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Heat Transfer Characteristics of A Low Density Concrete Wall

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HEAT TRANSFER CHARACTERISTICS OF A LOW DENSITY CONCRETE WALL

Report to

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Final Report

by

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Submitted by

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HEAT TRANSFER CHARACTERISTICS OF A LOW DENSITY CONCRETE WALL

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ABSTRACT

Tests were conducted to evaluate thermal performance of three concrete walls. A normal-weight concrete wall, a structural lightweight concrete wall, and a low density concrete wall were tested in the calibrated hot box facility of Construction Technology Laboratories, a division of the Portland Cement Association. This report covers experimental results for the low density concrete wall. Test results for the normal-weight and structural lightweight concrete walls are described in separate reports.

Each wall was subjected to steady-state, transient, and periodically varying temperature conditions in a calibrated hot box. Steady-state tests were used to define heat transmission coefficients. Data obtained during transient and periodic temperature variations were used to define dynamic thermal response of the wall. Thus, effects of heat storage capacity could be evaluated.

Conductivities derived from calibrated hot box tests were compared with results from hot plate and hot wire tests. Hot wire tests were also used to evaluate the influence of moisture on thermal conductivity. Data obtained from dynamic tests were compared with steady-state calculations.

Data obtained in this investigation are applicable to concrete wall assemblies in multi-family residential, commercial, and industrial structures. Results provide a data base for evaluation of building envelope performance in such structures, and are also applicable for defining thermal characteristics of concrete walls in passive solar systems.

HEAT TRANSFER CHARACTERISTICS OF A LOW DENSITY CONCRETE WALL

by

M. G. Van Geem and A. E. Fiorato*

INTRODUCTION

Tests were conducted to evaluate thermal performance of solid concrete walls under steady-state and dynamic temperature conditions. Steady-state tests were used to obtain average heat transmission coefficients including thermal conductivity, total thermal resistance (R_T), and thermal transmittance (U). Dynamic tests provided a measure of 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.(1-3)**

Objectives of the experimental investigation were to evaluate and compare thermal performance of three concrete walls. Wall C1 was constructed of normal-weight structural concrete, Wall C2 was constructed of structural lightweight concrete, and Wall C3 was constructed of low density concrete. This report describes experimental results of Wall C3. Tests of walls C1 and C2 are presented in separate reports.(4,5)

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

Also included in this report are data on thermal properties of control specimens cast from the same concrete used to cast Wall C3. Results are compared with test data for similar types of concrete.

Walls were tested in the calibrated hot box facility of Portland Cement Association's Construction Technology Laboratories (CTL).

TEST SPECIMEN

Wall C3 was a low density concrete wall with an average measured thickness of 8.52 in. (216 mm). The wall was cast horizontally and had overall nominal dimensions of 103x103 in. (2.62x2.62 m). All wall construction, including concrete mixing and casting, was done at CTL.

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

Mix designs for the three batches of concrete used to construct Wall C3 are given in Table 1. The nominal water-cement ratio varied from 0.68 to 0.84 for the three batches. Average fresh unit weight of the concrete was 56.1 pcf (899 kg/m^3). The unit weight of the third batch was significantly less than that of the first two batches. The increased amount of water relative to the amount of cement, and an increase in the amount of vinsol resin resulted in a lower unit weight.

TABLE 1 - WALL C3 CONCRETE MIX CHARACTERISTICS

Batch No.	Mix Proportions, lb/yd^3 (kg/m^3) Type I Cement	Perlite** (dry)	Water	Vinsol Resin,* ml/lb Cement	Fresh Concrete Nominal w/c	Unit Weight, pcf (kg/m^3)
1	784 (356)	268 (122)	534 (243)	3.4	0.68	59.0 (944)
2	779 (354)	268 (122)	576 (262)	5.0	0.74	60.4 (966)
3	650 (273)	207 (94)	503 (229)	5.8	0.84	48.8 (781)
Average	721 (328)	248 (113)	538 (245)	4.7	0.75	56.1 (899)

*Air-entraining admixture
**Unit weight of perlite was 8 pcf (130 kg/m^3).

Reinforcement consisted of a single layer of 6-mm diameter deformed bar reinforcement detailed as shown in Fig. 1. Reinforcing bars, spaced 12 in. (305 mm) center-to-center, were supported at a nominal height of 4 in. (102 mm) off the formwork base by concrete chairs. Chair supports, shown in Fig. 2, were constructed using the same concrete mix used for construction of Wall C3. Concrete rather than steel or plastic chairs were used since precise measurement of wall thermal properties required the elimination of possible thermal bridges.

Threaded coil inserts were cast into the wall at midthickness to aid in transporting the specimen after concrete had attained sufficient strength. Inserts are shown projecting through the side formwork in the upper part of Fig. 2.

Thermocouple wires were cast into the concrete wall at the same level as the reinforcing bars. Thermocouple leads penetrated the formwork edge, as shown in Fig. 3. A more detailed discussion of thermocouple placement and instrumentation is included in the subsection entitled, "Instrumentation" of the "Calibrated Hot Box Test Facility," section of this report.

Three batches of concrete for Wall C3 were prepared using the equipment shown in Fig. 4. Cement and perlite were added to the cone-shaped hopper shown on the right side of Fig. 4. These dry materials were transported mechanically (screw drive) to the mixer above the pump reservoir. Water and the air-entraining admixture were added to the mixer until the desired mix design was obtained. Concrete was then pumped from the mixer reservoir to the formwork through pump hose, as shown in

