OBJECTIVES

This report compares results determined from taped and embedded thermocouple measurements during calibrated hot box tests of a normal weight concrete wall. Differences in results for the two measurement techniques provide information on contact thermal resistance between taped thermocouples and normal weight concrete.

Results from steady-state tests are used to determine concrete thermal conductivity and wall thermal resistance. 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 walls previously tested.[4-9]

TEST SPECIMEN

An 8-in. (200-mm) normal weight concrete wall with embedded and taped surface thermocouples, designated Wall C6, was tested in CTL's calibrated hot box.

Wall Construction

Wall C6 was previously tested in the calibrated hot box as Wall C1. Details of construction and calibrated hot box test results of Wall C1 are given in Reference 9.

Wall C1 was built at CTL using techniques representative of field construction practices. Overall nominal wall dimensions were 103x103 in. (2.62x 2.62 m). The wall was reinforced with a single layer of No. 5 bars at the approximate wall midthickness spaced 12-in. (300-mm) center-to-center in each direction, as shown in Fig. 3.

The wall 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

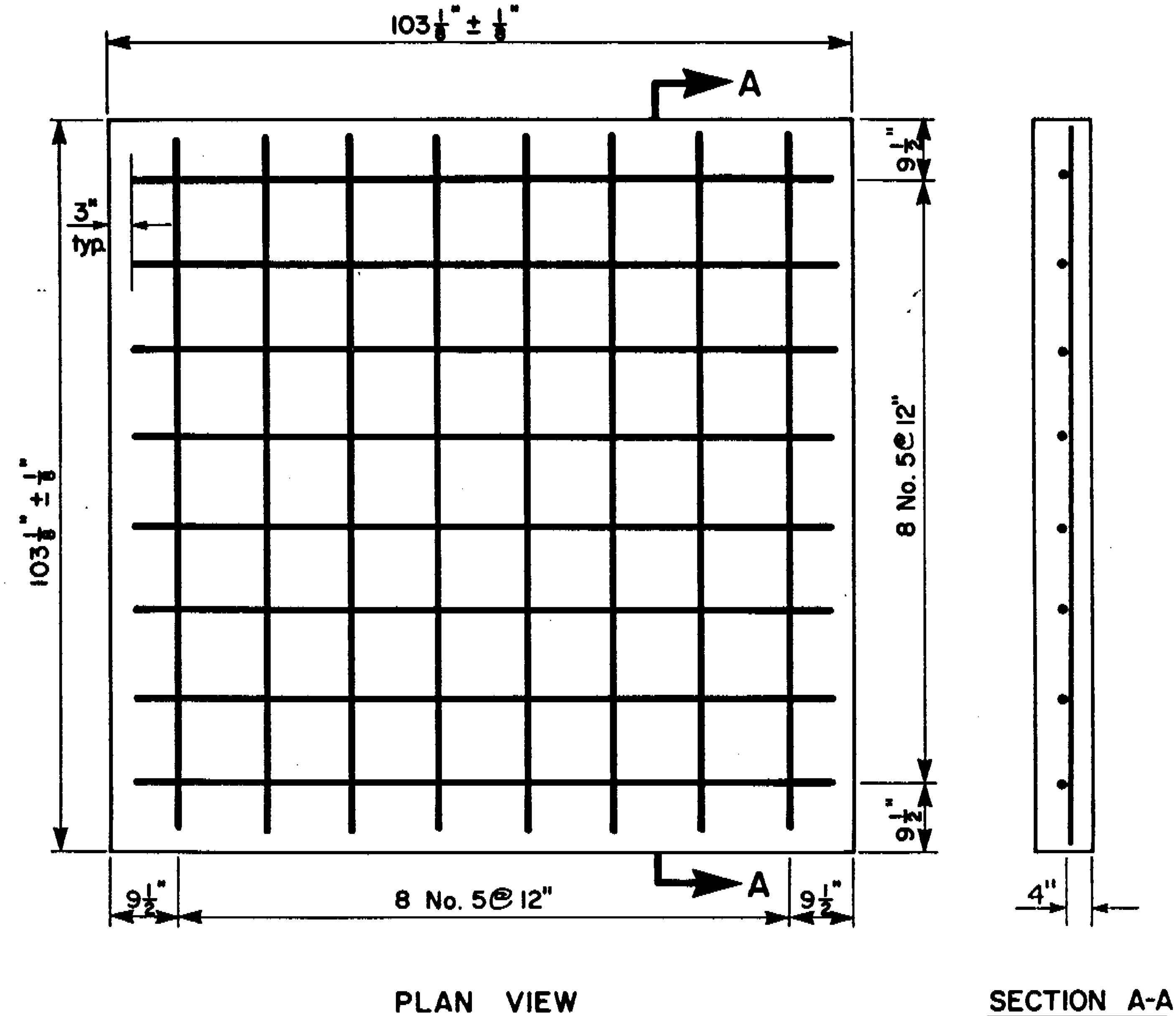


Fig. 3 Reinforcement Details for Normal Weight Concrete Wall

laboratory at an air temperature of 73±5°F (23±3°C) and 45±15% RH for five months. Wall faces were coated with a cementitious waterproofing material that seals minor surface imperfections. A textured, noncementitious 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 control specimens consisting of the concrete used in Wall C1 are given in Table 1. Thermal properties of the normal weight concrete in Wall C1 are given in Table 2. Properties in Tables 1 and 2 were determined within 10 months of calibrated hot box testing of Wall C1.

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, eight thermocouples were embedded in each side of the test wall and the wall was redesignated Wall C6. Thermocouple embedment procedures are described in the "Instrumentation" section of this report.

Wall C6 was tested in the calibrated hot box in January and February 1984. Physical properties of Wall C6 at the time of calibrated hot box testing are summarized in Table 3.

Instrumentation

Thermocouples corresponding to the American National Standard for Temperature Measurement Thermocouples (ANSI MC96.1), Type T, 20 gauge, were used to measure temperatures. There were 16 taped to each face of the test wall and 8 embedded in each face of the test wall. In addition, 16 thermocouples were located in the air space of each chamber. Thermocouples in each plane were spaced 20.6-in. (525-mm) apart in a 4x4 grid over the wall area.

TABLE 1 - PHYSICAL PROPERTIES OF WALL C1[9]

Property	Measured Value
Unit Weight of Wall, psf (kg/m^2)	100 (488)
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**	5715 (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 2 - THERMAL PROPERTIES OF NORMAL WEIGHT CONCRETE[9]

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 - PHYSICAL PROPERTIES OF WALL C6 AT TIME OF TEST

Property	Measured Value
Unit Weight, psf (kg/m^2)	99 (483)
Average Thickness, in. (mm)	8.31 (211)
Area, ft^2 (m^2)	73.6 (6.84)
Estimated Moisture Content,* % by ovendry weight	1.4

* Measured before calibrated hot box testing.

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

Thermocouples taped to the surface were securely attached 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.

The eight embedded thermocouples on each side of Wall C6 were located in the second and third rows of the 20-3/5-in. (525-mm) square grid. Locations of taped and embedded thermocouples on the outdoor wall surface are shown in Fig. 4. Taped and embedded thermocouples on the indoor wall surface were located directly opposite those on the outdoor surface.

Thermocouples were placed in eight 7/32-in. (6-mm) wide grooves cut on each side of the wall in line with the second and third rows of surface thermocouples. Grooves measured 3/32 to 1/8-in. (2 to 3-mm) deep by 5.5 to 6-in. (140 to 150-mm) long.

Figure 5 shows a groove cut into Wall C6. The cross (+) on the wall marks the location of a thermocouple junction subsequently taped to the wall. Discoloration of the concrete surface above and below the mark are due to epoxy removed from the wall surface after previous tests. Epoxy is used to secure tape over surface-mounted thermocouples to calibrated hot box specimen surfaces. Thermocouple junctions taped to Wall C6 were placed at the same location as those for Wall C1.

The embedded thermocouple junctions were located 2 in. (50 mm) from the surface thermocouple junctions as shown in Fig. 6. At least 4 in. (100 mm) of the thermocouple wires were embedded. Exposed leads of embedded thermocouples were taped to the wall for a length of approximately 4 in. (100 mm).

The grooves were filled flush with the wall surface using cement paste to secure the thermocouples in place. Fig. 7 shows a thermocouple cemented in