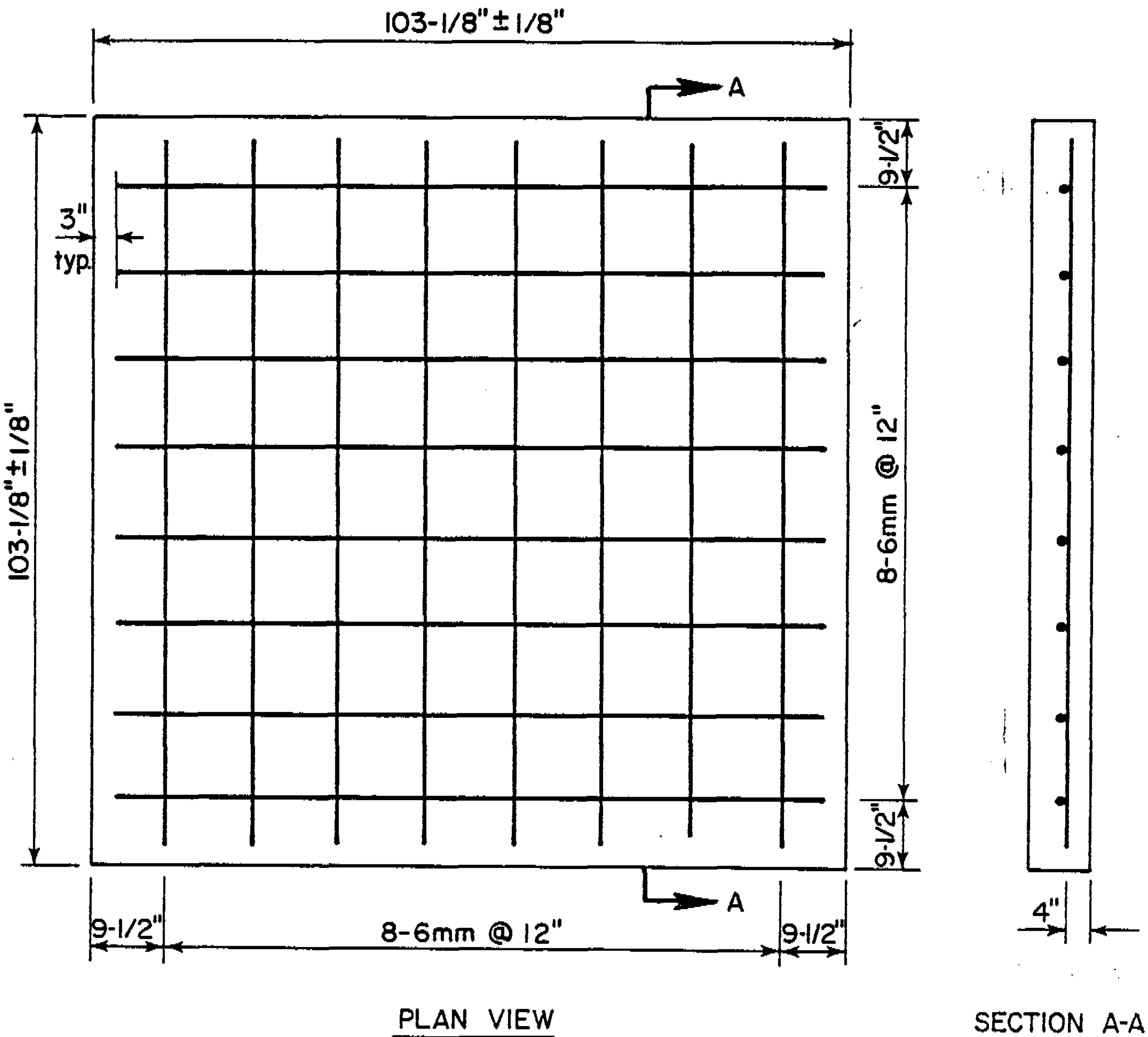


Fig. 1 Reinforcement Details for Low Density Concrete Wall C3

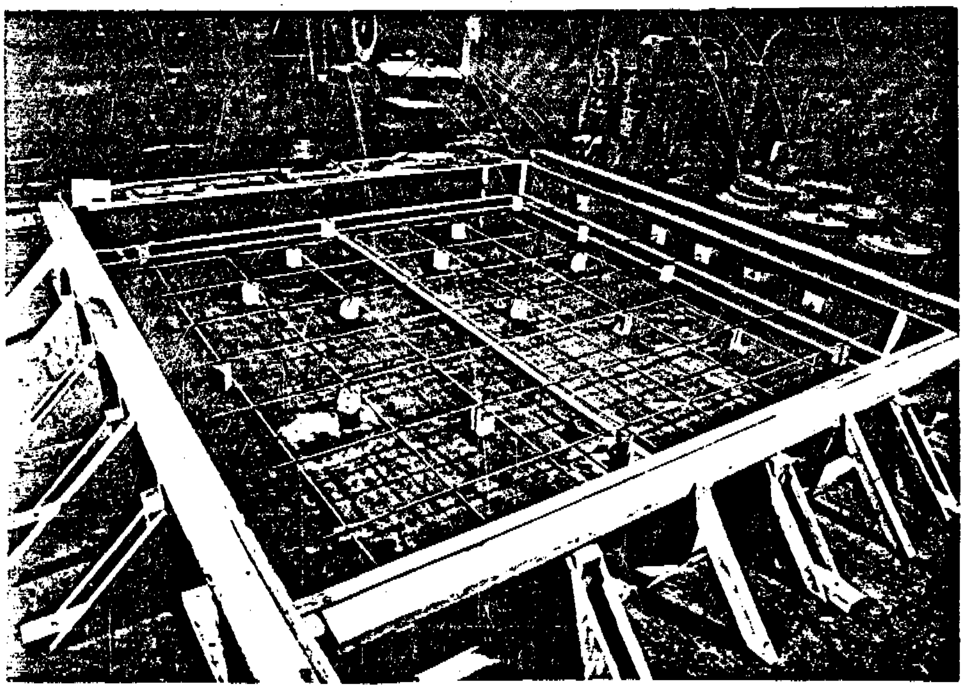


Fig. 2 Formwork and Reinforcement for Wall C3

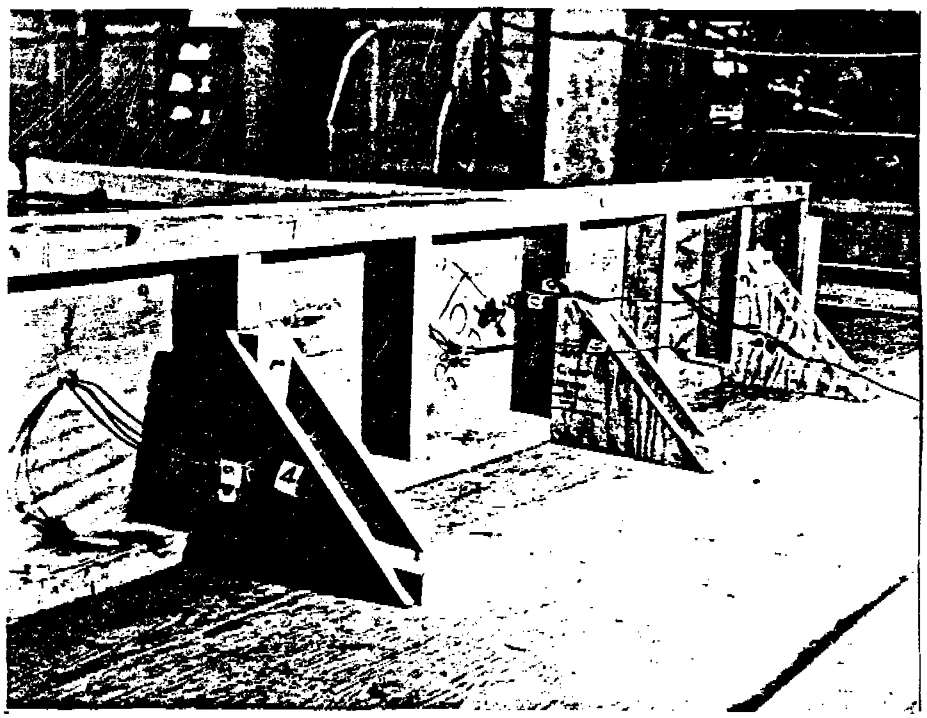


Fig. 3 Thermocouple Wire Leads

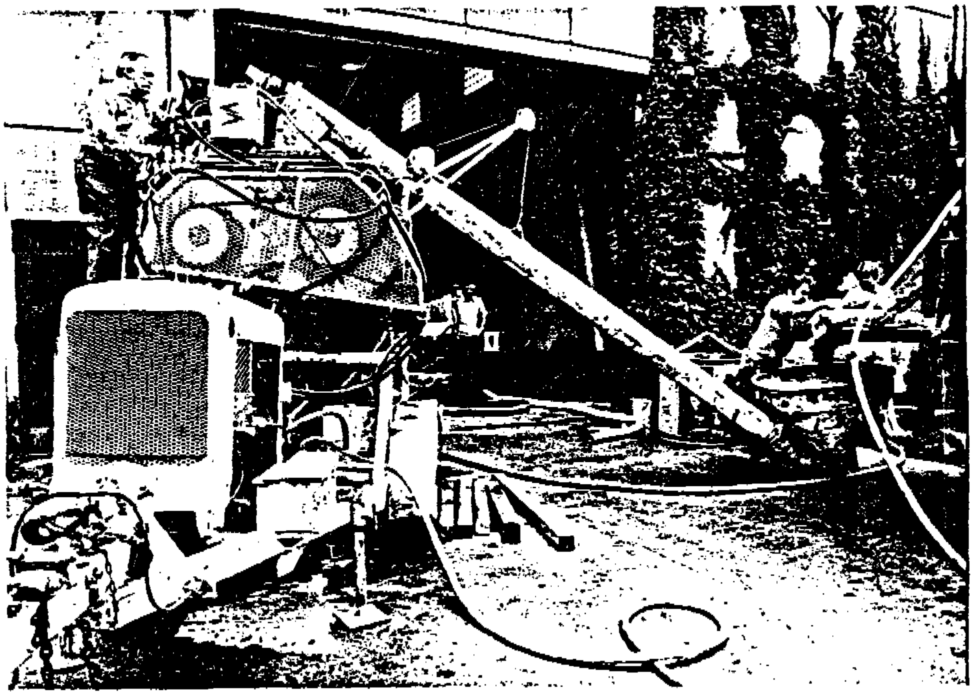


Fig. 4 Mixing and Pumping Equipment for Wall C3 Concrete

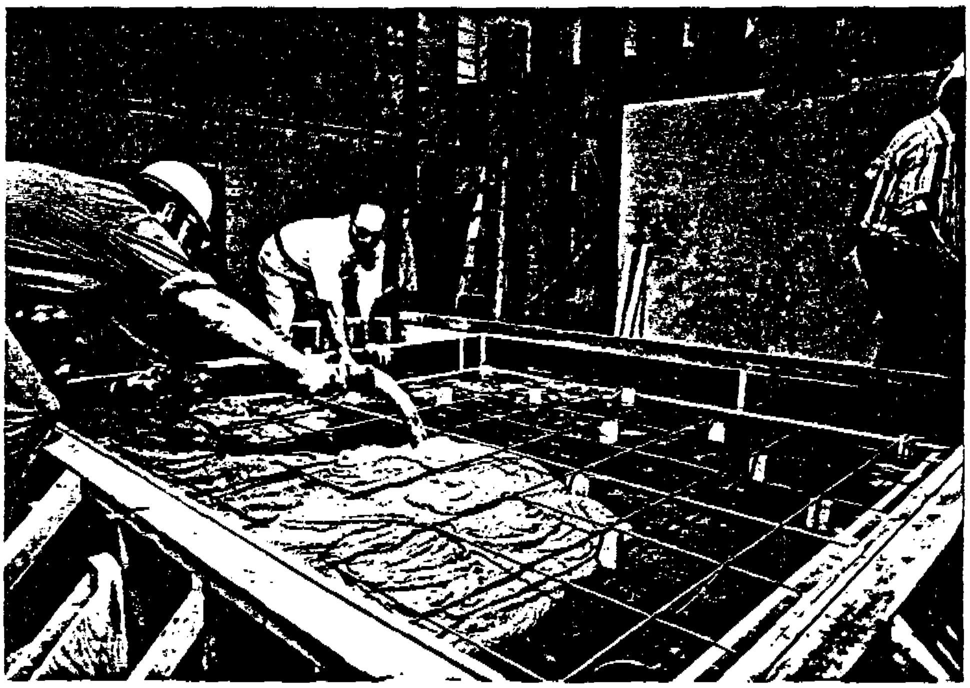


Fig. 5 Pumping Low Density Concrete into Formwork of Wall C3

Fig. 5. Generally, the fluid low density concrete was placed starting at one side of the form, and continuing to the opposite side. After the formwork was filled, the top surface of the concrete was screeded. Figure 6 shows the screeded surface of Wall C3. Plastic sheets were used to cover the surface of the wall for curing.

Wall C3 was allowed to cure in the formwork for 14 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% relative humidity (RH) for six months prior to testing.

Prior to testing, shrinkage cracks became visible on both sides of Wall C3. Cracks on the indoor and outdoor sides of the wall are shown in Figs. 7(a) and 7(b), respectively. To photograph the cracks, they were highlighted with a felt tip pen. This tends to make the crack widths look larger. An example of actual crack size compared to the marker and a ruler is shown in Fig. 8.

Faces of Wall C3 were coated with a cementitious waterproofing material that seals minor surface imperfections, including observed shrinkage cracks. A textured, noncementitious white paint was used as a finish coat. These coatings provided a uniform surface for both wall faces. Wall edges were left uncoated.

At the time Wall C3 was cast, control specimens were also cast for measurement of selected physical and thermal properties. Control specimens were taken, as detailed in Table 2,

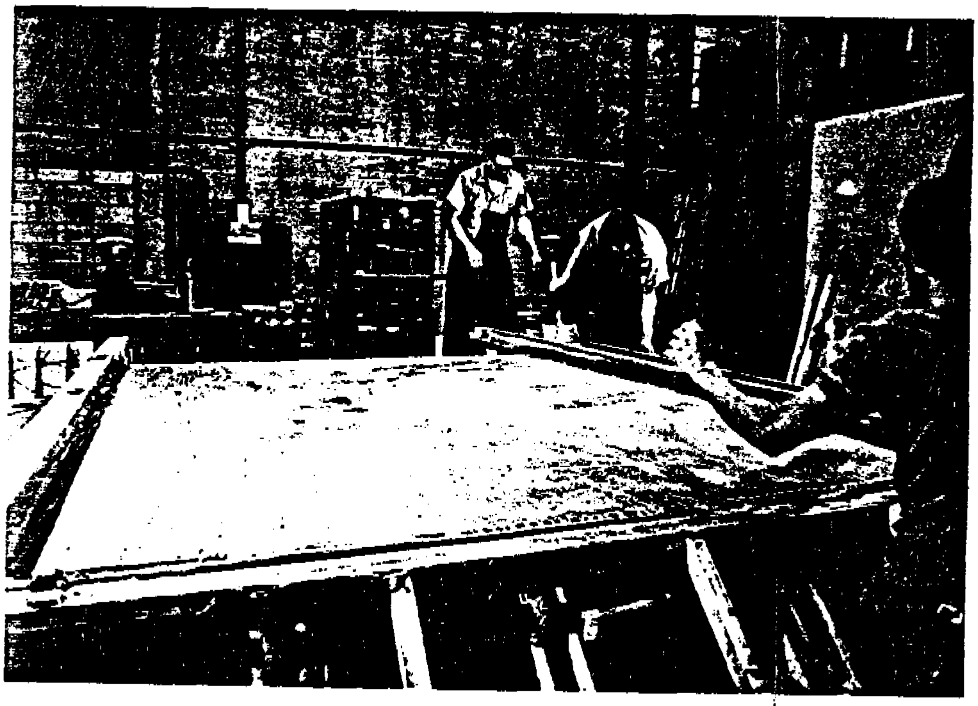
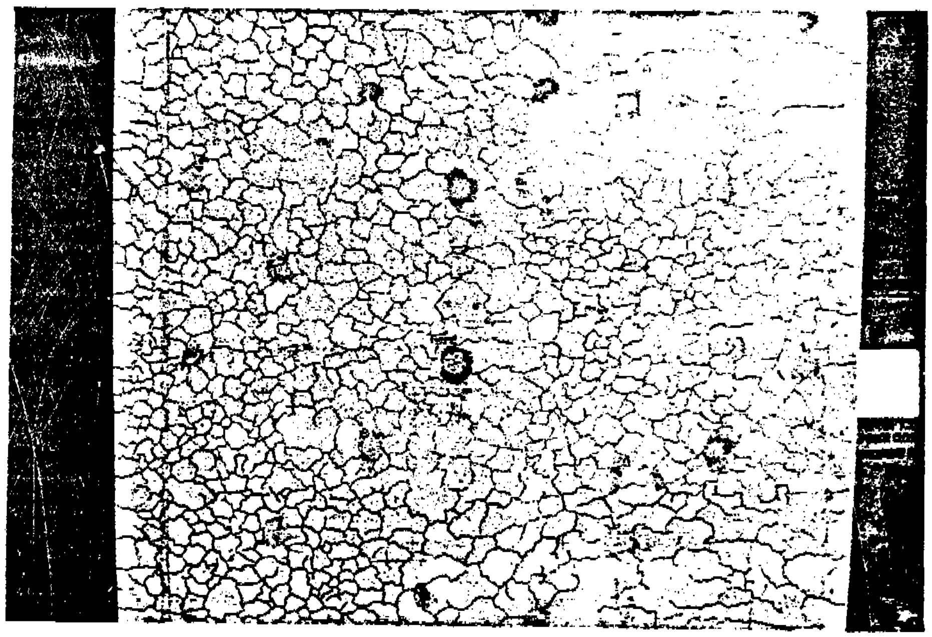
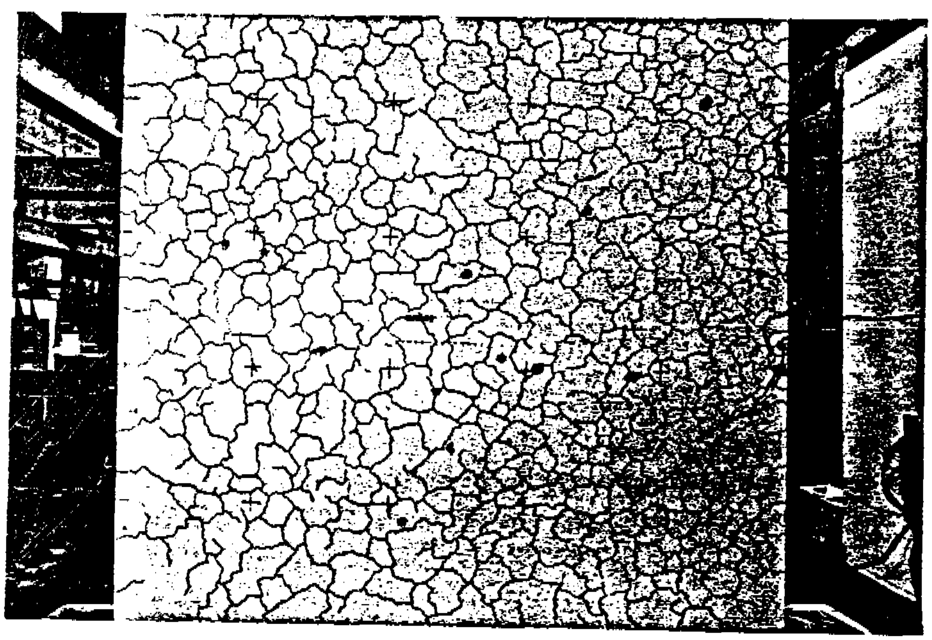