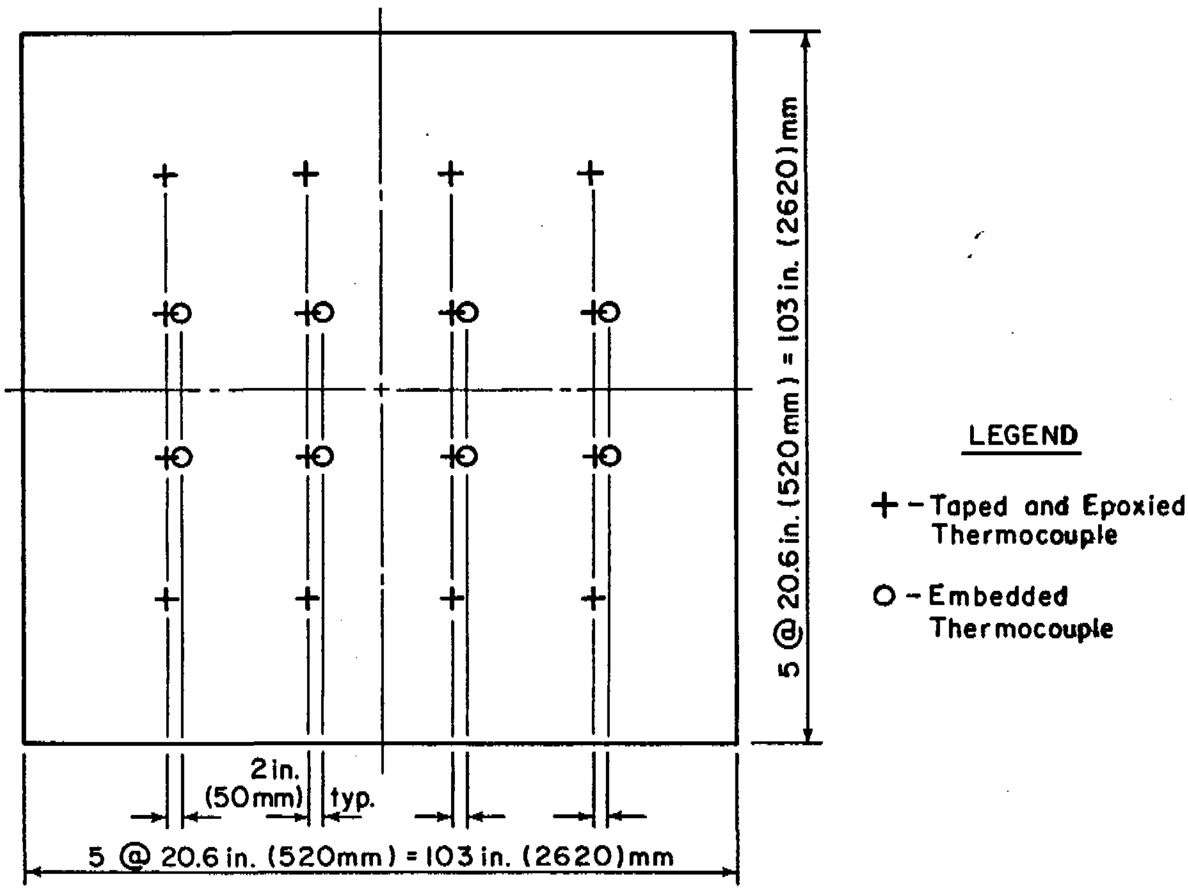


Fig. 4 Locations of Taped and Embedded Thermocouples on Outdoor Wall Surface

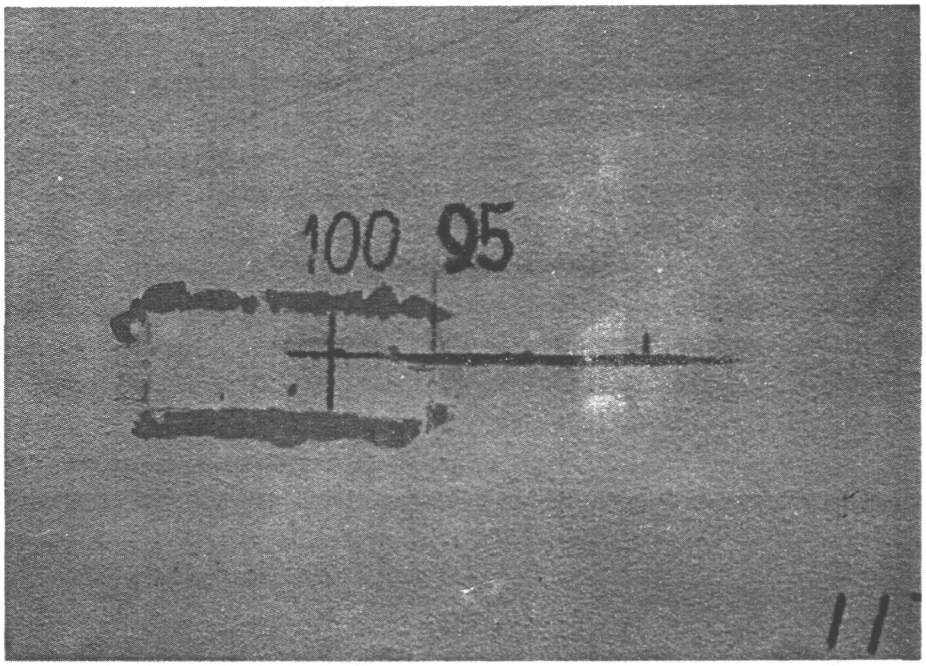


Fig. 5 Groove Cut in Wall Surface for Embedded Thermocouple

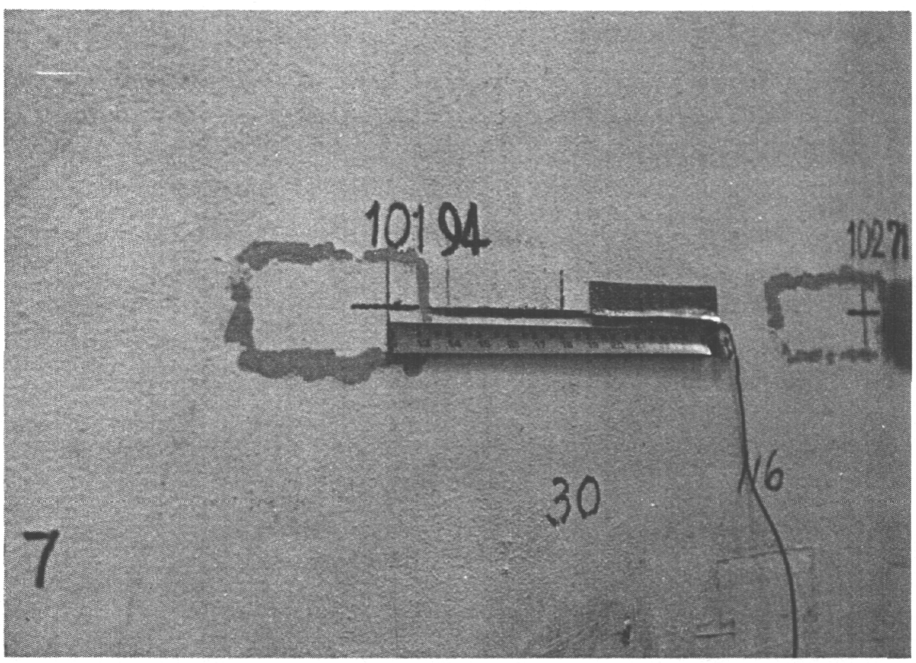


Fig. 6 Embedded Thermocouple Placed in Groove

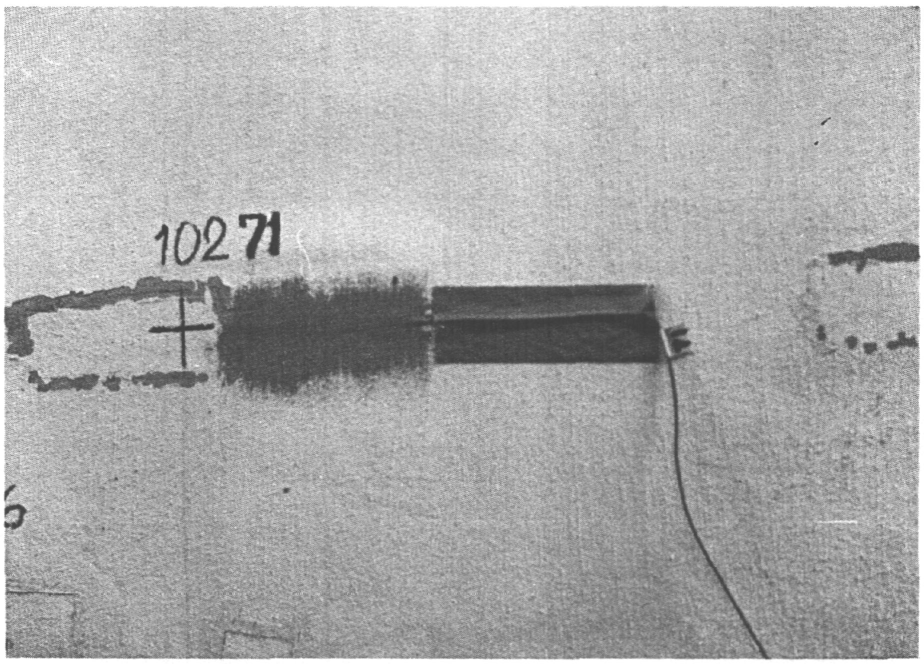


Fig. 7 Embedded Thermocouple Cemented in Place

place. Tape and hardened cement paste were painted 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. To mount heat flux transducers on concrete, 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. Heat flux transducers were then mounted on the wall using screws into the wood dowels. The silicon grease provided uniform contact between heat flux transducers and wall surfaces.

STEADY-STATE TESTS

Two steady-state calibrated hot box tests were performed on the normal weight concrete wall with embedded and taped surface thermocouples. Heat flow and temperature measurements were used to determine average thermal properties including thermal conductivity (k) and total thermal resistance (R_T). Design heat transmission coefficients are calculated for the wall and compared to measured values.

Thermal conductivity, k, and total thermal resistance, R_T, are determined from temperatures measured by taped and embedded surface thermocouples. Steady-state temperature profiles are compared and an estimate is made for the contact resistance between taped thermocouples and normal weight concrete for steady-state temperature conditions.

Design Heat Transmission Coefficients

Design values of total resistance and transmittance for Wall C6 are shown in Table 4. These were calculated in accordance with procedures established

TABLE 4 - 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. (200-mm) Normal Weight Concrete	0.69* (0.12)
3. Inside Air Film	0.68* (0.12)
Total R	1.54 (0.27)
Total U**	0.65 (3.70)

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

** Units for thermal transmittance, U, are $Btu/hr \cdot ft^2 \cdot °F$ ($W/m^2 \cdot K$).

by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers.[10]

Total resistance values, R_T, include surface resistances equal to 0.68 $hr \cdot ft^2 \cdot °F/Btu$ (0.12 $m^2 \cdot K/W$) for indoor and 0.17 $hr \cdot ft^2 \cdot °F/Btu$ (0.03 $m^2 \cdot K/W$) 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.

Resistances for construction materials were taken from the ASHRAE Handbook-1981 Fundamentals.[10] Resistances 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 averages of 16 consecutive hours of data collected after specimen temperatures reach equilibrium and the rate of heat flow through the test wall is constant.

Steady-state tests were run at two temperature differentials. For the first case, indoor air temperature was maintained at approximately 67°F (19°C) while outdoor air temperature was maintained at approximately -5°F (-21°C). This provided a nominal temperature differential of 72°F (40°C) and a mean temperature of 32°F (0°C). In the second case, indoor air temperature was maintained at approximately 77°F (25°C) while outdoor air temperature was maintained at approximately 121°F (50°C). This provided a nominal temperature differential of 44°F (24°C) and a mean temperature of 100°F (38°C).

Test Results

Steady-State Temperature Profiles

Temperature profiles from steady-state calibrated hot box tests on Wall C6 are illustrated in Fig. 8. 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_o = outdoor air temperature

t_2 = wall surface temperature, outdoor side, taped thermocouples

t_4 = wall surface temperature, outdoor side, embedded thermocouples

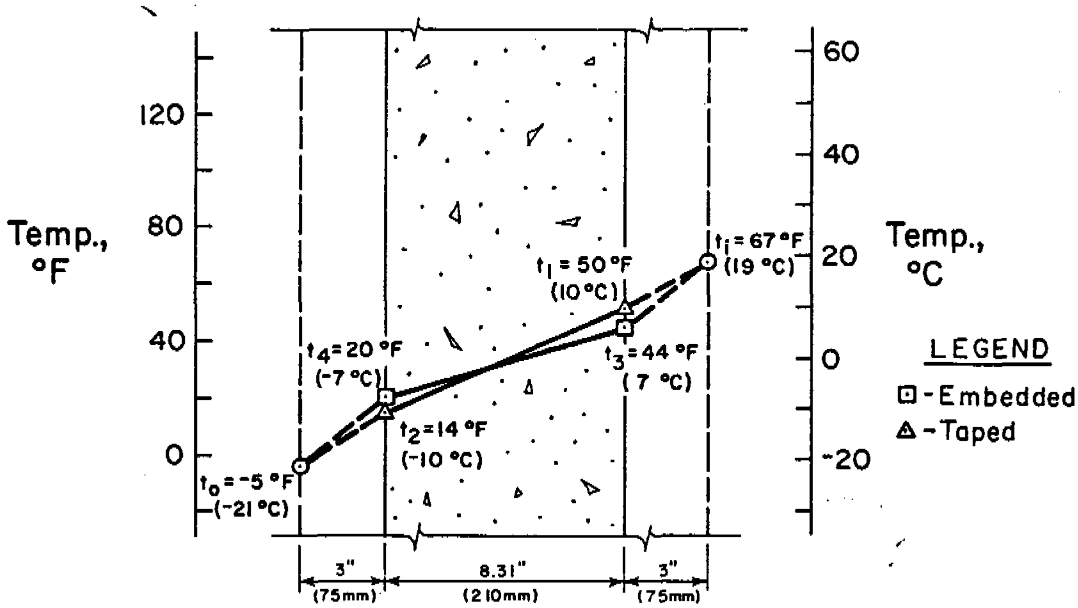
t_3 = wall surface temperature, indoor side, embedded thermocouples

t_1 = wall surface temperature, indoor side, taped thermocouples

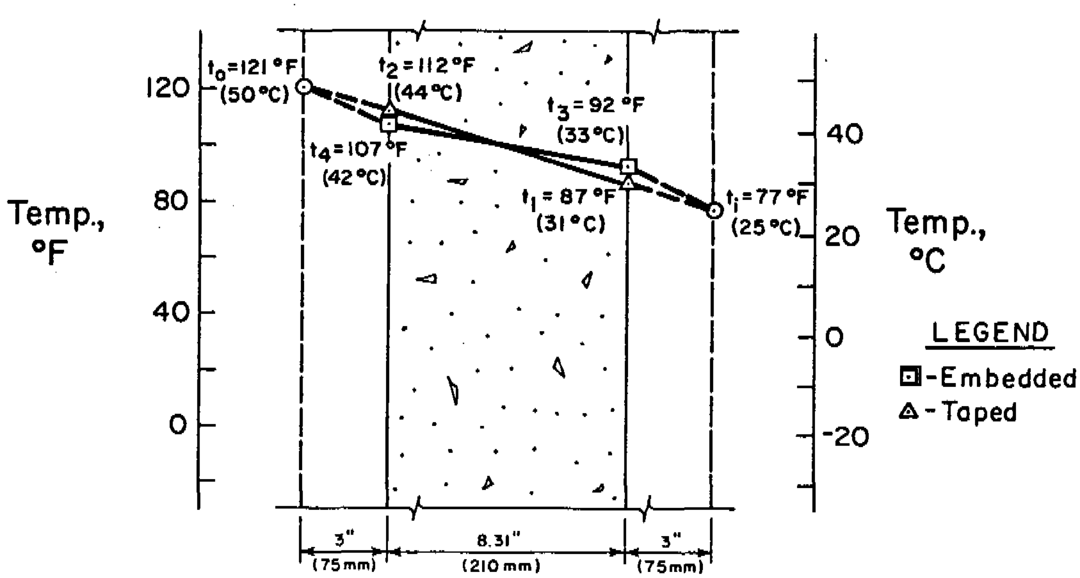
t_i = indoor air temperature

Temperature measurements of embedded surface thermocouples are significantly different from those of taped surface thermocouples. For the steady-state tests with wall mean temperatures of 32°F (0°C) and 100°F (38°C), the differences in embedded and taped thermocouple readings were 6°F (3°C) and 5°F (3°C), respectively. As expected, for both tests, temperatures measured by taped thermocouples were between air temperatures and wall surface temperatures measured by embedded thermocouples.

Surface-to-surface temperature differentials across the wall are smaller for embedded thermocouple temperatures than for taped thermocouple temperatures. For the steady-state test with a wall mean temperature of 32°F (0°C), the surface-to-surface temperature differentials are 36°F (20°C) for taped thermocouple measurements and 24°F (13°C) for embedded thermocouple measurements. Similarly, for a wall mean temperature of 100°F (38°C), the taped thermocouple temperature differential through the wall is 25°F (14°C) and



(a) Wall Mean Temperature = 32^{0}F (0^{0}C)



(b) Wall Mean Temperature = 100^{0}F (38^{0}C)

Fig. 8 Steady-State Temperature Profiles Across Wall C6 the embedded thermocouple temperature differential is 15°F (8°C). Measured temperatures from embedded surface thermocouples result in a 35% reduction in surface-to-surface temperature differential compared to taped thermocouple measurements.

Heat Flux

Mean wall temperature and heat flux for steady-state calibrated hot box tests are listed in Table 5. Wall mean temperature is the average of the indoor and outdoor wall surface temperatures. Wall mean temperatures are identical for taped and embedded surface thermocouple measurements.

The second column shows wall heat flux determined from each calibrated hot box test. Heat flux is determined from hourly data using Eq. (A1) in Appendix A.

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.

Concrete Thermal Conductivity Comparison

Table 6 summarizes thermal conductivities of concrete determined using different surface temperature measurements. Conductivity, k, is calculated using measured heat flux, surface temperatures, and concrete thickness.

Actual concrete thickness is 8.31 in. (211 mm). This thickness is used to determine conductivity measured by taped thermocouples. The average thickness of concrete between embedded thermocouple junctions on opposite sides of the wall is 8.19 in. (208 mm). This thickness is used to calculate conductivity measured by embedded thermocouples.

TABLE 5 - STEADY-STATE HEAT FLUX AND TEST CONDITIONS

Nominal Test Condition	q* Heat Flux, Btu/hr·ft^2 (W/m^2)	Relative Humidity		Laboratory Air Temperature	
		Indoor Chamber, %	Outdoor Chamber, %	Max., °F (°C)	Min., °F (°C)
t_m = 32°F (0°C)	-42.6 (-135)	18	20	71 (22)	71 (21)
t_m = 100°F (38°C)	31.8 (100)	18	19	72 (22)	71 (22)

*Measured by calibrated hot box.

TABLE 6 - THERMAL CONDUCTIVITIES DETERMINED USING TAPED AND EMBEDDED THERMOCOUPLE MEASUREMENTS

Wall Mean Temperature, °F (°C)	Thermal Conductivity k, Btu•in./hr•ft^2•°F (W/m•K)		
	Measured Using Taped Thermocouples, No. of T.C.'s		Measured Using Eight Embedded Thermocouples**
	16*	8**	
32 (0)	9.8 (1.41)	10.0 (1.44)	14.3 (2.06)
100 (38)	10.8 (1.56)	11.3 (1.63)	16.8 (2.42)
70*** (21)	10.4 (1.50)	10.7 (1.54)	15.7 (2.26)

* k determined using average indoor and outdoor surface temperatures measured by 16 thermocouples taped to each wall surface.

** k determined using average indoor and outdoor surface temperatures measured by 8 thermocouples located in the second and third rows of the 20-3/5-in. (525-mm) grid on each wall surface.

*** Values of k interpolated from measured results.

The second column of Table 6 lists thermal conductivities determined from the average temperatures measured by 16 thermocouples taped to each side of the wall. The third column lists conductivities determined from average temperatures measured by eight taped thermocouples located in the second and third rows of the 20-3/5-in. (525-mm) grid, the same locations as the embedded thermocouples. The fourth column of Table 6 lists conductivities determined using average temperatures measured by eight embedded thermocouples on each side of the wall.

The first and second rows of data in Table 6 list results from steady-state calibrated hot box tests. The third row lists information for a wall mean temperature of 70°F (21°C). These values were interpolated from steady-state test results for wall mean temperatures of 32°F (0°C) and 100°F (38°C).

Values of thermal conductivity determined using temperature measurements from taped and embedded thermocouples are 10.7 Btu in./hr$\cdot$ft$^2\cdot$°F (1.54 W/m$^2\cdot$K) and 15.7 Btu in./hr$\cdot$ft$^2\cdot$°F (2.26 W/m$^2\cdot$K), respectively, for a wall mean temperature of 70°F (21°C). The value calculated from taped thermocouple temperatures is 32% less than that calculated from embedded thermocouple temperatures. This is consistent with the differences in temperature differentials across the wall measured by taped and embedded thermocouples.