Fig. 6 Screeded Surface of Wall C3



(a) Indoor Surface of Wall



(b) Outdoor Surface of Wall

Fig. 7 Shrinkage Cracks on Surfaces of Wall C3 (Cracks have been highlighted with felt tip marking pen)

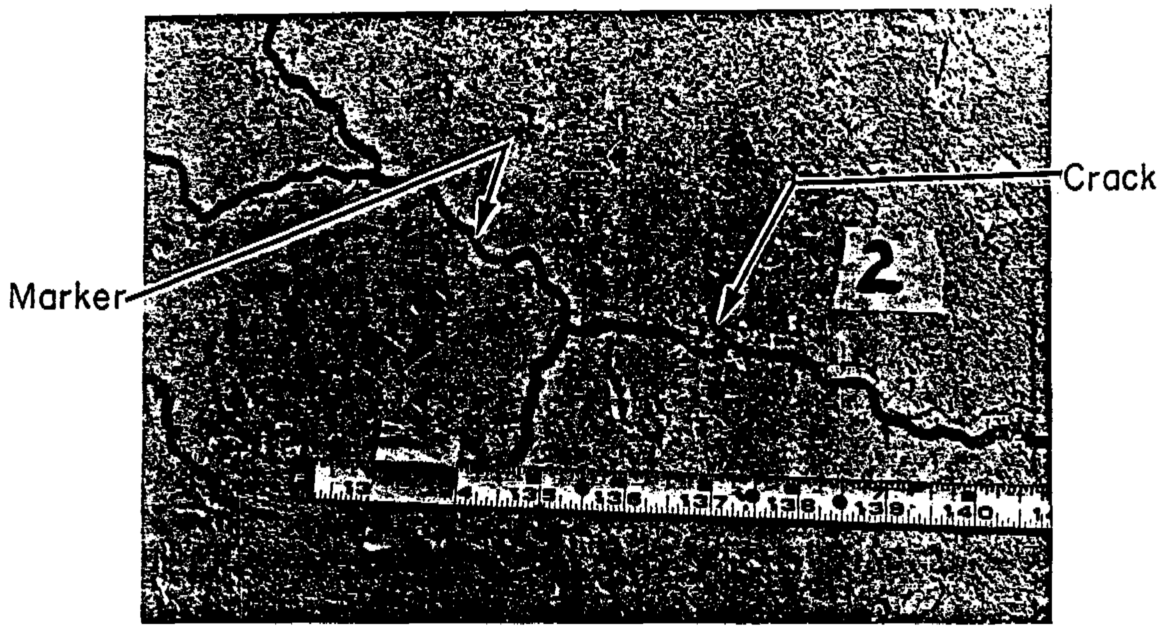


Fig. 8 Actual Crack Size

TABLE 2 - SPECIMENS FOR MEASUREMENT OF SELECTED THERMAL AND PHYSICAL PROPERTIES OF WALL C3

Concrete Batch No.	6x12-in. (152x305-mm) Cylinders			4x4x8-in. (102x102x203-mm) Prisms for Thermal Conductivity by Hot Wire Method	16x16x2-in. (406x406x51-mm) Prisms for Thermal Conductivity by Hot Plate Method	3x6-in. (76x152-mm) Cylinders for Specific Heat Tests
	Compressive Strength Tests	Splitting Tensile Strength Tests	Thermal Diffusivity Tests			
1 and 2*	8	3	6	6	2	10
3	2	3	0	0	2	0
Total	10	6	6	6	4	10

*Totals for both batches.

from each of the three batches required to cast Wall C3. Specimens were cast in individual molds.

PHYSICAL PROPERTIES OF CONCRETE

Unit weight, moisture content, compressive strength, and tensile splitting strength of 6x12-in. (152x305-mm) cylinders were determined. Unit weight of Wall C3 was also determined by measuring total weight of the wall. Physical properties are summarized in Table 3.

Unit Weight

Weights of Wall C3 and seven 6x12-in. (152x305-mm) cylinders were determined periodically while the specimens were air drying. The volume of Wall C3 was determined from average measured dimensions of each side and average wall thickness. Volume of each cylinder was calculated from measured cylinder dimensions. Unit weights then were calculated from measured weights and volumes.

Unit weights for Wall C3 and the 6x12-in. (152x305-mm) cylinders are summarized in Table 4 and Fig. 9. Unit weights decreased with time for the first three months and then remained fairly constant. The reduction in unit weight is due to evaporation of free water.

Equilibrium water contents are generally attained when the concrete is in equilibrium with air on all sides, and undergoes no further change in weight. Concrete is generally considered normally dry when the free water in the concrete has attained an equilibirum after an extended period of drying at 35 to 50%

TABLE 3 - PHYSICAL PROPERTIES OF WALL C3

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 (6.855)
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)

*Cured in molds for first 24 hours, then moist cured for 27 days.
**Cured in molds for first 14 days, then air cured for 204 days.

TABLE 4 - UNIT WEIGHT OF WALL AND CONTROL SPECIMENS

Age, days	Wall C3, pcf (kg/m^3)	Average for Seven Cylinders,** pcf (kg/m^3)
0	56.1 (899)	56.1 (899)
14	51.7 (828)	56.8 (910)
28	49.9* (799)	52.2 (836)
56	48.4 (775)	50.6 (811)
92	45.3 (726)	48.6 (779)
183	45.5 (729)	47.1 (755)
218	--	46.9 (751)

*Unit weight of Wall C3 at 29 days
**Three of the seven cylinders were cast from batch No. 3.

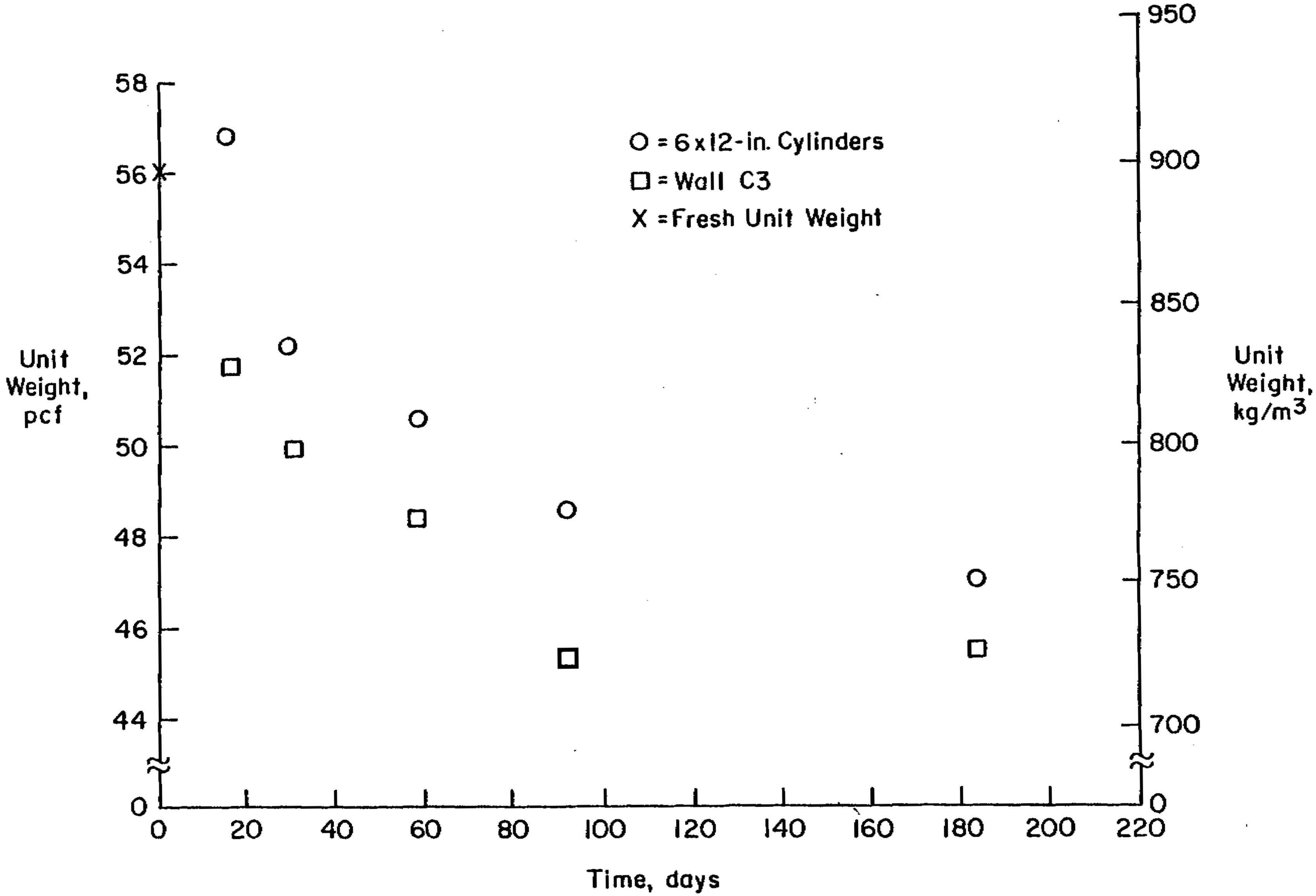


Fig. 9 Unit Weight of Wall C3 and Control Cylinders as a Function of Time

relative humidity.[6] For this report it is assumed that the concrete of Wall C3 was normally dry after six months of air curing. Using this assumption, the unit weight of Wall C3 in the normally dry state is taken to be 46 pcf (740 kg/m^3). Average unit weight of seven cylinders in the normally dry state is 47 pcf (750 kg/m^3).

Moisture Content

Average moisture content of Wall C3 at the time of calibrated hot box tests was determined from air dry unit weight of the wall and average ovendry unit weight of ten control specimens. Air dry unit weight of Wall C3 at the time of calibrated hot box tests was 46 pcf (740 kg/m^3). From the time of casting to the time of calibrated hot box tests, the unit weight of Wall C3 decreased by 11 pcf (180 kg/m^3).

Unit weight of the seven 6x12-in. (152x305-mm) cylinders listed in Table 4 had decreased by approximately 7 pcf (110 kg/m^3) 78 days after casting. As shown in Table 5, ovendrying three 4x4x8-in. (102x102x203-mm) prisms reduced their unit weight by 8 pcf (130 kg/m^3) from the unit weight found 78 days after casting. Therefore, the difference between the fresh and ovendry unit weights of the control specimens was approximately 15 pcf (240 kg/m^3). Assuming the unit weight of Wall C3 would have been 15 pcf (240 kg/m^3) less than the fresh unit weight had the wall been ovendried, and the unit weight of Wall C3 decreased by 11 pcf (180 kg/m^3) from the time of casting to the time of tests, 4 pcf (60 kg/m^3) of water remained in the

TABLE 5 - OVENDRY UNIT WEIGHTS OF CONTROL SPECIMENS FOR WALL C3*

Curing Conditions	Age at Time of Weight Measurement, days	Specimen No.**	Unit Weight, pcf (kg/m^3)
14 days in Mold; 64 days Air Dry 73°F (23°C) 45% RH	78	2H	58.3 (934)
		6H	58.6 (939)
		10H	51.2 (820)
		Average	56.0 (897)
14 days in Mold; 142 days Air Dry 73°F (23°C) 45% RH; Ovendry	156	2H	49.8 (797)
		6H	49.5 (793)
		10H	43.9 (704)
		Average	47.7 (765)

*4x4x8-in. (102x102x203-mm) prisms.
**All specimens cast from batch No. 1 or No. 2.

wall during calibrated hot box tests. Therefore, average moisture content relative to ovendry weight of Wall C3 was estimated to be 9.5% at the time of test.

Compressive Strength

Compressive strength of 6x12-in. (152x305-mm) concrete cylinders was determined in accordance with ASTM Designation: C39 "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens."[7] Two sets of data were obtained as follows:

1. Twenty-eight-day compressive strengths of five cylinders cured for 24 hours in molds, and then moist cured at 73±3°F (23±1.7°C) and 100% RH the remaining 27 days
2. Two hundred eighteen-day compressive strengths of four cylinders cured in molds for 14 days, and then air cured at 73±5°F (23±3°C) and 45±15% RH until Wall C3 was midway through thermal tests

Table 6 summarizes compressive strength results for moist cured 6x12-in. (152x305-mm) cylinders and air cured 6x12-in. (152x305-mm) cylinders. Because concrete in batch No. 3 differed significantly in unit weight from batch Nos. 1 and 2, average strength values should be interpreted with care.

Splitting Tensile Strength

Splitting tensile strength of 6x12-in. (152x305-mm) concrete cylinders was determined in accordance with ASTM Designation: C496, "Standard Test Method for Splitting Tensile Strength of

TABLE 6 - COMPRESSIVE STRENGTH OF CONTROL CYLINDERS FOR WALL C3

Specimen No.	Moist Cured*		Specimen No.	Air Cured**	
	Unit Weight, pcf (kg/m^3)	Compressive Strength, psi (MPa)		Unit Weight, pcf (kg/m^3)	Compressive Strength, psi (MPa)
1A	63.6 (1019)	800 (5500)	4B	51.9 (831)	1040 (7200)
3A	62.0 (993)	710 (4900)	6B	53.0 (849)	1070 (7400)
5A	64.7 (1036)	990 (6800)	8B	51.7 (828)	1010 (7000)
7A	65.1 (1043)	910 (6300)	10B+	38.7 (620)	390 (2700)
9A+	52.1 (835)	350 (2400)			
Average	61.5 (985)	750 (5200)	Average	48.8 (782)	880 (6100)

*Cured in molds for first 24 hours, moist cured for 27 days
**Cured in molds for first 14 days, air cured for 204 days
+These specimens cast from batch No. 3. All other specimens cast from batch No. 1 or 2.

Cylindrical Concrete Specimens."[7] Two sets of data were obtained as follows:

1. Twenty-eight-day splitting tensile strengths of three cylinders cured for 24 hours in molds, and then moist cured at 73±3°F (23±1.7°C) and 100% RH the remaining 27 days
2. Splitting tensile strengths of cylinders cured in molds for 14 days, and then cured at 73±5°F (23±3°C) and 45±15% RH until Wall C3 was midway through thermal tests

Table 7 summarizes splitting tensile strength results for moist cured and air cured 6x12-in. (152x305-mm) cylinders. Because concrete in batch No. 3 differed significantly in unit weight from batch Nos. 1 and 2, average strength values should be interpreted with care.

CALIBRATED HOT BOX TEST FACILITY

Tests were conducted in the calibrated hot box facility shown in Fig. 10. This facility was developed to permit realistic evaluation of thermal performance of large wall assemblies under steady-state or dynamic temperature conditions. Tests were performed in accordance with ASTM Designation: C976, "Standard Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box."[7]

Description

The following is a brief description of the calibrated hot box. Details are available in Reference 8.

TABLE 7 - SPLITTING TENSILE STRENGTH OF CONTROL CYLINDERS FOR WALL C3

Specimen No.	Moist Cured*		Specimen No.	Air Cured**	
	Unit Weight, pcf (kg/m^3)	Splitting Tensile Strength, psi (MPa)		Unit Weight, pcf (kg/m^3)	Splitting Tensile Strength, psi (MPa)
1C+	54.6 (875)	88 (610)	2D+	42.0 (673)	37 (260)
4C	65.3 (1046)	150 (1030)	6D	53.4 (855)	118 (810)
8C	65.3 (1046)	175 (1210)	10D+	37.4 (599)	33 (230)
Average	61.7 (988)	138 (950)	Average	44.3 (710)	63 (430)

*Cured in molds for first 24 hours, moist cured for 27 days
**Cured in molds for first 7 days, air cured for 184 days
+These specimens cast from batch No. 3. All other specimens cast from batch No. 1 or 2.

Fig. 10 - Calibrated Hot Box Test Facility

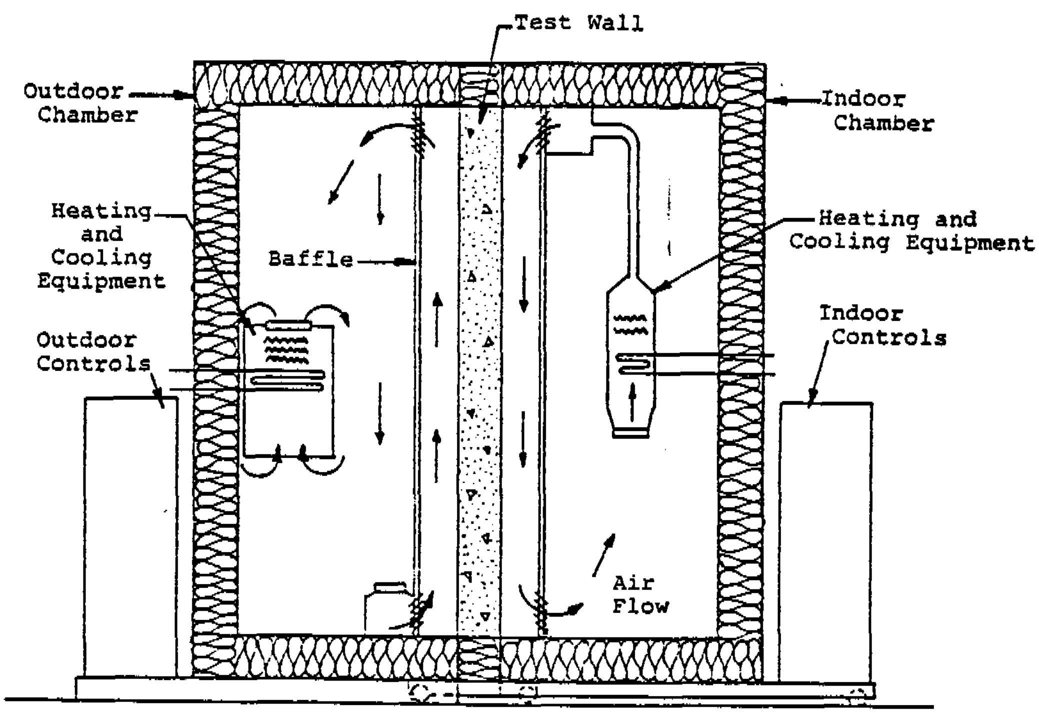


Fig. 11 - Schematic of Calibrated Hot Box

The facility consists of two highly insulated chambers as shown in Fig. 11. Walls, ceiling, and floors of each chamber were insulated with foamed urethane sheets to obtain a final thickness of 12 in. (305 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 chamber can be held at a constant temperature or cycled between -15 and 130°F (-26 and 54°C). Temperature cycles can be programmed to obtain the desired time-temperature relationship. The indoor chamber, which simulates an indoor environment, can be maintained at a constant room temperature between 65 and 80°F (18 and 27°C).

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 $3.52°K \cdot m^2/W$).

Instrumentation

Instrumentation was designed to monitor temperatures inside and outside of the chambers, air and surface temperatures on both sides of the test wall, interior temperatures within the test wall, laboratory air temperature, and heating energy input to the indoor chamber. Supplementary measurements monitor indoor cooling system performance as well as heat flux at selected locations on the specimen and chamber surfaces. 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 ASTM Designation: E230, "Standard Temperature-Electromotive Force (EMF) Tables for Thermocouples,"[7] 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 approximate midthickness of the test wall. Thermocouples were uniformly distributed on a 20-in. (508 mm) square grid over the wall area. Supplementary thermocouples were used to measure surface temperatures at selected locations.

Surface thermocouples were securely attached to the wall over a length of approximately 3 in. (76 mm). Tape that covered the sensors was painted the same color as the test wall surface. Thermocouples in air were located approximately 3 in. (76 mm) from the face of the test wall.

Internal thermocouples were cast 4 in. (102 mm) from the formwork base. To secure their location, thermocouples were taped to reinforcement or suspended by wire between reinforcement. To avoid any influence on internal heat flow through reinforcement, the thermocouple junction was not placed in contact with the reinforcement. Thermocouples were wired such that an electrical average of four thermocouple junctions, located along a horizontal line across the grid, was obtained. Thermocouple leads were then routed through side formwork, as shown in Fig. 3.

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

Heat flux transducers were also mounted on the wall specimen. To do this, 3/8-in. (10-mm) holes were drilled into Wall C3 at selected mounting locations. Wood dowels 3/8-in. (10-mm) in diameter were epoxied in place and sanded flush with the wall surface as shown in Fig. 12. The heat flux transducer surface in contact with the wall surface was coated with a thin layer of high conductivity silicon grease. Each heat flux transducer was then mounted on Wall C3 using screws into the wood dowels. Silicon grease provided uniform contact between the heat flux transducer and wall surface. Figure 13 shows a mounted heat flux transducer.

A watt-hour transducer was used to measure cumulative electrical energy input to the indoor chamber. The transducer is calibrated within a specified accuracy of $\pm 0.1\%$ of the measured reading, or approximately 2 watts.

A digital humidity and temperature measurement system was used to measure relative humidity and temperature in air streams on each side of the test specimen. Probes were located in the air streams approximately at the specimen mid-point. The relative humidity sensor is calibrated to within a specified accuracy of $\pm 4\%$.