Three test methods have been used to determine thermal conductivity of Wall C6 concrete. Figure 9 summarizes results and indicates test methods used. Thermal conductivity is shown as a function of moisture content of the concrete. Thermal conductivity increases as moisture content of a given concrete increases for any particular test method.[11]

Figure 9 indicates data from Wall C1 as being from Reference 9. Other data in the figure are from tests on Wall C6. The moisture content of Wall C6, 1.4%, is less than that for Wall C1, 2.1%, because of the normal drying

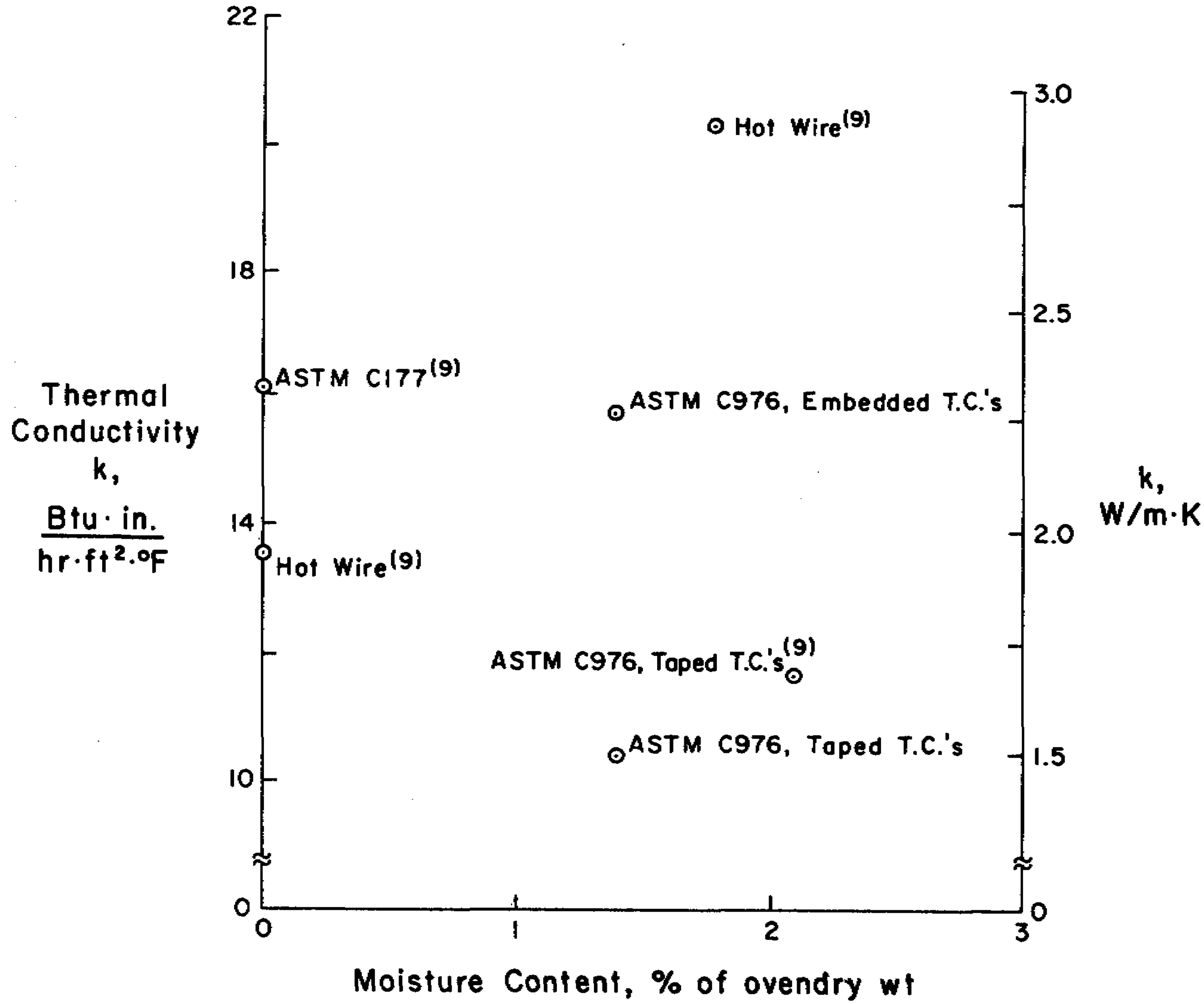


Fig. 9 Thermal Conductivity of Normal Weight Concrete

process of concrete during the two years between test programs. As stated previously calibrated hot box testing of Wall C1 was performed October through December 1981. Wall C6 was tested January through February 1984.

Measured thermal conductivity is greater for test methods using embedded rather than taped thermocouples. For guarded hot plate tests, ASTM Designation: C177, thermocouples were embedded into surfaces of each concrete specimen.[9] For hot wire tests concrete specimens are cast with a thermocouple embedded along their central axis.[9]

Results from this investigation are consistent with results from previous investigations. Thermal conductivities measured using embedded thermocouples range from 13 to 21 Btu•in./hr•ft^2•°F (1.9 to 3.0 W/m•K). Values increase with moisture content. Thermal conductivity determined from taped thermocouples increases from 10.4 to 11.7 Btu•in./hr•ft^2•°F (1.5 to 1.7 W/m•K) with an increase in concrete moisture content from 1.4 to 2.1% of ovendry weight.

The smaller thermal conductivity resulting from taped thermocouple measurements is expected since a contact resistance is introduced when thermocouples are taped to the wall surface. Imperfect thermal contact, thin air gaps, and wall surface imperfections cause the temperature readings of taped thermocouples to deviate from the true wall surface temperature. Taped thermocouples read temperatures that are between the true wall surface temperature and the chamber air temperature. The temperature differential across the wall measured by taped thermocouples is greater than that measured by embedded thermocouples. Therefore, the conductance of the wall calculated from temperatures measured by taped thermocouples is less than that calculated from temperatures measured by embedded thermocouples.

Total Thermal Resistance of Concrete

Total thermal resistance values, R_T, for Wall C6 are summarized in Table 7. Thermal resistances are calculated by dividing heat flux through the wall by surface-to-surface temperature differentials measured by either taped or embedded thermocouples. Total thermal resistances include the surface air film resistances listed in Table 4.

The second column of Table 7 lists total thermal resistances calculated using the average temperatures measured by 16 thermocouples taped to each side of the wall. The third column lists R_T values calculated from average temperatures measured by eight taped thermocouples located in the second and third rows of the 20-3/5-in. (525-mm) grid, the same location as the embedded thermocouples. The fourth column of Table 7 lists R_T values calculated using average temperatures measured by eight embedded thermocouples on each side of the wall.

The third row of Table 7 lists total thermal resistances for a wall with a mean temperature of 70°F (21°C). These values were interpolated from results of steady-state tests with wall mean temperatures of 32°F (0°C) and 100°F (38°C).

Total thermal resistance calculated using temperatures measured by the eight taped thermocouples on each side of the wall is 6% higher than the design total resistance. Total thermal resistance calculated using temperatures measured by the embedded thermocouples is 10% less than the design total resistance. The total thermal resistance calculated using temperatures from taped thermocouples is 15% greater than that calculated using temperatures from embedded thermocouples.

The sum of the design air film coefficients, 0.85 $hr \cdot ft^2 \cdot °F/Btu$ (0.15 $m^2 \cdot K/W$), is constant and is of the same order of magnitude as the

TABLE 7 - TOTAL THERMAL RESISTANCE, R_T, DETERMINED USING TAPED AND EMBEDDED THERMOCOUPLE MEASUREMENTS

Wall Mean Temperature, °F (°C)	Total Thermal Resistance, R_T,* hr•ft^2•°F/Btu (m^2•K/W)		
	Measured Using Taped Thermocouples, No. of T.C's		Measured Using Eight Embedded Thermocouples***
	16**	8***	
32 (0)	1.69 (0.30)	1.68 (0.30)	1.42 (0.25)
100 (38)	1.62 (0.29)	1.59 (0.28)	1.34 (0.24)
70+ (21)	1.65 (0.29)	1.63 (0.29)	1.38 (0.24)

* Total thermal resistances were calculated including design surface resistances from Table 4.

** R_T determined using average indoor and outdoor surface temperatures measured by 16 thermocouples taped to each wall surface.

*** R_T determined using average indoor and outdoor surface temperatures measured by 8 thermocouples located in the second and third rows of the 20-3/5-in. (525-mm) grid on each wall surface.

\+ Values for R_T interpolated from measured results.

Note: Design Total Thermal Resistance (from Table 4) is 1.54 hr·ft^2·°F/Btu (0.27 m^2·K/W).

concrete thermal resistance. Including this constant reduces the percent difference between R_T values determined from taped and embedded thermocouples 18%, compared to the 32% difference in thermal conductivity, k, determined from taped and embedded thermocouples.

Measured Surface Resistances

Measured surface or air film resistances are calculated by dividing measured indoor and outdoor air-to-surface temperature differentials by measured heat flux from calibrated hot box tests.

Table 8 summarizes measured indoor and outdoor surface resistances for taped and embedded thermocouple temperature measurements. Values for taped thermocouples are from the groups of eight taped thermocouples in the same positions as the embedded thermocouples.

Air film resistances measured by the calibrated hot box are approximately equal for the indoor and outdoor wall surfaces. This result is expected since air flow rates are approximately equal on the two sides of the wall. The sum of the measured indoor and outdoor surface film resistances is within 30% of the sum of the design surface film resistances, 0.85 $hr \cdot ft^2 \cdot °F/Btu$ (0.15 $m^2 \cdot K/W$). Measured surface film resistances vary depending on the indoor and outdoor chamber air temperatures and the test specimen material composition.

Measured surface resistances calculated from embedded surface thermocouple temperatures are about 0.13 $hr \cdot ft^2 \cdot °F/Btu$ (0.02 $m^2 \cdot K/W$) greater than values calculated from taped thermocouple measurements. This difference, 0.13 $hr \cdot ft^2 \cdot °F/Btu$ (0.02 $m^2 \cdot K/W$), is the thermal contact resistance between the taped thermocouples and normal weight concrete wall. Results are consistent for both steady-state tests and both wall surfaces. Thermal contact

TABLE 8 - MEASURED SURFACE RESISTANCES

Wall Mean Tempera-ture, °F (°C)	Measured Surface Resistance, $hr \cdot ft^2 \cdot °F/Btu$ ($m^2 \cdot K/W$)			
	Indoor Surface		Outdoor Surface	
	Taped Thermocouples	Embedded Thermocouples	Taped Thermocouples	Embedded Thermocouples
32 (0)	0.39 (0.07)	0.52 (0.09)	0.46 (0.08)	0.59 (0.10)
100 (38)	0.34 (0.06)	0.46 (0.08)	0.32 (0.06)	0.45 (0.08)

resistance is independent of wall surface and air temperatures for the steady-state tests performed on the normal weight concrete wall.

For a wall with a low thermal resistance, such as the normal weight concrete wall, this thermal contact resistance is of the same order of magnitude as the resistance of the wall. Thermal resistance of the concrete is 0.78 hr•ft^2•°F/Btu (0.14 m^2•K/W) from measurements of eight taped thermocouples and 0.53 hr•ft^2•°F/Btu (0.09 m^2•K/W) from measurements of eight embedded thermocouples. The total contact resistance for both wall surfaces is 0.26 hr•ft^2•°F/Btu (0.05 m^2•K/W). This is 50% of the concrete thermal resistance derived from embedded thermocouple measurements. For walls with higher thermal resistances, the contact resistance measurement error will be less significant.

Thermal contact resistance between taped thermocouples and normal weight concrete may be influenced by the type and size of thermocouples, and type of tape. As previously stated, for this study, 20 gauge, Type T thermocouples were taped to the normal weight concrete surface using duct tape.

DYNAMIC TEST

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 Procedure

A dynamic test is conducted by maintaining calibrated hot box indoor air temperature constant while outdoor air temperature is cycled over a predetermined temperature versus time relationship. The rate of heat flow through a test specimen is determined from hourly data using Eq. (A1) in Appendix A.

One 24-hour (diurnal) temperature cycle, denoted the NBS Test Cycle, was applied to Wall C6. This cycle has been applied to every wall tested in CTL's calibrated hot box.

The NBS Test 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.[12] 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 dynamic cycle was repeated until conditions of dynamic equilibrium were obtained. Equilibrium conditions were evaluated by repeatability of applied temperatures and measured heat flux. After equilibrium conditions were reached, the test was continued for a period of three days. Results are average readings for three consecutive 24-hour cycles. Duration of the dynamic test was nine days.

Test Results

Brief descriptions of symbols used in dynamic test result figures and tables are listed in Table 9. Symbols are described in detail in the following paragraphs.

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*Sol-air temperature is that temperature of outdoor air which, 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.[10]

TABLE 9 - ABBREVIATIONS FOR HEAT FLUX AND TEMPERATURE

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

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

q_{ss} = heat flux predicted from steady-state analysis using taped thermocouple measurements

q'_{ss} = heat flux predicted from steady-state analysis using embedded thermocouple measurements

q_w = heat flux measured by calibrated hot box

t_o = outdoor air temperature

t_2 = wall surface temperature, outdoor side, taped thermocouples

t_4 = wall surface temperature, outdoor side, embedded thermocouples

t_3 = wall surface temperature, indoor side, embedded thermocouples

t_1 = wall surface temperature, indoor side, taped thermocouples

t_i = indoor air temperature

t_m = average of wall surface temperature on indoor and outdoor side

Measured Temperatures

Measured temperatures for the NBS temperature cycle applied to Wall C6 are illustrated in Fig. 10 and listed in Table 10. Tables 10(a) and 10(b) list results in U.S. and SI units, respectively.

For Wall C6, outdoor air (t_0), outdoor surface - taped (t_2), indoor air (t_i), and indoor surface - taped (t_1) temperatures are average readings of 16 thermocouples placed as described in the "Instrumentation" section of this report. Indoor surface - embedded (t_3) temperatures and outdoor surface - embedded (t_4) temperatures, respectively, are average readings of 8 embedded thermocouples on the indoor and outdoor surfaces of the test wall.

Table 10(a) also lists calibrated hot box indoor and outdoor chamber relative humidities, and maximum and minimum laboratory air temperatures measured during the test.

Figure 11 illustrates differences between taped and embedded thermocouple measurements for indoor and outdoor surface temperatures. Maximum differences are 6.6°F (3.0°C) at Hour 14 for the outdoor surface and 0.9°F (0.4°C) at Hour 9 for the indoor surface.

Surface-to-surface (t_2-t_1) and surface-to-air (t_0-t_2, t_1-t_i) temperature differentials for taped thermocouple measurements are illustrated in Fig. 12(a). Surface-to-surface (t_4-t_3) and surface-to-air (t_0-t_4, t_3-t_i) temperature differentials for embedded thermocouple measurements are illustrated in Fig. 12(b). Air-to-air (t_0-t_i) temperature differentials are shown in both Figs. 12(a) and 12(b) for comparison purposes.