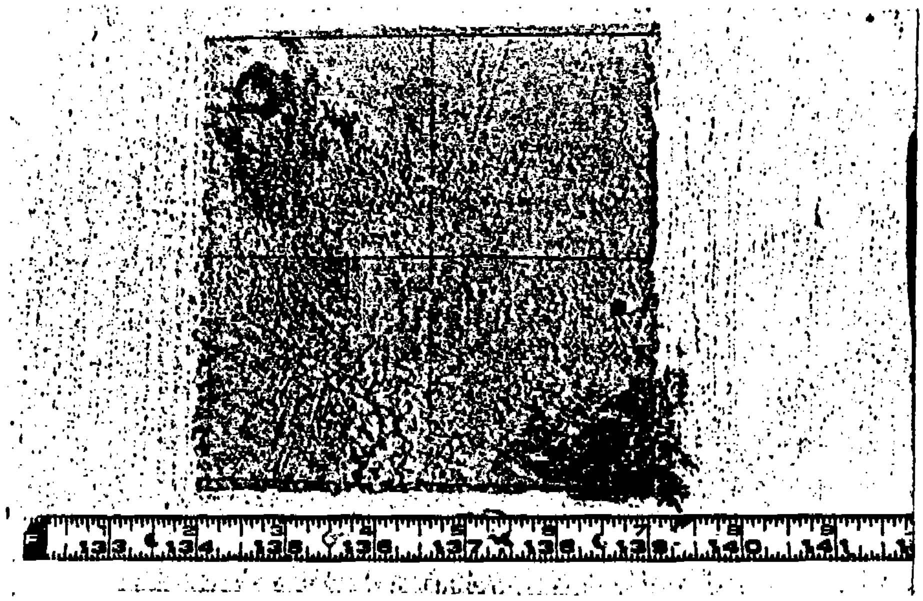


Fig. 12 Wood Dowels Epoxied in Concrete Wall for Heat Flux Transducer Mounting

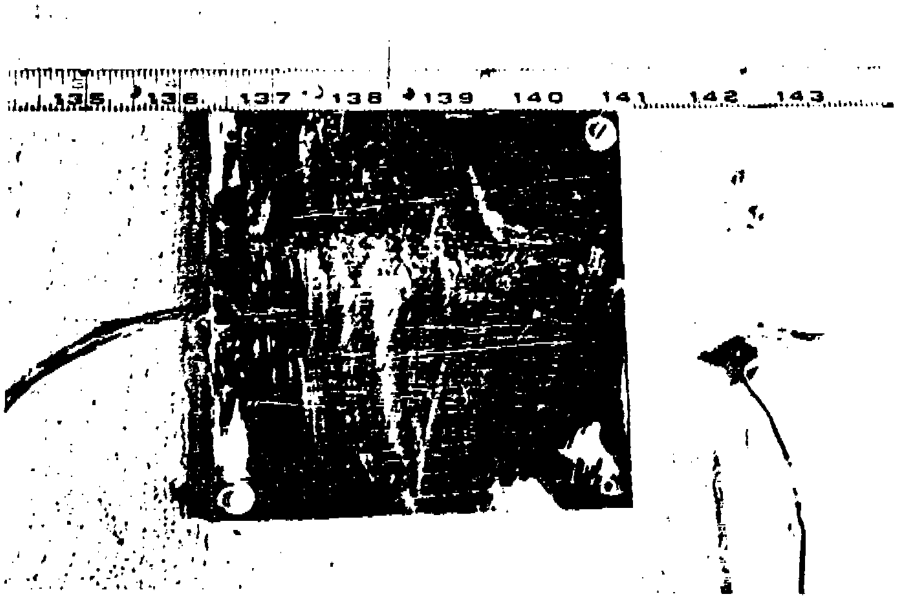


Fig. 13 Heat Flux Transducer Mounted on Wall

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. Data for air flow meters were monitored periodically and were not part of the automated data acquisition apparatus.

All measurements, with the exception of air flow rates, 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.

For tests described in this report, thermocouple channels were scanned every two minutes. Average temperature, humidity, and heat flux data were obtained from the 30 readings per hour. The cumulative watt-hour transducer output was scanned every hour.

<u>Calibration Procedure</u>

The following is a brief description of the calibration procedure used for determining heat flow through the test wall. Details are available in Ref. 9.

Heat flow through a test wall is determined from measurements of the amount of energy input to the indoor chamber required to maintain a constant temperature. The measured energy input must be adjusted for heat losses. Figure 14 shows sources of heat losses and gains by the indoor chamber where:

Q_W = heat transfer through test wall

Q_C = heat removed by indoor chamber cooling

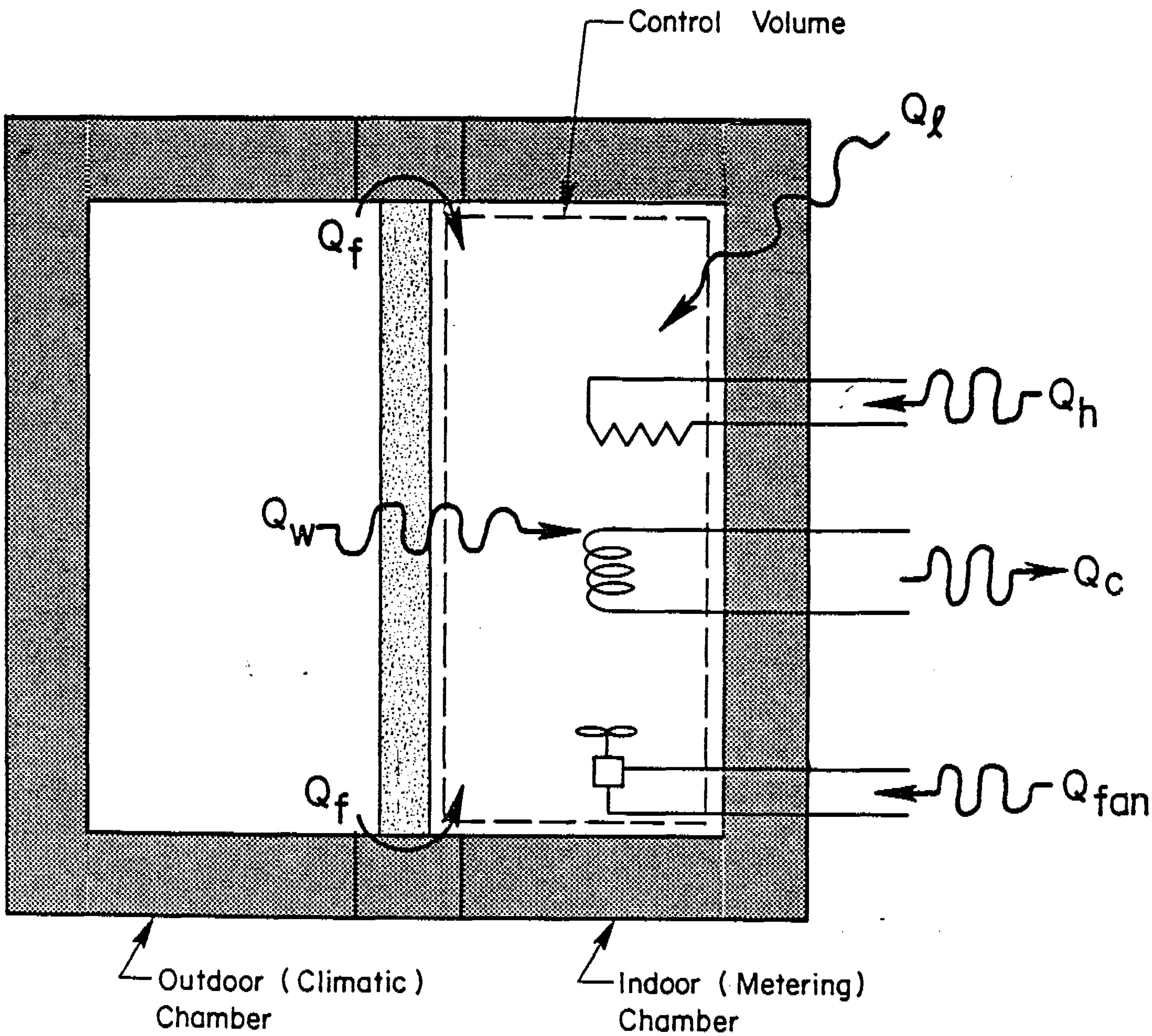


Fig. 14 Indoor (Metering) Chamber Energy Balance

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

Since net energy into the control volume shown in Fig. 14 equals zero, heat transfer through the test wall can be expressed by the following energy balance equation:

$$Q_w = Q_c - Q_h - Q_{fan} - Q_\ell - Q_f \tag{1}$$

The terms Q_h and Q_{fan} are measured by a watt-hour transducer. Heat flux transducers are used to check calculations of Q_ℓ. Steady-state calibrated hot box tests of two "standard" calibration specimens are used to refine calculations of Q_c and to determine Q_f.

The first calibration specimen, S1, has a relatively low thermal resistance of 5.7 hr·ft^2·°F/Btu (1.0 m^2·°K/W). It consists of 1-3/8-in. (34.9-mm) thick fiberglass and was specially fabricated to insure uniformity.

The second calibration wall, S2, has a relatively high thermal resistance of 17.3 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.

Indoor Chamber Cooling

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.

Heat removed by indoor chamber cooling is calculated assuming an ideal basic vapor compression refrigeration cycle. Adjustments are made to compensate for inefficiencies in the actual refrigeration cycle.

For the ideal basic vapor compression cycle, the rate of heat transfer between the cooling coils and the indoor chamber is:[10]

$$Q'_c = (h_2 - h_1)m \tag{2}$$

where:

Q'_c = rate of heat transfer from cooling coils

m = mass flow rate of refrigerant

h_1 = enthalpy of refrigerant leaving cooling coils

h_2 = enthalpy of refrigerant entering expansion valve

Refrigerant flow rate, m, is measured with a flow meter. Enthalpy leaving coils, h_1, is calculated from measured temperature and pressure of refrigerant at a point down line from the cooling coils. Refrigerant at this location is assumed to be a superheated vapor. Enthalpy entering expansion valve, h_2, is calculated from the measured temperature of refrigerant entering the expansion valve. Refrigerant at this location is assumed to be a saturated liquid.

Deviation from the ideal vapor cycle may result from a combination of heat transfer through finite temperature differences, irreversible adiabatic compression, and pressure losses in the evaporator and condenser.[10] In addition, refrigerant entering the expansion valve may not be saturated liquid.

Adjustments made to compensate for inefficiencies in the actual cycle are based on steady-state calibrated hot box test results for the two "standard" calibration specimens. Results indicate that inefficiencies are linearly related to refrigerant flow rate and the air temperature of the indoor chamber. For Wall C3 a reference efficiency was established based on particular values of refrigerant flow rate and the indoor chamber air temperature. The heat removed from indoor chamber cooling, Q_c, was determined from values of Q_c' adjusted to consider changes in efficiencies from the reference values.

Laboratory Losses

Heat losses or gains from the laboratory to the indoor chamber, Q_ℓ, are calculated based on 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. Two heat flux transducers mounted on the inside surface of the indoor chamber are used as a check on calculated laboratory losses. One heat flux transducer is mounted on the ceiling and one is mounted on a wall.

For steady-state and dynamic tests performed on Wall C3, the indoor chamber air and laboratory air temperatures were 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.

Flanking Losses

Heat loss or gain from flanking around the test specimen, Q_f, is determined from steady-state tests of standard calibration walls. The flanking loss Q_f can be determined from Eq. (1) when all other terms in the equation are known. 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:

$$Q_w = \frac{A \cdot C \cdot (t_2 - t_1)}{3.413} \tag{3}$$

where:

Q_w = heat transfer through test wall, W·hr/hr

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

C = average thermal conductance, Btu/hr·ft^2·°F

t_2 = average temperature of outside wall surface, °F

t_1 = average temperature of inside wall surface, °F

3.413 = conversion factor from W·hr/hr to Btu/hr

Thus, Q_f can be determined from Eq. (1) 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 relationship:

$$Q_f = 0.235\ (t_2 - t_1) \tag{4}$$

where:

Q_f = heat loss or gain from flanking around test specimen, W·hr/hr

t_2 = average temperature of outside wall surface, °F

t_1 = average temperature of inside wall surface, °F

Since Q_f is the residual from Eq. (1), it may include other undetermined losses from the indoor chamber.[9]

THERMAL PROPERTIES OF CONCRETE UNDER STEADY-STATE CONDITIONS

Thermal conductivity and thermal transmittance of Wall C3 were derived from steady-state tests using the calibrated hot box. Specific heat, thermal conductivity, and thermal diffusivity were also obtained from tests performed on control specimens.

Specific Heat

Specific heats of concrete control specimens and constituent aggregates were measured using a method similar to U.S. Army Corps of Engineers Specification CRD-C124-73, "Method of Test for Specific Heat of Aggregates, Concrete, and Other Materials (Method of Mixtures)."[11] The concrete test sample was selected from pulverized parts of five 3x6-in. (76x152-mm) cylinders cured one day in molds, and then 27 days at 73±3°F (23±1.7°C) and 100% RH.

Test Method

The method used determines the specific heat of saturated materials. Crushed samples of low density concrete were boiled to ensure the material was saturated. The sample was boiled for four hours, submerged in water for 16 hours, and boiled again for 2-1/2 hours. The material was then cooled under running water and submerged in room temperature water for 2 hours.