Heat Flux

Measured and calculated heat flux values are illustrated in Fig. 13 and listed in Table 11. Tables 11(a) and 11(b) list results in U.S. and SI

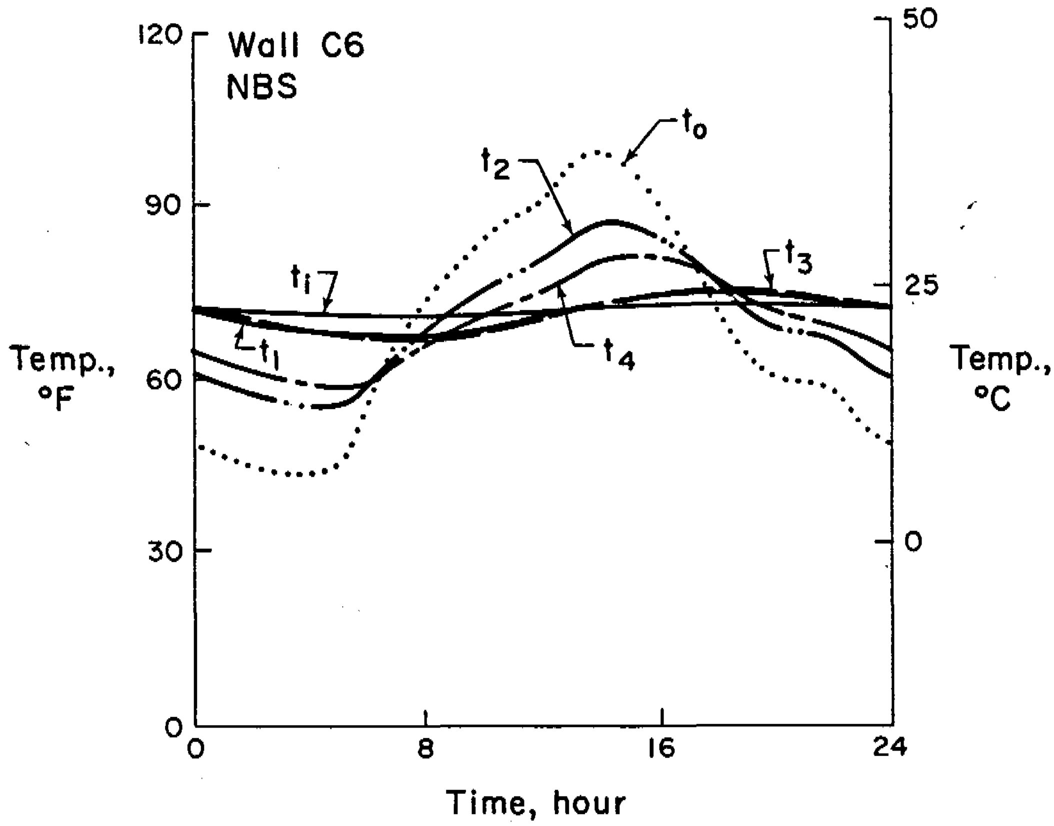


Fig. 10 Measured Temperatures for NBS Test Cycle
Applied to Wall C6

TABLE 10(a) - MEASURED TEMPERATURES FOR NBS TEST CYCLE APPLIED TO WALL C6

Time, hr	Measured Temperatures, °F					
	t_o Outdoor Air	t_2 Outdoor Surf., Taped	t_4* Outdoor Surf., Embedded	t_3* Indoor Surf., Embedded	t_1 Indoor Surf., Taped	t_i Indoor Air
1	46.8	59.0	63.3	71.8	71.6	72.2
2	44.7	57.2	61.7	70.8	70.8	71.9
3	44.1	56.1	60.4	69.8	70.0	71.7
4	43.8	55.3	59.4	68.9	69.2	71.5
5	45.0	55.1	58.7	68.0	68.5	71.3
6	54.9	58.7	59.9	67.3	68.0	71.2
7	66.1	64.1	62.8	66.9	67.6	71.1
8	73.3	68.3	65.6	66.9	67.7	71.1
9	79.3	72.0	68.2	67.3	68.2	71.2
10	84.8	75.6	70.9	68.1	68.9	71.4
11	87.9	78.3	73.3	69.0	69.7	71.7
12	90.9	80.8	75.3	70.1	70.7	72.0
13	97.5	84.9	78.4	71.4	71.7	72.2
14	99.6	87.4	80.8	72.5	72.7	72.6
15	96.3	87.1	81.7	73.7	73.7	72.9
16	91.7	85.6	81.6	74.8	74.6	73.2
17	84.2	82.5	80.5	75.7	75.3	73.3
18	72.6	77.0	77.7	76.2	75.7	73.4
19	64.7	72.4	74.7	76.3	75.7	73.4
20	60.4	69.4	72.2	75.9	75.2	73.3
21	59.6	68.0	70.7	75.2	74.5	73.1
22	58.6	66.8	69.6	74.4	73.8	72.8
23	51.3	63.1	67.2	73.6	73.1	72.6
24	48.4	60.6	64.9	72.7	72.3	72.4
Mean	68.6	70.2	70.0	71.6	71.6	72.2

*Average readings of 8 thermocouples, not 16.

Calibrated Hot Box Relative Humidity:
Indoor Chamber - 18%
Outdoor Chamber - 19%

Laboratory Air Temperature:
Max. - 72°F (22°C)
Min. - 71°F (21°C)

TABLE 10(b) - MEASURED TEMPERATURES FOR NBS TEST CYCLE APPLIED TO WALL C6, SI UNITS

Time, hr	Measured Temperatures, °C					
	t_o Outdoor Air	t_2 Outdoor Surf., Taped	t_4* Outdoor Surf., Embedded	t_3* Indoor Surf., Embedded	t_1 Indoor Surf., Taped	t_i Indoor Air
1	8.2	15.0	17.4	22.1	22.0	22.3
2	7.0	14.0	16.5	21.6	21.5	22.2
3	6.7	13.4	15.8	21.0	21.1	22.1
4	6.6	12.9	15.2	20.5	20.7	22.0
5	7.2	12.8	14.8	20.0	20.3	21.8
6	12.7	14.8	15.5	19.6	20.0	21.8
7	18.9	17.8	17.1	19.4	19.8	21.7
8	22.9	20.2	18.7	19.4	19.8	21.7
9	26.3	22.2	20.1	19.6	20.1	21.8
10	29.3	24.2	21.6	20.0	20.5	21.9
11	31.1	25.7	22.9	20.6	21.0	22.1
12	32.7	27.1	24.1	21.2	21.5	22.2
13	36.4	29.4	25.8	21.9	22.1	22.4
14	37.6	30.8	27.1	22.5	22.6	22.5
15	35.7	30.6	27.6	23.2	23.2	22.7
16	33.1	29.8	27.6	23.8	23.7	22.9
17	29.0	28.1	26.9	24.3	24.1	23.0
18	22.6	25.0	25.4	24.6	24.3	23.0
19	18.2	22.4	23.7	24.6	24.3	23.0
20	15.8	20.8	22.4	24.4	24.0	22.9
21	15.4	20.0	21.5	24.0	23.6	22.8
22	14.8	19.3	20.9	23.5	23.2	22.7
23	10.7	17.3	19.5	23.1	22.8	22.6
24	9.1	15.9	18.3	22.6	22.4	22.5
Mean	20.3	21.2	21.1	22.0	22.0	22.4

*Average readings of 8 thermocouples, not 16.

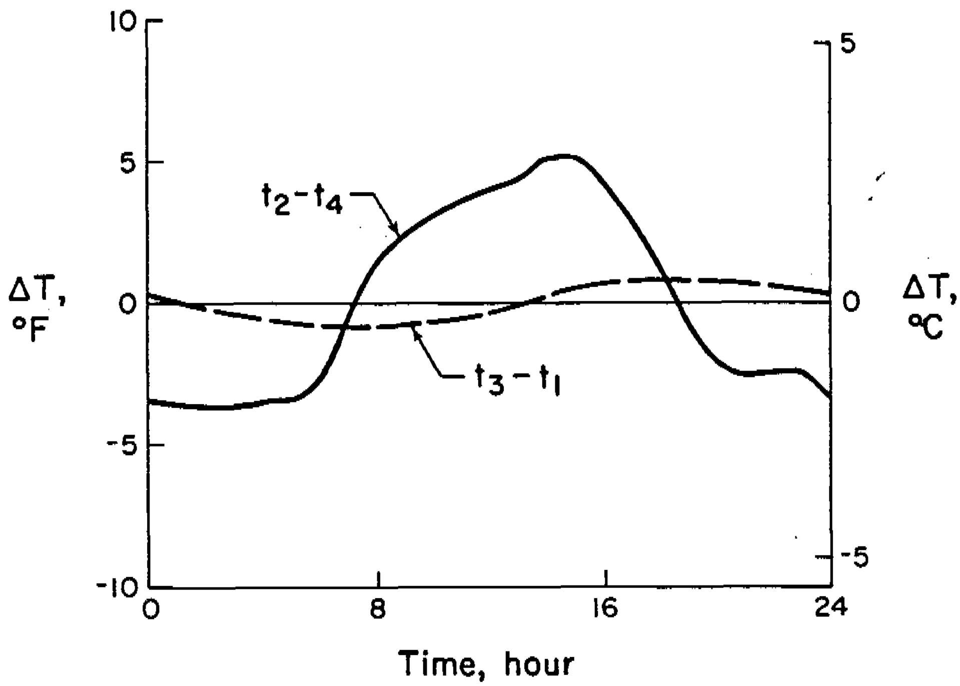
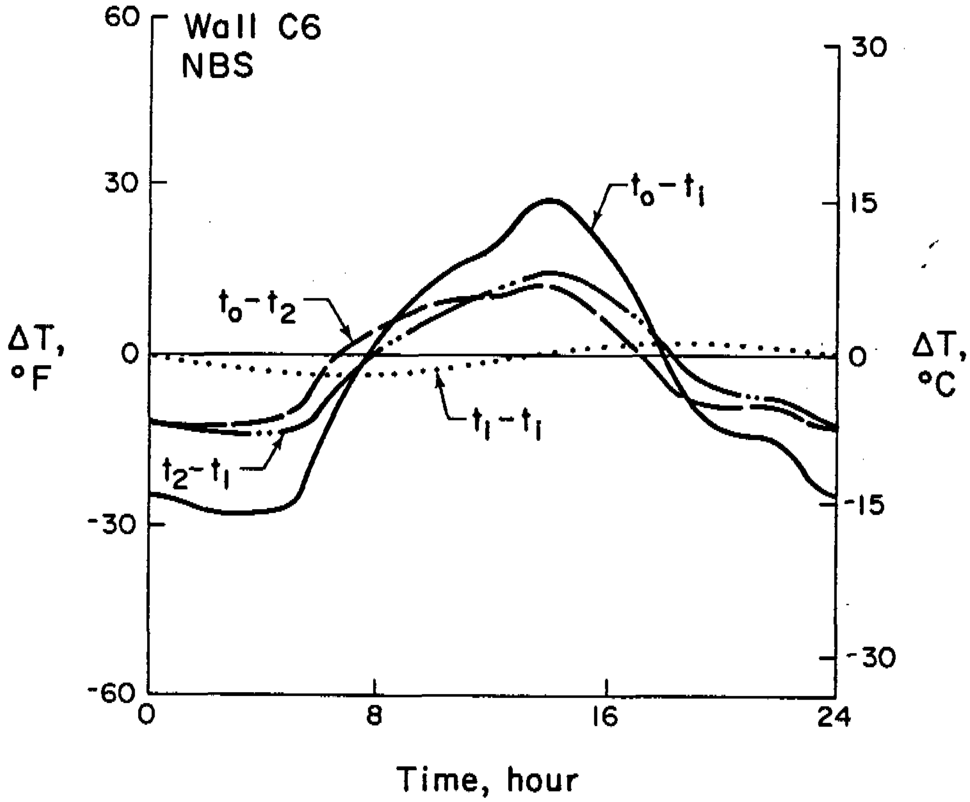
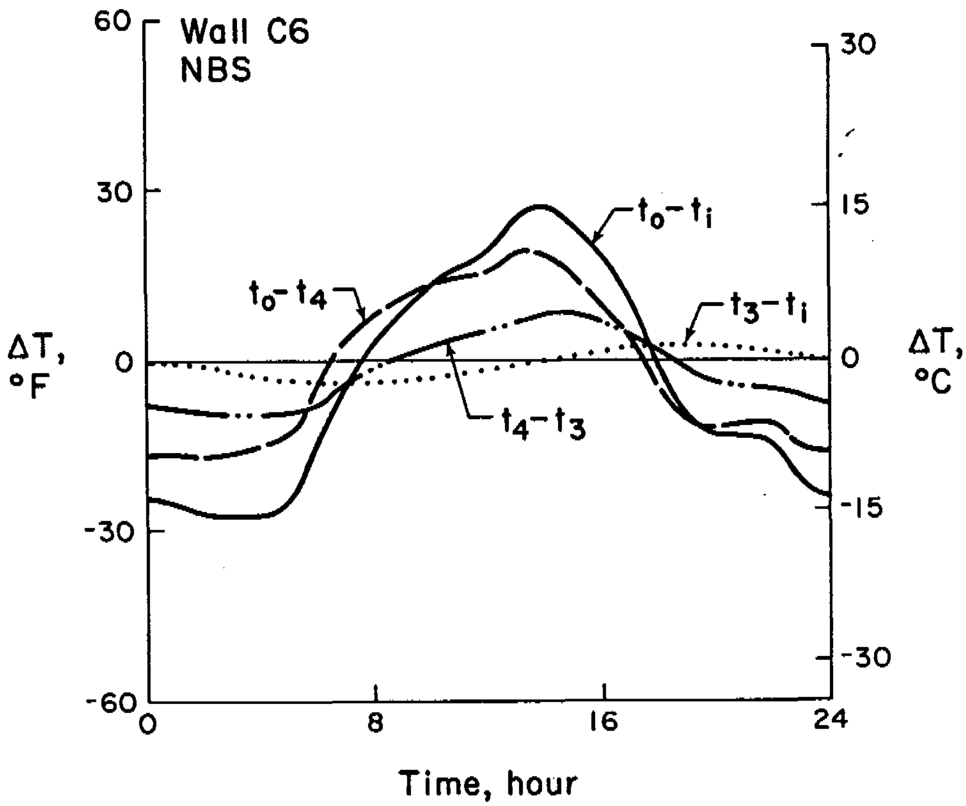


Fig. 11 Differences Between Taped and Embedded Thermocouple Measurements



(a) Taped Thermocouple Measurements

Fig. 12 Temperature Differentials for NBS Test Cycle Applied to Wall C6



(b) Embedded Thermocouple Measurements

Fig. 12 Temperature Differentials for NBS Test Cycle Applied to Wall C6

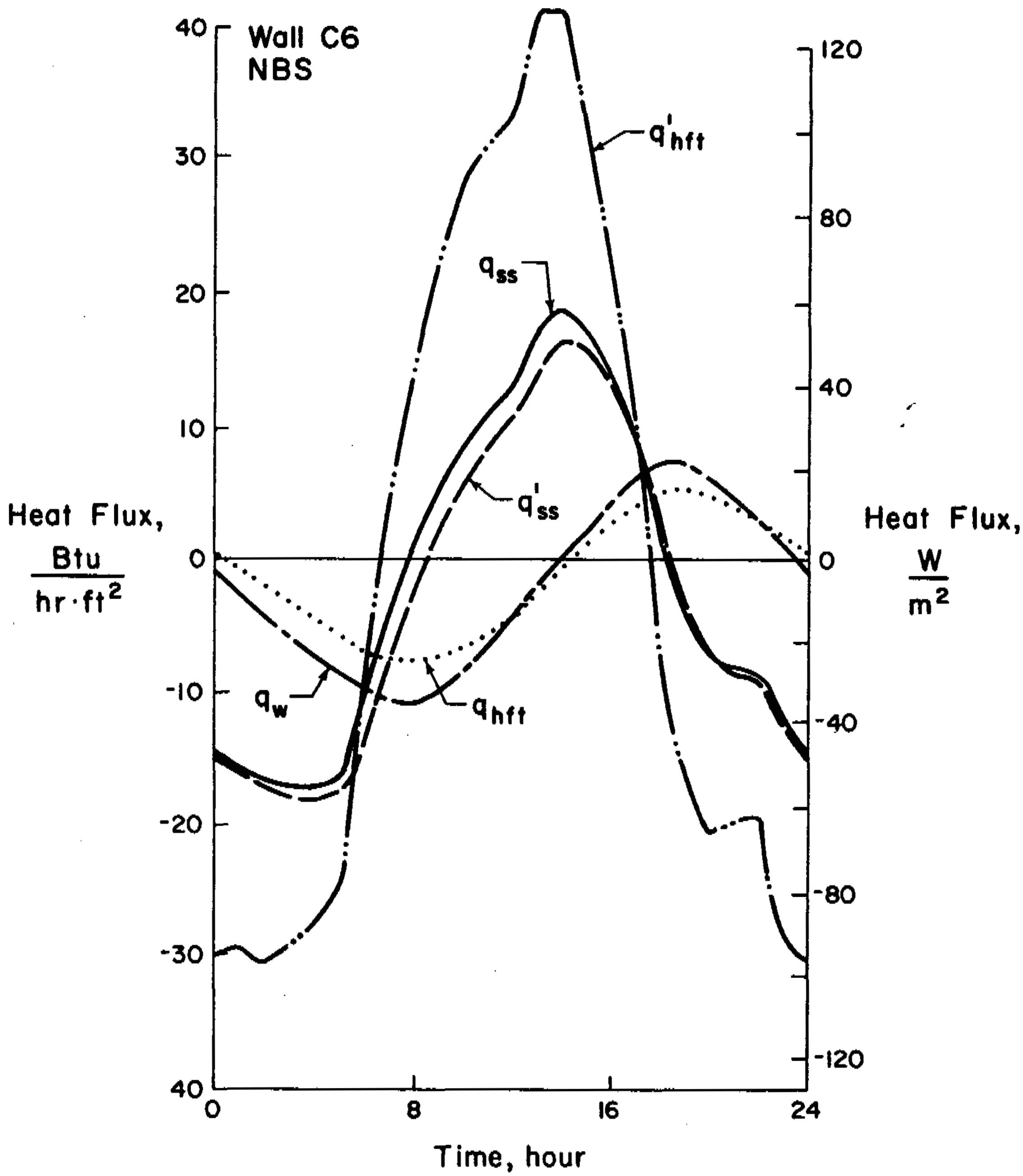


Fig. 13 Heat Flux for NBS Test Cycle Applied to Wall C6

TABLE 11(a) - HEAT FLUX FOR NBS TEST CYCLE APPLIED TO WALL C6

Time, hr	Measured Heat Flux, Btu/hr•ft			Calculated Heat Flux, Btu/hr•ft	
	q_w Calib. Hot Box	q_{hft} HFT @ Inside Surf.	q'_{hft} HFT @ Outside Surf.	q_{ss} Steady-State Taped	q'_{ss} Steady-State Embedded
1	-2.7	-0.8	-29.2	-15.7	-16.2
2	-4.3	-2.0	-30.6	-16.8	-17.4
3	-5.9	-3.4	-29.1	-17.2	-18.0
4	-7.3	-4.7	-27.7	-17.3	-18.1
5	-8.7	-5.8	-24.5	-16.6	-17.7
6	-10.1	-7.0	-10.2	-11.5	-14.0
7	-11.0	-7.7	4.7	-4.4	-7.6
8	-11.0	-7.8	13.9	0.7	-2.5
9	-10.1	-7.5	21.3	4.8	1.8
10	-8.5	-6.7	28.3	8.5	5.5
11	-6.6	-5.6	30.9	10.8	8.2
12	-4.4	-4.4	33.0	12.7	10.1
13	-2.2	-2.7	41.1	16.7	13.7
14	-0.4	-1.1	41.2	18.7	16.3
15	1.7	0.6	32.5	17.0	15.7
16	4.0	2.4	21.9	13.9	13.3
17	6.0	3.9	9.3	9.1	9.3
18	7.0	4.8	-6.9	1.6	2.9
19	7.0	5.1	-16.5	-4.1	-3.2
20	6.0	4.7	-20.7	-7.3	-7.1
21	4.5	3.9	-19.8	-8.2	-8.6
22	2.7	2.9	-19.5	-8.7	-9.3
23	0.9	1.8	-28.6	-12.5	-12.3
24	-0.8	0.5	-30.1	-14.6	-14.9
Mean	-2.3	-1.5	-0.6	-1.7	-2.9

TABLE 11(b) - HEAT FLUX FOR NBS TEST CYCLE APPLIED TO WALL C6, SI UNITS

Time, hr	Measured Heat Flux, W/m²			Calculated Heat Flux, W/m²	
	q_w Calib. Hot Box	q_{hft} HFT @ Inside Surf.	q'_{hft} HFT @ Outside Surf.	q_{ss} Steady-State Taped	q'_{ss} Steady-State Embedded
1	-8.6	-2.4	-92.0	-49.4	-51.0
2	-13.6	-6.5	-96.7	-53.0	-54.8
3	-18.6	-10.7	-91.7	-54.3	-56.7
4	-23.0	-14.7	-87.5	-54.4	-57.1
5	-27.3	-18.4	-77.2	-52.3	-55.8
6	-31.8	-21.9	-32.2	-36.3	-44.1
7	-34.7	-24.3	15.0	-13.8	-24.1
8	-34.8	-24.7	43.9	2.3	-7.8
9	-31.8	-23.7	67.2	15.1	5.6
10	-27.0	-21.2	89.1	26.7	17.4
11	-20.8	-17.8	97.5	34.2	26.0
12	-14.0	-13.7	104.2	40.1	31.8
13	-7.1	-8.4	129.6	52.7	43.3
14	-1.2	-3.5	130.0	58.9	51.4
15	5.5	2.0	102.6	53.8	49.5
16	12.7	7.7	69.1	43.9	42.0
17	19.0	12.3	29.3	28.6	29.5
18	22.0	15.1	-21.9	5.0	9.1
19	22.2	16.0	-52.0	-13.0	-10.2
20	18.9	14.9	-65.3	-23.1	-22.5
21	14.2	12.4	-62.4	-26.0	-27.2
22	8.4	9.0	-61.6	-27.6	-29.3
23	3.0	5.6	-90.3	-39.3	-38.8
24	-2.4	1.6	-94.9	-46.2	-46.9
Mean	-7.1	-4.8	-2.0	-5.3	-9.2

units, respectively. 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. Measured heat flux is not affected by the surface temperature measurement technique.

Heat flux measured on Wall C6 using 4x4-in. (100x100-mm) heat flux transducers located on indoor and outdoor wall surfaces were denoted q_{hft} and q'_{hft}, respectively. Heat flux transducer data were calibrated using results from steady-state calibrated hot box tests for Wall C6.

Heat flux predicted by steady-state analysis was calculated from wall surface temperatures. Heat flux predicted using temperature measurements from taped thermocouples is denoted q_{ss}. Values were calculated on an hourly basis 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 using taped thermocouple measurements, Btu/hr•ft²•(W/m²)

R = wall thermal resistance, hr•ft²•°F/Btu (m²•K/W)

t_2 = average wall surface temperature, outdoor side, taped thermocouples, °F (°C)

t_1 = average wall surface temperature, indoor side, taped thermocouples, °F (°C)

Wall surface temperatures, t_2 and t_1, are average readings of 16 thermocouples taped on each side of the wall. Wall resistance, R, is dependent on wall mean temperature and was derived from steady-state calibrated hot box test results using taped thermocouple temperature measurements.

Heat flux predicted by steady-state analysis based on temperature measurements from embedded thermocouples is denoted q'_{ss}. Values were calculated on an hourly basis from wall surface temperatures using the following equation:

$$q'_{ss} = (t_4 - t_3)/R' \qquad (2)$$

where

q'_{ss} = heat flux through wall predicted by steady-state analysis using embedded thermocouple measurements, Btu/hr•ft^2 (W/m^2)

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

t_4 = average wall surface temperature, outdoor side, embedded thermocouples, °F (°C)

t_3 = average wall surface temperature, indoor side, embedded thermocouples, °F (°C)

Wall surface temperatures, t_4 and t_3, are average readings of eight thermocouples embedded in each side of the wall. Wall resistance, R', is dependent on wall mean temperature and was derived from steady-state calibrated hot box test results using embedded thermocouple temperature measurements.

Figure 13 shows that the curve for steady-state heat flux calculated from embedded thermocouple measurements, q'_{ss}, generally is shifted downward from the curve calculated from taped thermocouple measurements, q_{ss}. The amplitude for q'_{ss} is 4% less than that of q_{ss}. This result is expected since taped thermocouple measurements, the basis for q_{ss}, are more strongly influenced by outdoor chamber air temperature fluctuations than embedded thermocouple measurements, the basis for q'_{ss}. As stated in the "Total Thermal Resistance of Concrete" section, taped thermocouple measurements are a combination of surface and air temperatures.

Discussion of Test Results

Surface Temperatures

The differences between embedded and taped thermocouple readings shown in Fig. 11 will affect dynamic test results that utilize surface temperatures. For example, a dynamic thermal resistance, or R value,* for a given temperature condition will be different depending on whether taped or embedded thermocouples are used to measure surface temperatures.

Surface temperatures for dynamic temperature cycles theoretically can be used in heat transfer equations to predict measured heat flows. Mr. Ken Childs, Oak Ridge National Laboratory, has shown in Ref. 13 that errors in measured surface temperatures, such as thermal contact resistance between thermocouples and normal weight concrete, affect predicted heat flows.

Based on results of the test program, it is recommended that thermocouples for measuring surface temperatures be embedded in surfaces of normal weight concrete walls to minimize the contact thermal resistance between thermocouples and the wall surface.

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.

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*A dynamic R value is the sum of the temperature differences across a wall or other component measured at discrete intervals for a period of time, divided by the sum of heat flows through a component measured at the same intervals.

For each temperature measurement technique, Table 12 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, 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. The row in Table 12 labeled "Taped" lists thermal lags determined from the difference in peaks between outdoor air temperatures, t_0, and indoor surface temperatures measured by taped thermocouples, t_1. The row labeled "Embedded" lists thermal lags determined from the difference in peaks between outdoor air temperatures, t_0, and indoor surface temperatures measured by embedded thermocouples, t_3.

In the second measure, illustrated in Fig. 14, lag is calculated as the time required for the maximum or minimum heat flux, q_w, to be reached after the maximum or minimum heat flux based on steady-state predictions, q_{ss} or q'_{ss}, is attained. The second measure is also used to determine thermal lag for heat flux transducer data. Thermal lags for calibrated hot box heat flux measurements and heat flux transducer measurements are based on q_{ss} for taped thermocouples and q'_{ss} for embedded thermocouples.

Thermal lag values are calculated to the nearest one-half hour since hot box data are collected and analyzed at hourly intervals.

Thermal lags determined from surface and air temperatures are similar to those determined from measured heat flux.

As can be seen in Table 12, thermal lags are identical for taped and embedded thermocouple measurement techniques. This is because peak temperatures occur at the same hours for the two measurement techniques.

TABLE 12 - THERMAL LAG FOR NBS TEST CYCLE APPLIED TO WALL C6

Thermocouple Placement	Measured Thermal Lag, hrs							
	Calibrated Hot Box					Heat Flux Transducer		
	Outdoor Air vs. Indoor Surf. Temp.*		Steady-State vs. Cal. Hot Box Heat Flux**		Avg.	Steady-State vs. Heat Flux Trans. Heat Flux**		Avg.
	@ Max.	@ Min.	@ Max.	@ Min.		@ Max.	@ Min.	
Taped	4.5	3.5	4.5	4	4	5	4	4.5
Embedded	4.5	3.5	4.5	4	4	5	4	4.5

* Thermal lags for taped thermocouple measurements are the time delay between peaks in t_0 and t_1. Thermal lags for embedded thermocouple measurements are the time delay between peaks in t_0 and t_3.

** Thermal lags are based on q_{ss} values for taped thermocouple measurements and q'_{ss} for embedded thermocouple measurements.

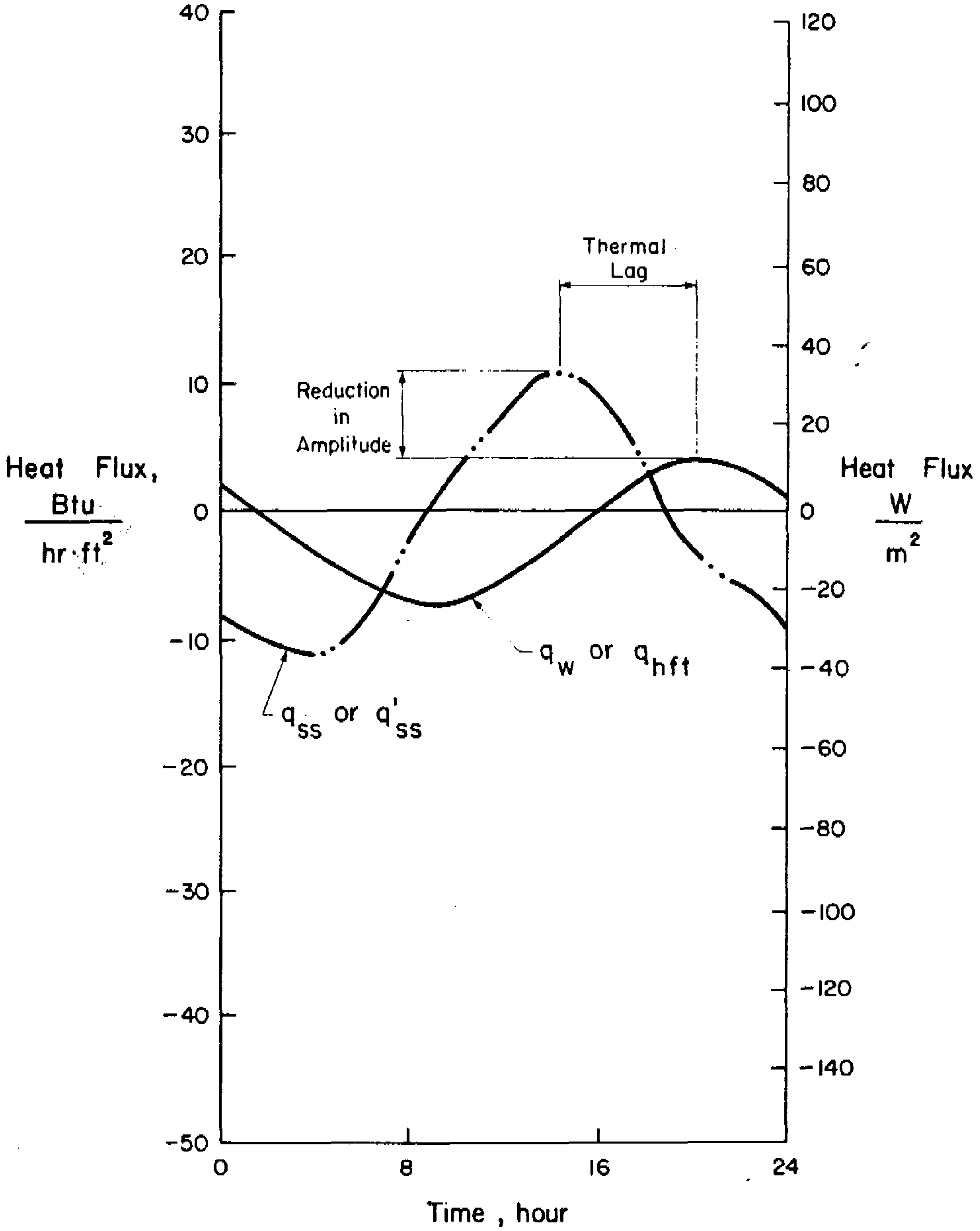

Fig. 14 Definition of Thermal Lag and Reduction in Amplitude

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 also dependent on the temperature cycle applied to the test specimen.