To determine specific heat, the sample was heated in a warm bath at 115±1°F (46.1±0.6°C) and then transferred to a calorimeter containing room temperature water. After acquiring necessary data, the material was then cooled in water at 35°F (2°C) and again transferred to the calorimeter. The specific heat was found by measuring the temperature change of the water in the calorimeter.

To calculate specific heat of the material in a dry state, weights of the material in the particular dry state, and the saturated surface dry (SSD)* state must be known. Whiting, Litvin, and Goodwin(12) used the following equation to calculate specific heat of concrete for various moisture conditions:

$$c = \frac{c_{SSD} + \gamma(y-1)}{1 + \gamma(y-1)} \qquad (5)$$

where:

c = specific heat of samples at any moisture content

c_{SSD} = specific heat of saturated surface dry samples

y = moisture content expressed as a fraction of the SSD moisture content

γ = SSD moisture content

*A SSD material is a saturated material with surface water removed.

$$\gamma = \frac{W_{SSD} - W_{OD}}{W_{SSD}} \tag{6}$$

where:

W_{SSD} = SSD weight of sample

W_{OD} = ovendry weight of sample

Results

Specific heats for Wall C3 concrete are compared with previous perlite concrete test results(13) in Table 8. Values are for low density concrete in saturated surface dry, air dry, and ovendry conditions. Specific heats in the air dry and ovendry conditions were calculated using Eqs. (5) and (6).

Unit weight of ovendry perlite concrete from the previous test would be less than 29 pcf (460 kg/m^3), the unit weight of the same concrete in the air dry condition. Therefore, the unit weight of the ovendry concrete from the previous test was significantly less than that for Wall C3. Ovendry Wall C3 concrete had a higher specific heat than ovendry concrete from the previous test because of the higher unit weight of Wall C3. The specific heats of saturated and air dry Wall C3 concete were less than those from the previous test due to the lower moisture contents of the saturated and air dry Wall C3 concrete.

Thermal Conductivity

The guarded hot plate (ASTM Designation: C177) and hot wire methods were used to determine thermal conductivity of Wall C3 control specimens. In addition, thermal conductivity of Wall C3 was derived using steady-state calibrated hot box tests.

TABLE 8 - SPECIFIC HEAT OF LOW DENSITY CONCRETE

Specimen	Saturated Surface Dry			Air Dry			Ovendry	
	Unit Weight, pcf (kg/m^3)	Moisture Content, % ovendry weight	Specific Heat, Btu/lb·°F (J/kg·°K)	Unit Weight, pcf (kg/m^3)	Moisture Content, % ovendry weight	Specific Heat, Btu/lb·°F (J/kg·°K)	Unit Weight, pcf (kg/m^3)	Specific Heat, Btu/lb·°F (J/kg·°K)
Wall C3	68 (1090)	62	0.444 (1860)	46 (740)	9.5	0.179 (750)	42 (670)	0.100 (420)
Previous[13] Perlite Concrete Test*	-- --	133	0.610 (2550)	29** (460)	27***	0.283 (1180)	-- --	0.093 (390)

*Sample preparation included 5 days of submersion in water, followed by 5 hours of boiling.
**Average air dry unit weight of 3-3x6-in. (76x152-mm) cylinders moist cured for seven days, and then air cured for 21 days.
***Assumed

Guarded Hot Plate

Average apparent thermal conductivity of two 5.6x5.6x1.93-in. (142x142x49.1-mm) specimens was determined in accordance with ASTM Designation: C177, "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Guarded Hot Plate"(7) at Dynatech R/D Company in Cambridge, Mass.(14) Specimens were cured for seven days in molds and approximately one year at 73±5°F (23±3°C) and 45±15% RH. Specimens were cut to size from two 16x16x2-in. (406x406x51-mm) samples, and were ovendried prior to testing.

In standard practice, thermocouples are placed on the surface of test specimens. For tests conducted at Dynatech R/D Company, thermocouples were embedded into two surfaces of each specimen. Fine wire thermocouples in silica protective tubes were fitted tightly into 0.020x0.020-in. (0.51x0.51-mm) grooves that had been cut into specimen surfaces.

According to Tye & Spinney,(15) if thermocouples are not embedded in the specimen, a contact resistance may be introduced between the thermocouple junction and the concrete surface. This will result in an artificially large temperature difference across the specimen. Consequently, the derived value of conductivity will be too low.(15)

Apparent thermal conductivity of ovendry samples obtained by hot plate test at a mean specimen temperature of 70°F (21°C) was 1.44 Btu·in./hr·ft^2·°F (0.207 W/m·°K).

Hot Wire Method

The hot wire method was used to determine apparent thermal conductivity of moist, air dry, and ovendry prisms. Concrete prisms were cast with a nickel-chromium constantan thermocouple embedded along their central longitudinal axis. Figure 15 shows a mold for the 4x4x8-in. (102x102x204-mm) prisms.

To test a specimen using the hot wire method, a thermocouple reading is taken, electrical current is supplied to the wire, and additional temperature readings are made at selected intervals for a period of ten minutes. Apparent thermal conductivity is calculated from the measured current, the resistance of the wire, and the thermocouple readings.[16]

Thermal conductivity was measured for two sets of specimens. A first set of three specimens was cured in molds for 14 days, and then air cured at 73±5°F (23±3°C) and 45±15% RH for 64 days. Conductivity of these specimens was determined for the air dry and ovendry conditions.

A second set of three specimens was cured in molds for 24 hours, and then moist cured at 73±3°F (23±1.7°C) and 100% RH for 100 days. Specimens were first tested immediately after removal from the moist cure room. Tests were then conducted after specimens had been air dried for 7, 26, and 54 days. A final test was performed on specimens after they had been ovendried.

Average apparent thermal conductivity for air cured specimens in the air dry condition, 17.3% moisture content relative to ovendry weight, was 3.05 Btu·in./hr·ft^2·°F (0.440 W/m·°K). Average apparent thermal conductivity for ovendry air cured

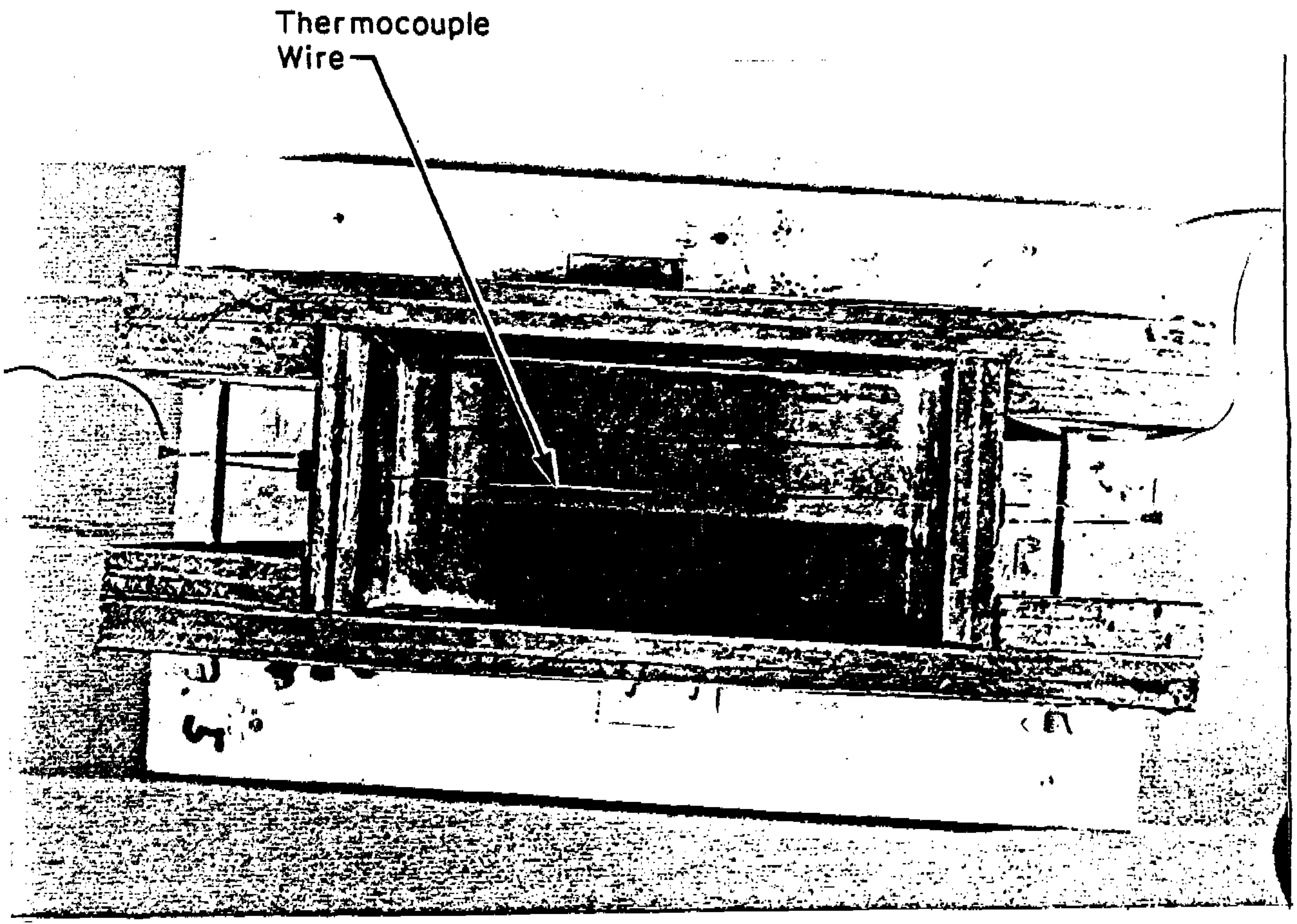


Fig. 15 Mold for Hot Wire Conductivity Specimen with Embedded Thermocouple

specimens was 1.49 Btu·in./hr·ft^2·°F (0.215 W/m·°K). Hot wire test results for the three moist cured samples are shown in Table 9. Each moist cured specimen was tested at five different moisture contents.

Calibrated Hot Box

Apparent thermal conductivity of concrete in Wall C3 can also be derived from steady-state calibrated hot box tests. Steady-state 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.

Since, for homogeneous specimens, thermal conductivity is equal to conductance times wall thickness, Eq. (3) can be modified as follows:

$$k = \frac{3.413 \cdot t \cdot Q_W}{A \cdot (t_2 - t_1)} \qquad (7)$$

where:

k = thermal conductivity, Btu·in./hr·ft^2·°F

t = wall thickness, in.

Q_W = heat transfer through test wall, W·hr/hr

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

t_2 = average temperature of outside wall surface, °F

t_1 = average temperature of inside wall surface, °F

3.413 = conversion factor from W·hr/hr to Btu/hr

Thermal conductivity was determined from steady-state test data using Eq. (7). The amount of heat passing through the test wall, Q_W, was calculated from Eq. (1).

TABLE 9 - THERMAL CONDUCTIVITY AT DIFFERENT MOISTURE CONTENTS OF CONCRETE FOR WALL C3, HOT WIRE METHOD

Length of Time Air Cured,* days	Moisture Content, % ovendry weight	Unit Weight, pcf (kg/m^3)	Moisture Content, % volume	k Thermal Conductivity, $\frac{Btu \cdot in.}{hr \cdot ft^2 \cdot {}^\circ F}$ ($W/m \cdot {}^\circ K$)	$\frac{k_{(moist)}}{k_{(ovendry)}}$
63**	0	46 (730)	0	1.32 (0.190)	1
54	28.9	59 (940)	21.2	3.12 (0.450)	2.36
26	34.6	62 (990)	25.4	3.18 (0.459)	2.41
7	40.8	64 (1030)	29.9	3.20 (0.461)	2.42
0	48.7	68 (1090)	35.7	3.91 (0.564)	2.96

*All specimens cured 24 hours in molds and 100 days at 73±3°F (23±1.7°C) and 100% RH prior to air curing.
**Ovendry

Values of conductivity are reported in Table 10 for three different mean wall temperatures. Mean wall temperature is the average of the indoor wall surface temperature, t_1, and the outdoor wall surface temperature, t_2. At a mean wall temperature of 70°F (21°C), thermal conductivity of Wall C3 is 1.44 $Btu\cdot in./hr\cdot ft^2\cdot°F$ (0.207 $W/m\cdot°K$).