Reduction in amplitude is defined as the percent reduction in peak heat flux when compared to peak heat flux calculated using steady-state theory. Reduction in amplitude is illustrated in Fig. 14. Values for reduction in amplitude were calculated using the following equation:

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

where

- A = reduction in amplitude, %
- q^m = maximum or minimum measured heat flux through wall
- $\bar{q}$ = mean measured heat flux through wall
- q^m_{ss} = maximum or minimum heat flux through wall predicted by steady-state analysis
- $\bar{q}_{ss}$ = mean heat flux through wall predicted by steady-state analysis

Reduction in amplitude values for taped thermocouple temperature measurements are based on q_{ss}. Reduction in amplitude values for embedded thermocouple temperature measurements are based on q'_{ss}.

Table 13 lists reduction in amplitude values for the NBS Test Cycle for the two surface temperature measurement techniques used on Wall C6.

Amplitudes for heat flux transducer data, q_{hft}, are generally not the same as those for measured heat flux, q_w. Heat flux transducer measurements are affected by discontinuities in contact between the heat flux transducer

TABLE 13 - REDUCTION IN AMPLITUDE FOR NBS TEST CYCLE APPLIED TO WALL C6

Thermocouple Placement	Measured Reduction in Amplitude, %*					
	Calibrated Hot Box			Heat Flux Trans.		
	@ Max.	@ Min.	Avg.	@ Max.	@ Min.	Avg.
Taped	54	44	49	68	59	64
Embedded	52	42	47	66	58	62

* Reduction in amplitude values are based on q_{ss} values for taped thermocouple measurements and q'_{ss} for embedded thermocouple measurements.

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.

As can be seen from Table 13, reduction in amplitude values based on temperature measurements of embedded thermocouples are approximately 2% less than those based on taped thermocouple measurements. This is because steady-state heat flux calculated from embedded thermocouple measurements, q'_{ss}, has a smaller amplitude than does steady-state heat flux calculated from taped thermocouple measurements, q_{ss}.

Total Heat Flux

Another measure of dynamic thermal performance is total heat flux through a test specimen, illustrated in Fig. 15. The curve marked "q_w" is measured heat flux through a test wall. Areas enclosed by the measured heat flux curve and the horizontal axis are 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. Table 14 lists this value, denoted as q_w^T, for the NBS Test Cycle applied to Wall C6.

A similar procedure is used to calculate total heat flux over a 24-hr period for predictions based on steady-state analysis, denoted q_{ss}^T in Table 14. Values in the row labeled "Taped" are determined from steady-state heat flux calculated using taped thermocouple measurements. Values in the row labeled "Embedded" are determined from steady-state heat flux calculated using embedded thermocouple measurements.

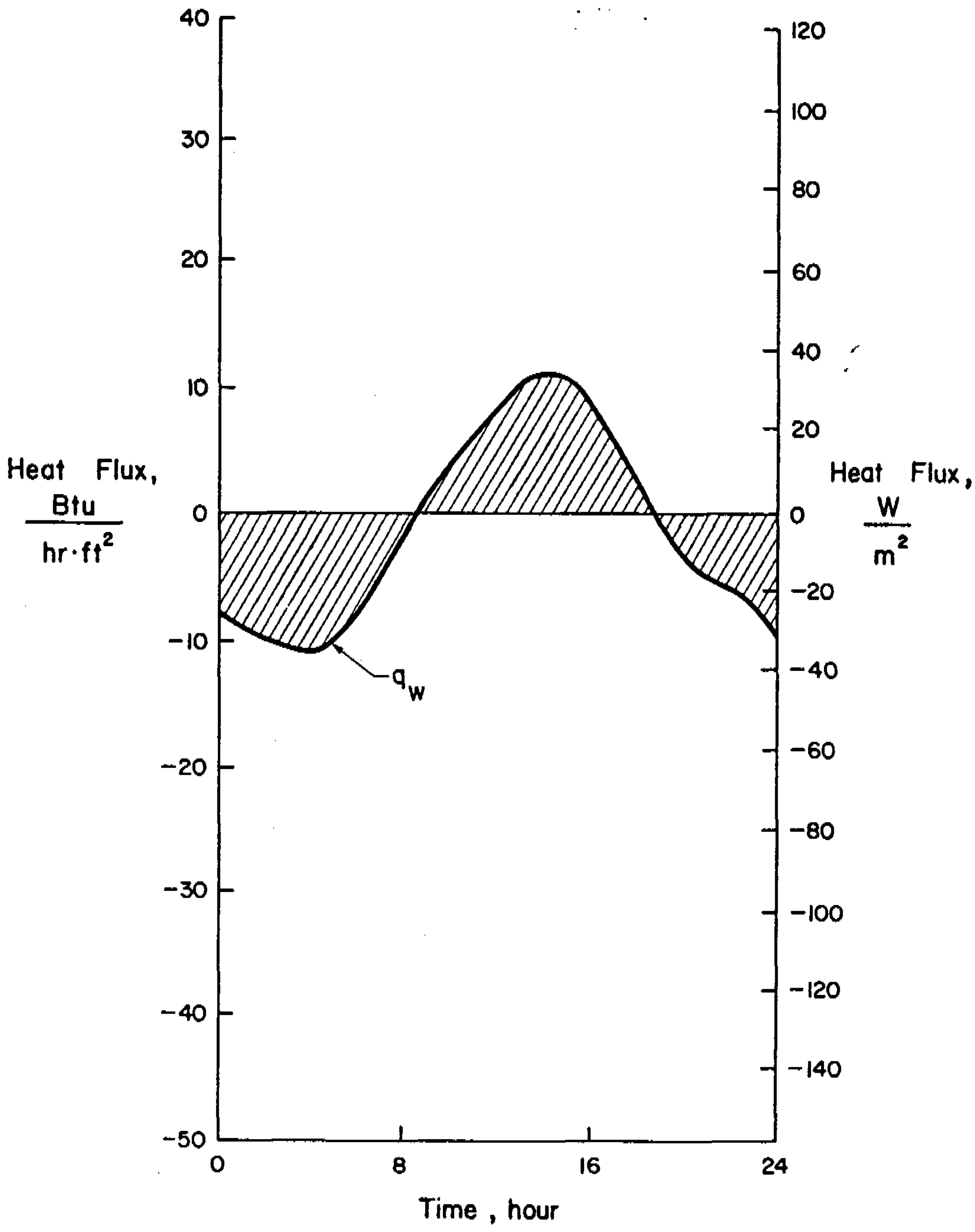

Fig. 15 Definition of Total Heat Flux

TABLE 14 - TOTAL AND NET HEAT FLUX FOR NBS TEST CYCLE APPLIED TO WALL C6

Thermocouple Placement	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			Measured		Calculated		
	q_w^T	q_{hft}^T	q_{ss}^T *	$\frac{q_w^T}{q_{ss}^T}$ *	$\frac{q_{hft}^T}{q_{ss}^T}$ *	q_w^N	q_{hft}^N	q_{ss}^N *	$\frac{q_w^N}{q_{ss}^N}$ *	$\frac{q_{hft}^N}{q_{ss}^N}$ *
Taped	133.9 (422.6)	97.8 (308.5)	269.4 (850.0)	50	36	-54.1 (-170.8)	-36.5 (-115.3)	-40.4 (-127.4)	134	91
Embedded	133.9 (422.6)	97.8 (308.5)	263.7 (831.9)	51	37	-54.1 (-170.8)	-36.5 (-115.3)	-70.0 (-220.7)	77	52

* Total and net heat flux values are based on q_{ss} for taped thermocouple measurements and q'_{ss} for embedded thermocouple measurements.

Total heat flux for heat flux transducer data were calculated in the same manner and are denoted q^T_{hft} in Table 14.

Total heat flux based on steady-state analysis, q^T_{ss}, for embedded thermocouple measurements is 1% less than q^T_{ss} for taped thermocouple measurements. This is due to the fact that the steady-state heat flux calculated from embedded thermocouple measurements has a smaller amplitude than that calculated from taped thermocouple measurements.

The columns labeled "Total Heat Flux Comparisons" list measured heat flux as a percentage of heat flux predicted using steady-state analysis.

"Total Heat Flux Comparisons" for taped and embedded thermocouple measurements differ by 1%. Since q^T_w and q^T_{hft} are the same for the two temperature measurement techniques, changes in "Total Heat Flux Comparisons" for the two techniques are due only to differences in steady-state heat flux calculated from taped and embedded thermocouple measurements, denoted q^T_{ss}.

It should be noted that comparison of measured heat flux values for a test wall is limited to the specimen and dynamic cycle evaluated in this program. Results are for a diurnal test cycle and should not be arbitrarily assumed to represent annual heating and cooling loads. In addition, results are for an opaque wall assembly. As such, they are representative of only one component of the building envelope.

Net Heat Flux

Total heat flux is 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, multiplied 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 flow. These values can be found by totaling values of "q" from columns of Table 11. Net heat flux values are denoted by the superscript "N" in Table 14.

"Net Heat Flux Comparisons" list measured heat flux as a percentage of heat flux predicted using steady-state analysis. Measured calibrated hot box net energy theoretically should be equal to net energy based on steady-state predictions. Since q_w^N and q_{hft}^N are the same for the two temperature measurement techniques, changes in "Net Heat Flux Comparisons" for the two techniques are due only to differences in steady-state heat flux calculated from taped and embedded thermocouple measurements, denoted q_{ss}^T.

TRANSIENT TEST

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.

Test Procedure

Results of a transient test are determined from data collected in the period of time between two steady-state tests. After a wall is in 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.

For the transient test on Wall C6, initial wall mean temperature was 72.8°F (22.7°C). The initial temperature differential across the wall was less than 1°F (0.5°C). The final wall mean temperature was 32.2°F (0.1°C). The final indoor and outdoor air temperatures, respectively, were 66.5°F

(19.2°C) and -5.2°F (-20.7°C). This provided a nominal temperature differential between the two chambers of 72°F (40°C).

Test Results

Figure 16 illustrates measured temperatures for the transient test on Wall C6. Values are shown as a function of time. Tables 15(a) and 15(b), respectively, list measured temperatures in U.S. units and SI units.

Table 9 in the "Dynamic Tests" section lists brief descriptions of symbols used in test data figures and tables. Symbols are described more thoroughly in the "Test Results" portion of the "Dynamic Tests" section.

Figure 17 illustrates measured temperature differentials for the transient test on Wall C6. The difference between indoor surface temperatures measured by taped and embedded thermocouples is denoted t_3-t_1. The difference between outdoor surface temperatures measured by taped and embedded thermocouples is denoted t_2-t_4. Figure 17 shows that the value of t_3-t_1 approaches the value of t_2-t_4 as the wall reaches steady-state equilibrium.

Measured heat flux from calibrated hot box tests, q_w, heat flux measured by heat flux transducers, q_{hft} and q'_{hft}, and calculated heat flux using steady-state theory, q_{ss} and q'_{ss}, are illustrated in Fig. 18. Tables 16(a) and 16(b) list measured and calculated heat flux in U.S. and SI units, respectively. Measured results show that Wall C6 prolonged the consequences of a sudden change in outdoor chamber air temperature, when compared to steady-state theory.

Heat flux predicted by steady-state theory was calculated from temperature measurements of both taped and embedded thermocouples. As can be seen in Fig. 18, steady-state heat flux calculated from embedded thermocouple