Discussion of Results

An increase in moisture content of concrete increases its conductivity. Figure 16 shows the ratio of conductivity of low density concrete at a particular moisture content to conductivity of the ovendry concrete plotted as a function of moisture content. Data were obtained from hot wire tests of moist cured specimens, and are listed in Table 9. The broken line shown in the figure is based on the assumption that a 5% increase in moisture content leads to a 20% increase in thermal conductivity over the ovendry value.(17) Data from hot wire tests show a greater increase in conductivity with moisture content than is predicted by the assumed relationship.

Results from calibrated hot box tests indicate an increase in thermal conductivity of low density concrete with mean temperature. Figure 17 shows thermal conductivity as a function of mean wall temperature. Data were obtained from steady-state calibrated hot box tests of Wall C3 and are listed in Table 10.

The following equations have been used to estimate thermal conductivity of ovendry and air dry concrete:(18)

TABLE 10 - THERMAL CONDUCTIVITY DERIVED FROM CALIBRATED HOT BOX STEADY-STATE TEST RESULTS OF WALL C3

Mean Wall Temperature, °F (°C)	Thermal Conductivity, $\frac{Btu \cdot in.}{hr \cdot ft^2 \cdot °F}$ (W/m·°K)
52.6 (11.1)	1.38 (0.199)
89.5 (31.9)	1.50 (0.216)
99.8 (37.7)	1.56 (0.225)

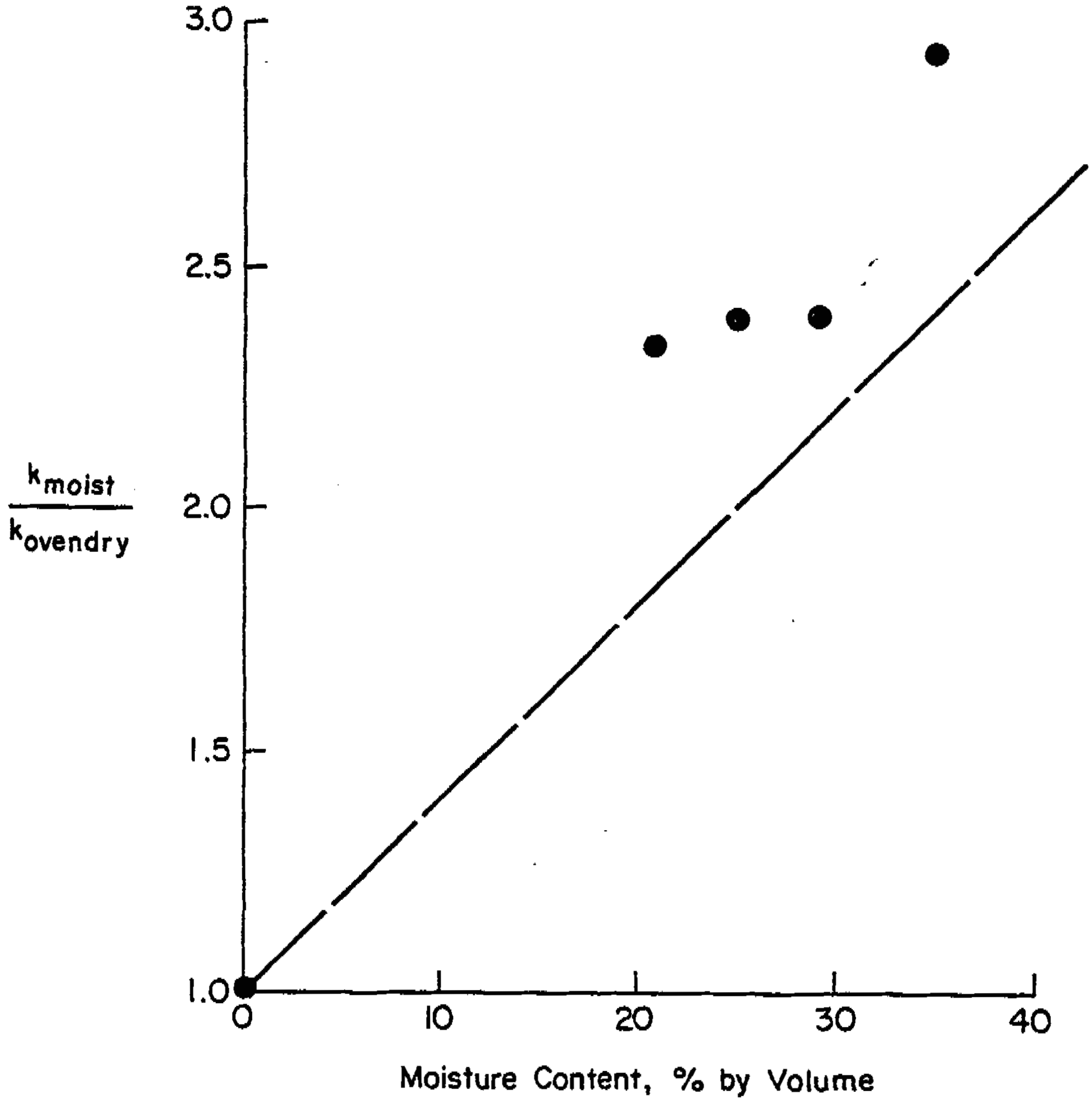


Fig. 16 Thermal Conductivity of Low Density Concrete as a Function of Moisture Content

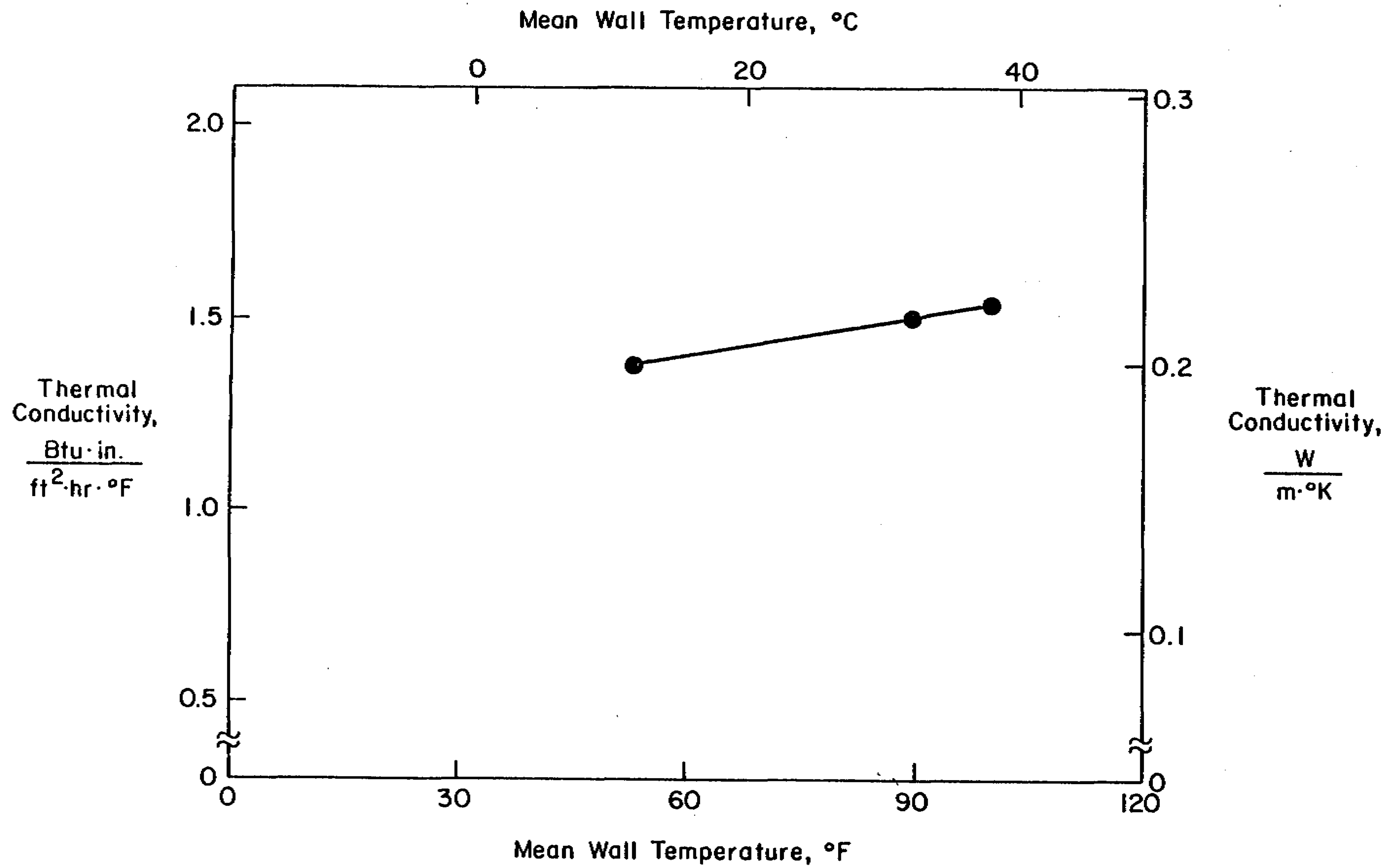


Fig. 17 Thermal Conductivity of Low Density Concrete as a Function of Temperature

Ovendry:

U.S. units $k = 0.5e^{0.02\rho}$ (8)

S.I. units $k = 0.072e^{1250\rho}$

Air Dry:

U.S. units $k = 0.6e^{0.02\rho}$ (9)

S.I. units $k = 0.0865e^{1250\rho}$

where:

k = thermal conductivity, Btu·in./hr·ft^2·°F (W/m·°K)

ρ = ovendry unit weight of concrete, pcf (kg/cm^3)

Estimated values of thermal conductivity calculated from Eqs. (8) and (9) are given in Table 11. The ovendry unit weight of Wall C3 was taken to be 42 pcf (670 kg/m^3).

In addition to listing estimated values, Table 11 summarizes measured values of thermal conductivity for ovendry and air dry low density concrete. Guarded hot plate test results for ovendry concrete were within 5% of those from hot wire tests. Measured thermal conductivities for ovendry concrete were greater than the conductivity estimated using Eq. (8). For air dry concrete, calibrated hot box test results were within 5% of the value estimated using Eq. (9). Thermal conductivity of air dry low density concrete specimens measured by the hot wire method was higher than other measured or estimated values. This was due to the higher moisture content of the hot wire test specimens and differences between the hot wire and guarded hot plate test methods.

TABLE 11 - THERMAL CONDUCTIVITY OF WALL C3

Test Method or Equation	Thermal Conductivity,* $\frac{Btu \cdot in.}{hr \cdot ft^2 \cdot °F}$ (W/m·°K)	
	Ovendry Concrete	Air Dry Concrete
Guarded Hot Plate, ASTM Designation: C177**	1.44 (0.207)	--
Hot Wire Method	1.49 (0.215)	3.05+ (0.440)
Calibrated Hot Box, ASTM Designation: C976	--	1.44++ (0.207)
Estimated using Eq. (8)	1.16 (0.167)	--
Estimated using Eq. (9)	--	1.39 (0.200)

*For 70°F (21°C) mean temperature of specimen
**Specimens cured in molds for 14 days, then air cured for approximately one year prior to ovendrying.
+17.3% moisture content relative to ovendry weight
++9.5% moisture content relative to ovendry weight

Thermal Diffusivity

Thermal diffusivity was determined using 6x12-in. concrete cylinders according to U.S. Army Corps of Engineers Specification CRD-C36-73, "Method of Test for Thermal Diffusivity of Concrete."(19) Test specimens were cured in their molds for 24 hours, and then moist cured at 73±3°F (23±1.7°C) and 100% RH for 58 days. Measured thermal diffusivity was 0.00849 ft^2/hr (0.219 mm^2/s) for the low density concrete.