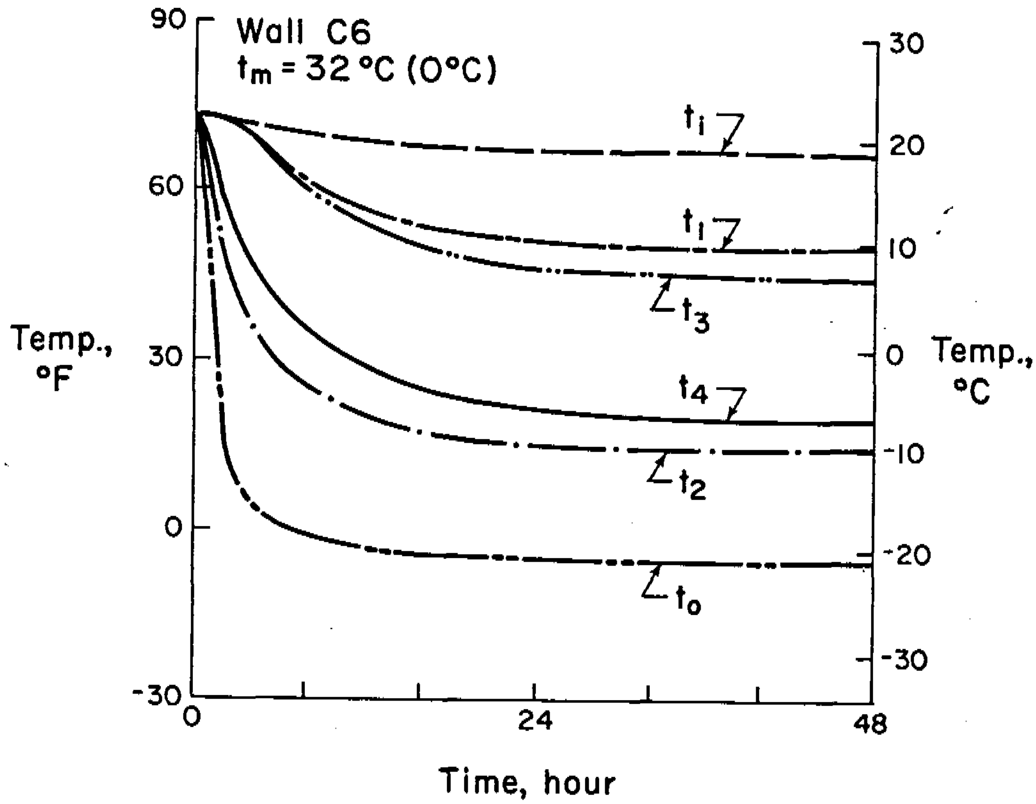

Fig. 16 Measured Temperatures for Transient Test

TABLE 15(a) - MEASURED TEMPERATURES FOR TRANSIENT TEST

Time, hr	Measured Temperatures, °F					
	t_0 Outdoor Air	t_2 Outdoor Surf., Taped	t_4* Outdoor Surf., Embedded	t_3* Indoor Surf., Embedded	t_1 Indoor Surf., Taped	t_i Indoor Air
0	72.8	73.0	72.6	72.9	72.6	72.4
1	39.8	60.1	66.8	72.9	72.6	72.4
2	14.3	45.5	56.8	72.4	72.2	72.3
3	7.2	38.6	50.4	70.8	70.7	71.9
4	4.3	34.6	46.0	68.5	68.7	71.3
5	2.3	31.4	42.6	65.9	66.6	70.7
6	0.8	28.9	39.6	63.5	64.6	70.2
7	-0.2	26.9	37.2	61.3	62.6	69.7
8	-0.9	25.1	35.0	59.2	61.1	69.3
9	-1.6	23.6	33.1	57.5	59.7	68.9
10	-2.2	22.3	31.4	55.9	58.5	68.6
11	-2.8	21.1	29.9	54.5	57.4	68.3
12	-3.2	20.1	28.6	53.2	56.4	68.1
13	-3.5	19.3	27.5	52.1	55.5	67.9
14	-3.7	18.7	26.6	51.1	54.8	67.7
15	-3.9	18.0	25.7	50.3	54.2	67.5
16	-4.0	17.5	25.0	49.5	53.7	67.4
17	-4.3	17.0	24.3	48.8	53.2	67.3
18	-4.4	16.7	23.8	48.3	52.8	67.2
19	-4.5	16.3	23.3	47.8	52.4	67.1
20	-4.6	16.0	22.9	47.3	52.1	67.0
21	-4.7	15.8	22.5	47.0	51.8	67.0
22	-4.8	15.5	22.1	46.6	51.6	67.0
23	-4.9	15.3	21.8	46.3	51.4	66.9
24	-4.9	15.2	21.6	46.1	51.3	66.9
26	-5.0	14.9	21.2	45.7	51.0	66.8
28	-5.1	14.8	20.9	45.3	50.8	66.8
30	-5.1	14.6	20.7	45.2	50.7	66.8
32	-5.1	14.5	20.6	45.0	50.5	66.7
34	-5.1	14.5	20.5	44.9	50.5	66.6
36	-5.1	14.4	20.3	44.8	50.4	66.6
38	-5.1	14.3	20.3	44.7	50.3	66.6
40	-5.1	14.3	20.2	44.6	50.3	66.4
42	-5.2	14.2	20.1	44.6	50.3	66.6
44	-5.2	14.2	20.1	44.6	50.2	66.5
46	-5.2	14.2	20.1	44.5	50.1	66.5
48	-5.2	14.2	20.0	44.5	50.2	66.5

*Average readings of 8 thermocouples, not 16.

TABLE 15(b) - MEASURED TEMPERATURES FOR TRANSIENT TEST, SI UNITS

Time, hr	Measured Temperatures, °C					
	t_0 Outdoor Air	t_2 Outdoor Surf., Taped	t_4* Outdoor Surf., Embedded	t_3* Indoor Surf., Embedded	t_1 Indoor Surf., Taped	t_1 Indoor Air
0	22.7	22.8	22.6	22.7	22.6	22.5
1	4.3	15.6	19.3	22.7	22.6	22.5
2	-9.8	7.5	13.8	22.5	22.3	22.4
3	-13.8	3.7	10.2	21.5	21.5	22.2
4	-15.4	1.4	7.8	20.3	20.4	21.8
5	-16.5	-0.3	5.9	18.8	19.2	21.5
6	-17.3	-1.7	4.2	17.5	18.1	21.2
7	-17.9	-2.9	2.9	16.3	17.0	20.9
8	-18.3	-3.8	1.7	15.1	16.2	20.7
9	-18.7	-4.7	0.6	14.2	15.4	20.5
10	-19.0	-5.4	-0.3	13.3	14.7	20.3
11	-19.3	-6.1	-1.2	12.5	14.1	20.2
12	-19.5	-6.6	-1.9	11.8	13.6	20.0
13	-19.7	-7.0	-2.5	11.2	13.1	19.9
14	-19.8	-7.4	-3.0	10.6	12.7	19.8
15	-19.9	-7.8	-3.5	10.1	12.3	19.7
16	-20.0	-8.1	-3.9	9.7	12.0	19.7
17	-20.1	-8.3	-4.3	9.4	11.8	19.6
18	-20.2	-8.5	-4.6	9.0	11.5	19.6
19	-20.3	-8.7	-4.9	8.8	11.4	19.5
20	-20.3	-8.9	-5.1	8.5	11.2	19.5
21	-20.4	-9.0	-5.3	8.3	11.0	19.4
22	-20.4	-9.1	-5.5	8.1	10.9	19.4
23	-20.5	-9.3	-5.7	8.0	10.8	19.4
24	-20.5	-9.3	-5.8	7.8	10.7	19.4
26	-20.6	-9.5	-6.0	7.6	10.5	19.3
28	-20.6	-9.6	-6.2	7.4	10.4	19.3
30	-20.6	-9.7	-6.3	7.3	10.4	19.3
32	-20.6	-9.7	-6.4	7.2	10.3	19.3
34	-20.6	-9.8	-6.4	7.2	10.3	19.2
36	-20.6	-9.8	-6.5	7.1	10.2	19.2
38	-20.6	-9.8	-6.5	7.0	10.2	19.2
40	-20.6	-9.9	-6.6	7.0	10.2	19.1
42	-20.7	-9.9	-6.6	7.0	10.1	19.2
44	-20.6	-9.9	-6.6	7.0	10.1	19.2
46	-20.7	-9.9	-6.6	6.9	10.1	19.2
48	-20.7	-9.9	-6.7	6.9	10.1	19.2

*Average readings of 8 thermocouples, not 16.

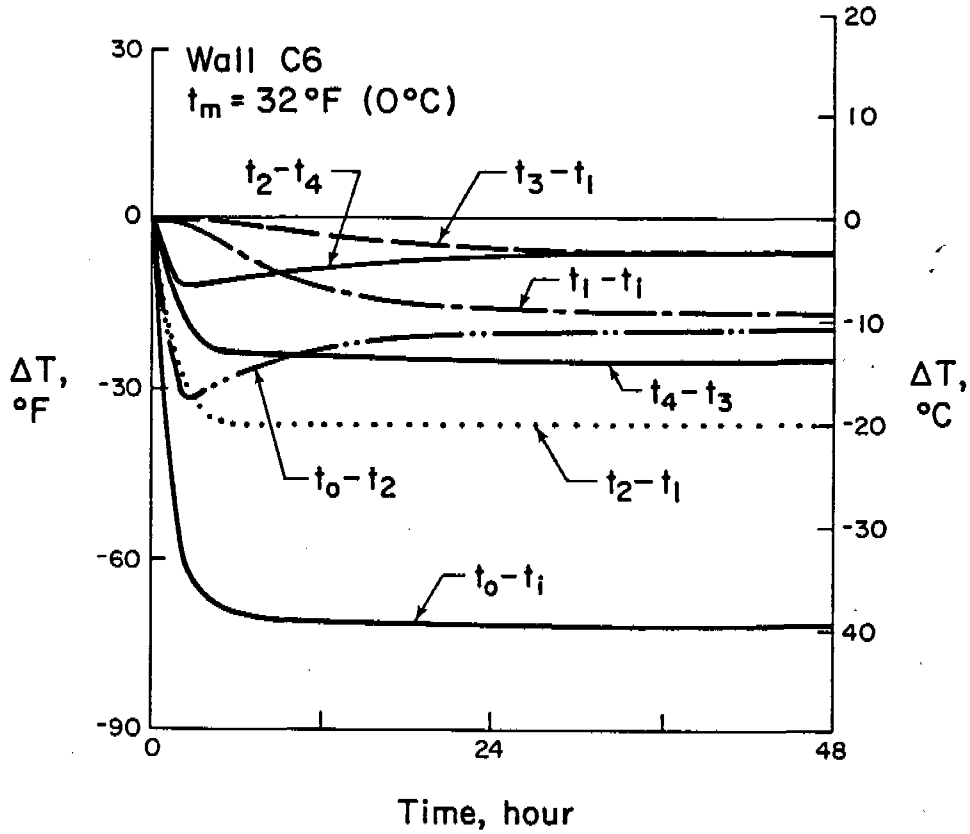

Fig. 17 Temperature Differentials for Transient Test

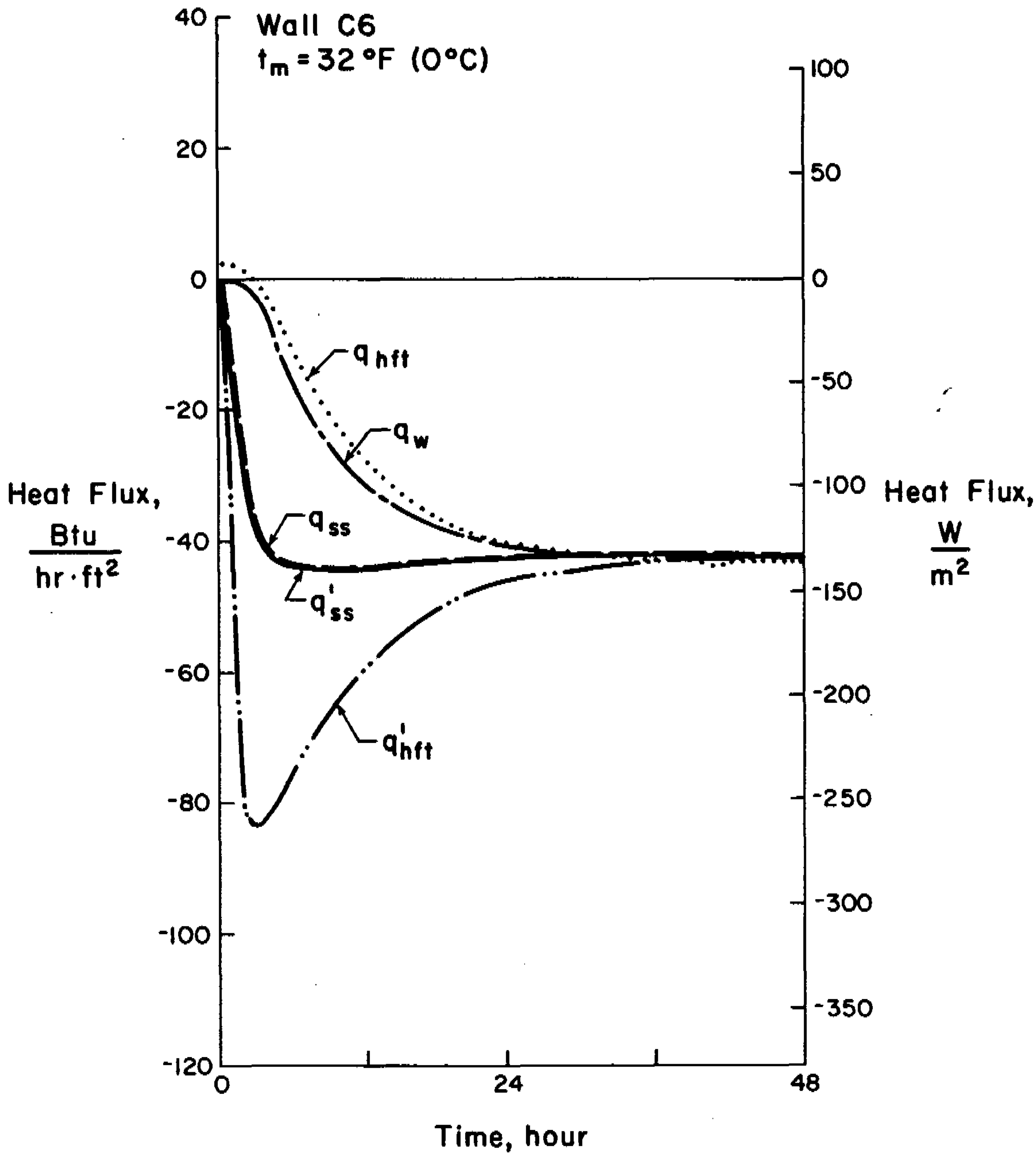

Fig. 18 Heat Flux for Transient Test

TABLE 16(a) - HEAT FLUX FOR TRANSIENT TEST

Time, hr	Measured Heat Flux, $Btu/hr \cdot ft^2$			Calculated Heat Flux, $Btu/hr \cdot ft^2$	
	q_w Calib. Hot Box	q_{hft} HFT @ Inside Surf.	q'_{hft} HFT @ Outside Surf.	q_{ss} Steady-State, Taped	q'_{ss} Steady-State, Embedded
0	-0.2	2.0	1.5	0.5	-0.6
1	0.0	2.0	-46.1	-15.5	-11.8
2	-0.6	1.4	-81.2	-32.8	-29.7
3	-3.2	-0.8	-83.5	-39.4	-38.3
4	-7.9	-4.0	-81.3	-41.7	-41.8
5	-12.3	-7.5	-77.9	-42.7	-43.1
6	-16.0	-11.1	-74.9	-43.2	-43.8
7	-19.5	-14.5	-71.1	-43.2	-44.0
8	-22.6	-17.5	-68.0	-43.4	-44.0
9	-25.5	-20.3	-65.7	-43.4	-44.1
10	-27.7	-23.0	-63.3	-43.5	-44.1
11	-29.8	-25.5	-60.8	-43.5	-44.1
12	-31.4	-27.7	-59.0	-43.4	-44.0
13	-32.7	-29.5	-57.0	-43.3	-43.8
14	-34.2	-31.4	-55.3	-43.2	-43.7
15	-35.4	-32.4	-53.5	-43.2	-43.6
16	-36.6	-34.0	-52.0	-43.1	-43.4
17	-37.5	-35.2	-51.2	-43.1	-43.3
18	-38.1	-36.0	-49.9	-43.0	-43.3
19	-38.9	-37.2	-49.4	-43.0	-43.2
20	-39.1	-37.8	-48.5	-42.9	-43.1
21	-39.4	-38.7	-47.3	-42.9	-43.1
22	-40.0	-39.3	-47.0	-42.9	-43.0
23	-40.7	-39.7	-46.4	-42.9	-43.0
24	-40.9	-40.5	-46.0	-42.9	-43.0
26	-41.4	-41.1	-44.9	-42.8	-42.8
28	-41.7	-41.7	-45.0	-42.8	-42.8
30	-41.8	-41.8	-44.1	-42.8	-42.8
32	-41.5	-42.3	-44.1	-42.7	-42.7
34	-41.9	-42.6	-43.6	-42.7	-42.7
36	-41.9	-42.7	-43.3	-42.7	-42.7
38	-42.2	-42.6	-43.7	-42.7	-42.7
40	-42.7	-43.7	-42.7	-42.7	-42.7
42	-42.6	-43.1	-43.1	-42.8	-42.7
44	-42.3	-43.2	-43.1	-42.7	-42.7
46	-42.2	-43.1	-43.1	-42.7	-42.6
48	-42.7	-43.2	-43.6	-42.7	-42.8

TABLE 16(b) - HEAT FLUX FOR TRANSIENT TEST, SI UNITS

Time, hr	Measured Heat Flux, W/m^2			Calculated Heat Flux, W/m^2	
	q_w Calib. Hot Box	q_{hft} HFT @ Inside Surf.	q'_{hft} HFT @ Outside Surf.	q_{ss} Steady-State, Taped	q'_{ss} Steady-State, Embedded
0	-1	6	5	2	-2
1	0	6	-145	-49	-37
2	-2	4	-256	-104	-94
3	-10	-2	-263	-124	-121
4	-25	-13	-257	-131	-132
5	-39	-24	-246	-135	-136
6	-51	-35	-236	-136	-138
7	-62	-46	-224	-136	-139
8	-71	-55	-214	-137	-139
9	-80	-64	-207	-137	-139
10	-87	-73	-200	-137	-139
11	-94	-81	-192	-137	-139
12	-99	-87	-186	-137	-139
13	-103	-93	-180	-136	-138
14	-108	-99	-174	-136	-138
15	-112	-102	-169	-136	-137
16	-115	-107	-164	-136	-137
17	-118	-111	-161	-136	-137
18	-120	-113	-157	-136	-137
19	-123	-117	-156	-136	-136
20	-123	-119	-153	-135	-136
21	-124	-122	-149	-135	-136
22	-126	-124	-148	-135	-136
23	-128	-125	-146	-135	-136
24	-129	-128	-145	-135	-136
26	-131	-130	-142	-135	-135
28	-132	-131	-142	-135	-135
30	-132	-132	-139	-135	-135
32	-131	-133	-139	-135	-135
34	-132	-135	-138	-135	-135
36	-132	-135	-137	-135	-135
38	-133	-134	-138	-135	-135
40	-135	-138	-135	-135	-135
42	-134	-136	-136	-135	-135
44	-133	-136	-136	-135	-135
46	-133	-136	-136	-135	-134
48	-135	-136	-137	-135	-135

measurements, q'_{ss}, reaches the final steady-state heat flux at about the same time as steady-state heat flux calculated from taped thermocouple measurements, q_{ss}. Under transient test conditions, embedded and taped thermocouple measurements respond similarly to variations in outdoor air temperatures.

Table 17 lists time required to reach 99.5, 95, 90, and 63% of the final steady-state heat flux achieved during a transient test. Heat flux based on steady-state analysis calculated from both taped and embedded thermocouple temperature readings predicted 95% of the final heat flux would be reached after 4 hours. Calibrated hot box test results show that 95% of the final heat flux is reached after 23 hours. The amount of time required for Wall C6 to reach 95% of the final heat flux was 5.75 times greater than steady-state predictions. Similarly, the amount of time required for Wall C6 to reach 63% of the final heat flux was 5.0 times greater than steady-state predictions. Massive walls, such as Wall C6, "damp out" effects of a sudden change in outdoor air temperatures.

The calculated time constant for Wall C6 is 1.4 hr. 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 reach 63.2% of the new steady-state equilibrium heat flow after a time period equal to the time constant.(14)

The following equation for a homogeneous wall was used to calculate the time constant of Wall C6:(14)

$$t_c = \frac{r \cdot c \cdot d \cdot (x)^2}{(\pi)^2} \tag{4}$$

TABLE 17 - SUMMARY OF TRANSIENT TEST RESULTS

Heat Flux	Measured				Calculated			
	Calib. Hot Box		HFT @ Indoor Surf.		Steady-State, Taped		Steady-State, Embedded	
	q_w, Btu/hr·ft^2 (W/m^2)	Time to Reach q_w, hr	q_{hft}, Btu/hr·ft^2 (W/m^2)	Time to Reach q_{hft}, 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	-42.4 (-134)	39	-43.1 (-136)	39	-42.5 (-134)	5	-42.5 (-134)	5
95% of Final Heat Flux	-40.5 (-128)	23	-41.2 (-130)	26	-40.6 (-128)	4	-40.6 (-128)	4
90% of Final Heat Flux	-38.4 (-121)	19	-39.0 (-123)	22	-38.4 (-121)	3	-38.4 (-121)	3
63% of Final Heat Flux	-26.9 (-85)	10	-27.4 (-86)	12	-27.0 (-85)	2	-27.0 (-85)	2

where

t_c = characteristic time constant of Wall C6, hr (s)

r = resistivity of concrete, or reciprocal of conductivity of concrete, hr•ft•°F/Btu (m•K/W)

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

d = density of concrete, lb/ft^3 (kg/m^3)

x = thickness of concrete, ft (m)

Concrete density and wall thickness were 143 pcf (2290 kg/m^2) and 8.31 in. (211 mm), respectively. Specific heat of the air dry concrete, from Table 2, was 0.193 Btu/lb•°F (808 J/kg•K). Thermal conductivity of Wall C6 determined from calibrated hot box tests and embedded thermocouple measurements was 15.7 Btu•in./hr•ft^2•°F (2.26 W/m•K).

Details on the derivation, calculation, and significance of time constants are available in Reference 14.

SUMMARY AND CONCLUSIONS

This report presents results of an experimental investigation of heat transmission characteristics for a 143 pcf (2240 kg/m^3) normal weight concrete wall with taped and embedded thermocouples for measuring surface temperatures. The effects of surface temperature measurement technique on calibrated hot box test results were investigated. Tests were conducted under steady-state and dynamic temperature conditions.

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

1. Two steady-state tests with nominal temperature differentials of 44°F (24°C) and 72°F (40°C) were performed on Wall C6. Steady-state surface temperatures measured by embedded thermocouples were consistently between 5 and 6°F (2.8 and 3.3°C) closer to the wall mean

temperature than temperatures measured by taped thermocouples. Steady-state air-to-surface temperature differentials were 5 to 6°F (2.8 to 3.3°C) greater for embedded thermocouple measurements. Steady-state surface-to-surface temperature differentials were 10 to 12°F (5.6 to 6.7°C) less for embedded thermocouple measurements.

2. Thermal conductivities of Wall C6 concrete determined from steady-state calibrated hot box test results using embedded and taped thermocouples, respectively, were 15.7 and 10.7 Btu•in./hr•ft^2•°F (2.26 and 1.54 W/m•K). Conductivity based on taped thermocouple measurements was 32% less than that based on embedded thermocouple measurements. These values are consistent with conductivities measured during a previous test program.(9)

3. Total thermal resistance, R_T, of Wall C6 determined using embedded and taped thermocouples, respectively, were 1.38 and 1.63 hr•ft^2•°F/Btu (0.24 and 0.29 m^2•K/W). Values are for a mean wall temperature of 75°F (24°C) and include standard surface film resistances. Total thermal resistance based on taped thermocouple measurements was 15% greater than that based on embedded thermocouple measurements.

4. Measured surface resistances calculated from embedded surface thermocouple temperatures were about 0.13 hr•ft^2•°F/Btu (0.02 m^2•K/W) greater than values calculated from taped thermocouple measurements. This difference is the contact resistance between taped thermocouples and the normal weight concrete wall.

5. The total thermal contact resistance between taped thermocouples and the two surfaces of Wall C6 is 0.26 hr•ft^2•°F/Btu (0.02 m^2•K/W). This value is equal to 50% of the concrete resistance determined from embedded thermocouple measurements.

6. Embedded and taped thermocouples gave different surface temperature measurements for the NBS Dynamic Temperature Cycle applied to Wall C6. Differences in temperature measurements were a maximum of 6.6°F (3.0°C) for the outdoor wall surface and 0.9°F (0.4°C) for the indoor wall surface. The differences between embedded and taped thermocouple readings will affect some dynamic test results that utilize surface temperatures.

7. Based on results of the test program, it is recommended that thermocouples for measuring surface temperatures be embedded in surfaces of normal weight concrete walls to minimize the contact resistance between thermocouples and the wall surface.

8. For the NBS Test Cycle applied to Wall C6, heat flux predicted by steady-state calculations based on embedded thermocouple temperature measurements had an amplitude 4% smaller than steady-state heat flux based on taped thermocouple measurements.

9. Thermal lag, a dynamic thermal performance parameter, is not affected by surface temperature measurement technique. Average thermal lag measured by the calibrated hot box was 4 hours for the NBS Test Cycle applied to Wall C6.

10. Reduction in amplitude, a dynamic thermal performance parameter, is not significantly affected by surface temperature measurement technique. Average measured reductions in amplitude determined using embedded and taped thermocouple measurements were 47 and 49%, respectively.

11. Total heat flux calculated from measured wall temperatures for the NBS Test Cycle applied to Wall C6 are nearly identical for the two surface temperature measurement techniques. The ratio of measured

total heat flux to calculated total heat flux determined using embedded thermocouple measurements is 1% greater than that determined using taped thermocouple measurements.

12. Transient test results are similar for both surface temperature measurement techniques. The amount of time required for Wall C6 to reach 95% of the final heat flux was 6 times greater than that predicted by steady-state analysis using either taped or embedded thermocouple measurements.

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

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Construction and preparation of specimens were performed by Mr. E. A. Valko, Mr. P. P. Hordorwich and Mr. J. A. Chavez. Mr. D. C. Discher assisted with data reduction.

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 - CALIBRATED HOT BOX INSTRUMENTATION AND CALIBRATION

Calibrated hot box tests were performed according to ASTM Designation: C976, "Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box."[1]

Instrumentation

Instrumentation was designed to monitor temperatures inside and outside the indoor chamber, air and surface temperatures on both sides of the test wall, and heating energy input to the indoor chamber. Additional measurements monitor indoor chamber cooling system performance. Basically, the instrumentation provides a means of monitoring the energy required to maintain constant temperature in the indoor chamber while temperatures in the outdoor chamber are varied. This energy, when corrected for thermal losses, provides a measure of heat flow through the test wall.

Thermocouples corresponding to the American National Standard for Temperature Measurement Thermocouples (ANSI MC96.1) Type T, 20 gauge, were used to measure temperatures in the air space of each chamber. Thermocouples were uniformly distributed on a 20-3/5-in. (525-mm) square grid over the wall area. Thermocouples were located approximately 3 in. (75 mm) from the face of the test wall.

Thermocouples used to measure the specimen surface and internal temperatures are described in the "Test Specimen" section of this report.

Laboratory and interior surface temperatures of the indoor chamber sides were measured. These temperatures provided data for evaluating heat transfer between the chamber and the laboratory. Temperature data were supplemented with heat flux transducer measurements on chamber surfaces.

A digital humidity and temperature measurement system was used to measure relative humidity and temperature in air streams on each side of the test wall. Probes were located in the air streams approximately at the specimen mid-point.

A watt-hour transducer was used to measure cumulative electrical energy input to the indoor chamber.

Measurements were monitored with a programmable digital data acquisition system capable of sampling and recording up to 124 independent channels of data at preselected time intervals. The data acquisition system is interfaced with a microcomputer that is programmed to reduce and store data. Channels were scanned every two minutes. Average temperature and supplementary data were obtained from average readings for one hour. The cumulative watt-hour transducer output was scanned every hour.

Air flow rates in each chamber were measured with air flow meters located approximately at the wall geometric center. Each flow rate meter was mounted perpendicular to the air flow. Air flow is vertical on both sides of the specimen. Air velocity is uniform and averages 20 ft/min. (0.10 m/s). Data for air flow meters were monitored periodically and were not part of the automated data acquisition apparatus. Reference 2 gives more information on instrumentation of CTL's calibrated hot box.

Calibration Procedure

Heat flow through a test wall is determined from measurements of the amount of energy input to the indoor chamber to maintain a constant temperature. The measured energy input must be adjusted for heat losses. Figure A1 shows sources of heat losses and gains by the indoor chamber where:

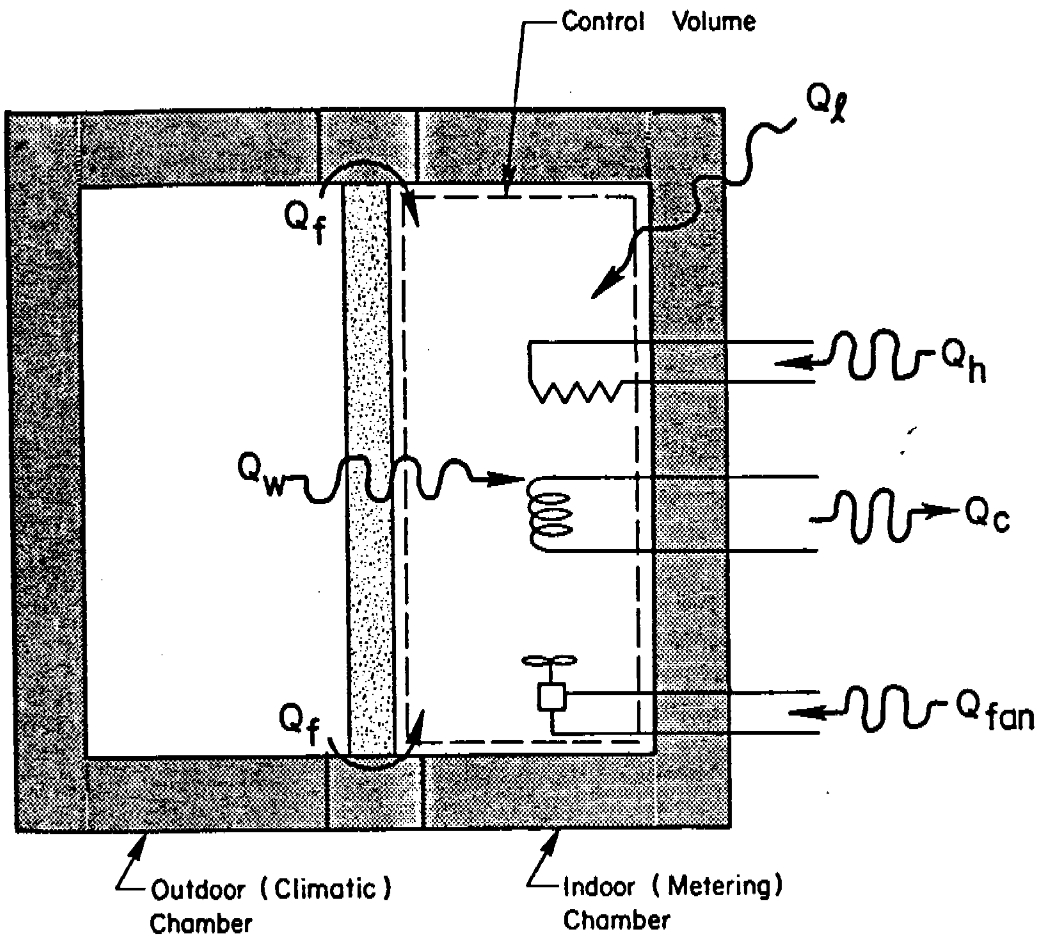

Fig. A1 Indoor (Metering) Chamber Energy Balance

Q_w = heat transfer through test wall

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. A1 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:

$$Q_w = Q_c - Q_h - Q_{fan} - Q_\ell - Q_f \qquad \text{(A1)}$$

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:

$$Q_w = A \cdot C \cdot (t_2 - t_1) \tag{A2}$$

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. (A1) 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:

$$Q_f = 0.802\ (t_2 - t_1) \quad \text{U.S. units} \qquad \text{(A3)}$$

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

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. (A1), 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.