Thermal diffusivity can also be calculated from the following formula:

$$\alpha = \frac{k}{\rho \cdot c} \tag{10}$$

where:

α = thermal diffusivity, ft^2/hr (m^2/s)

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

ρ = unit weight, pcf (kg/m^3)

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

If any three of the values of conductivity, specific heat, unit weight, or diffusivity are known, the fourth can be calculated. Since measured values of diffusivity and specific heat are for saturated specimens, conductivity and unit weight used in Eq. (10) should also be for saturated specimens.

Calculated thermal diffusivity of saturated concrete for Wall C3 is 0.0108 ft^2/hr (0.278 mm^2/s). Measured conductivities from hot wire tests of specimens with an average moisture content of 49% relative to ovendry weight were used as input to Eq. (10). This moisture content was 21% less than the SSD moisture content measured from specific heat samples. For Wall

C3, calculated diffusivity was 27% greater than the measured value.

It appears that test methods for conductivity, specific heat, and diffusivity of concrete do not correlate well with theoretical expectations. This may be attributed to differing effects of moisture on each particular test procedure.

Thermal Transmittance

Total thermal resistance (R_T) and thermal transmittance (U) values for the three mean wall temperatures used in the calibrated hot box tests are listed in Table 12. Overall coefficients were obtained by correcting measured data obtained from steady-state calibrated hot box tests to account for standard surface resistance coefficients. Surface resistances were taken as 0.68 $hr \cdot ft^2 \cdot °F/Btu$ ($0.12°K \cdot m^2/W$) for inside and 0.17 $hr \cdot ft^2 \cdot °F/Btu$ ($0.03°K \cdot m^2/W$) for outside. These values are commonly used in design and are considered to represent still air on the inside and an air flow of 15 mph (24 km/hr) on the outside.

Steady-State Temperature Profiles

Temperature profiles of all steady-state tests with a temperature differential across the wall significantly different from zero are illustrated in Figs. 18 through 21. The following notation is used to designate average measured temperatures:

t_i = indoor chamber air temperature

t_1 = wall surface temperature, indoor side

t_3 = internal wall temperature at approximate midthickness

TABLE 12 - TOTAL THERMAL RESISTANCE (R_T) AND THERMAL TRANSMITTANCE (U) VALUES FOR LOW DENSITY CONCRETE WALL C3*

Mean Wall Temperature, °F (°C)	R_T, $\frac{hr \cdot ft^2 \cdot °F}{Btu}$ ($m^2 \cdot °K/W$)	U, $\frac{Btu}{hr \cdot ft^2 \cdot °F}$ ($W/m^2 \cdot °K$)
52.6 (11.4)	7.02 (1.24)	0.142 (0.81)
89.5 (31.9)	6.53 (1.15)	0.153 (0.87)
99.8 (37.7)	6.31 (1.11)	0.158 (0.90)

*Corrected for standard surface resistance coefficients

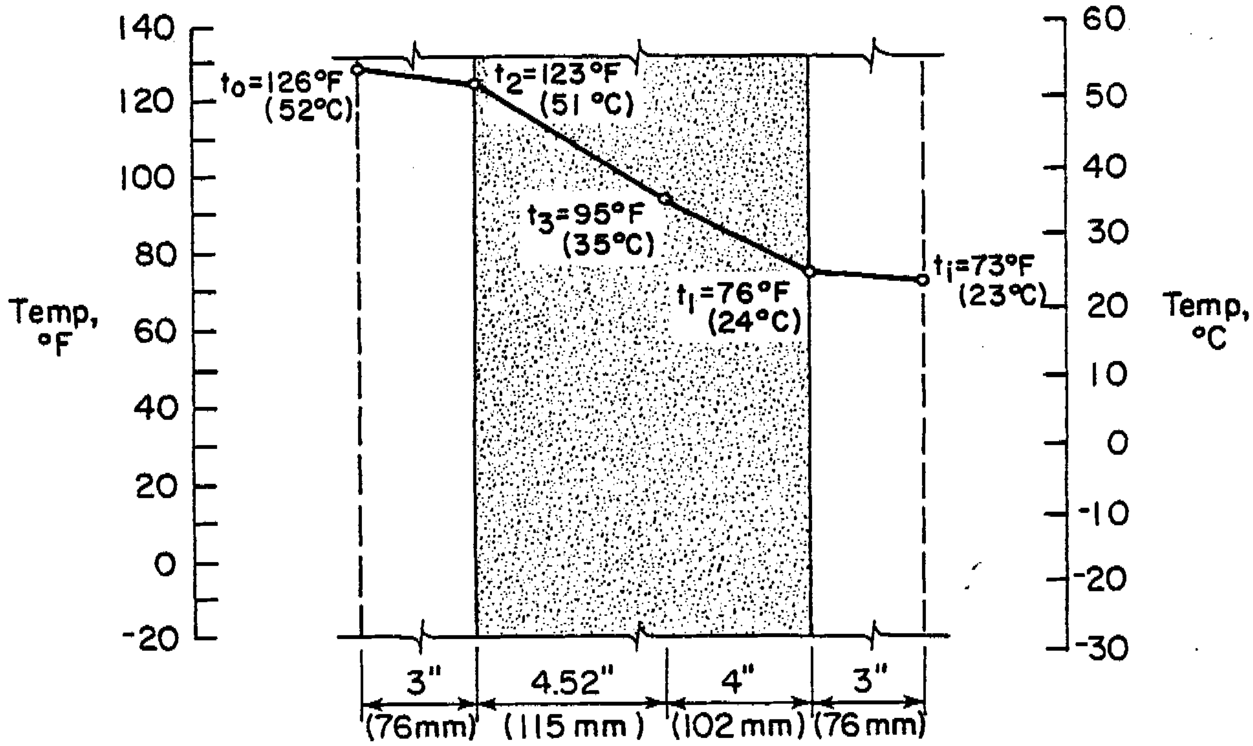


Fig. 18 Temperature Profile Across Wall C3, Mean Wall Temperature - 100°F (38°C)

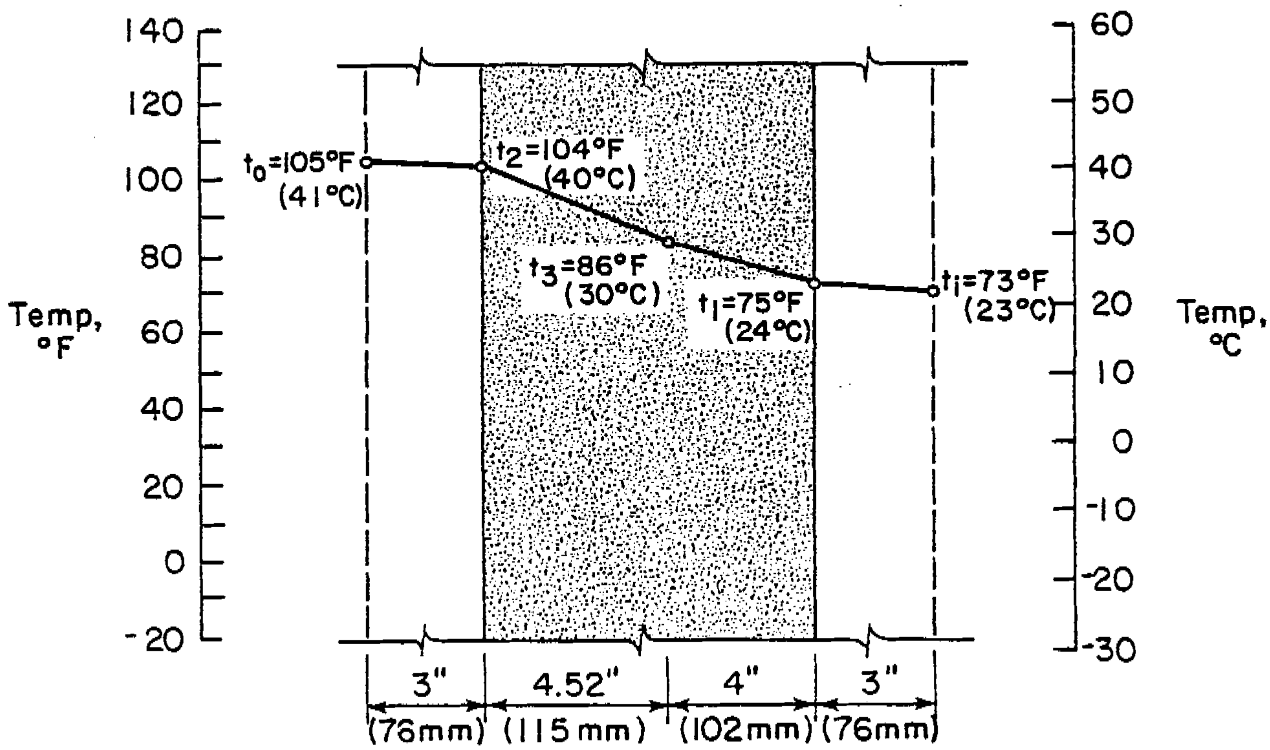


Fig. 19 Temperature Profile Across Wall C3, Mean Wall Temperature = 89°F (32°C)

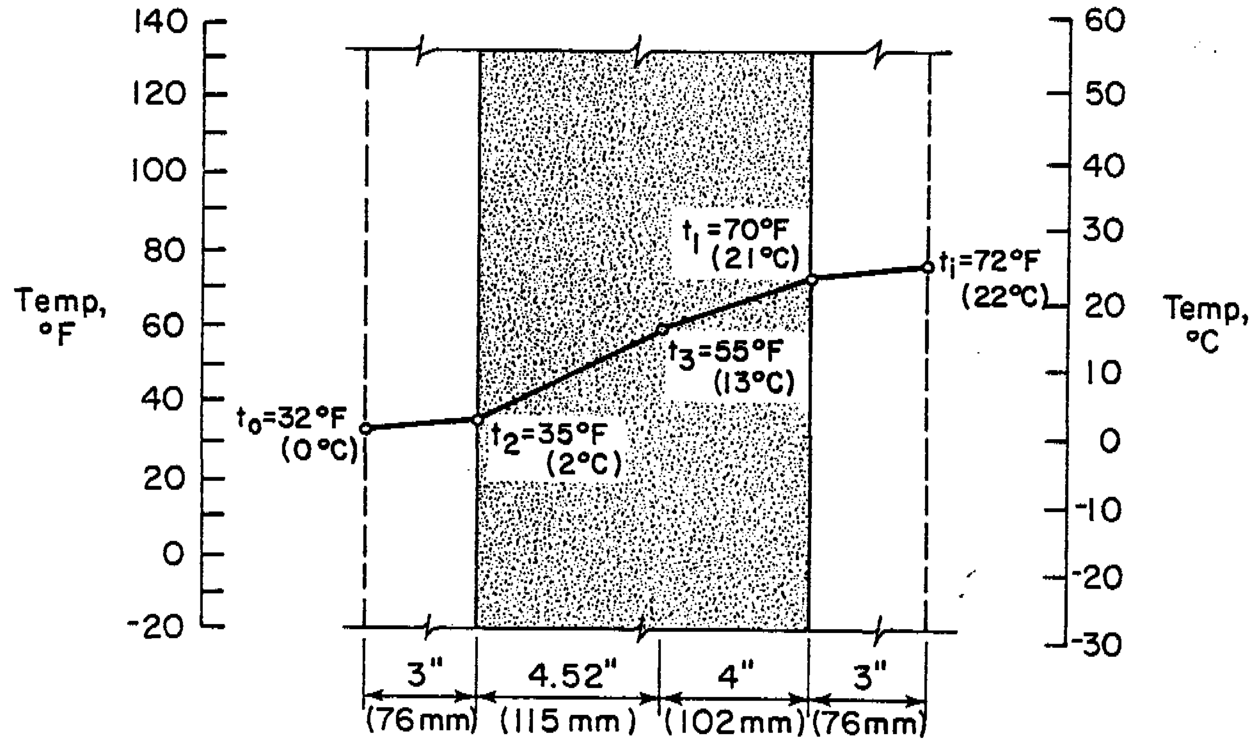


Fig. 20 Temperature Profile Across Wall C3, Mean Wall Temperature = 53°F (11°C)

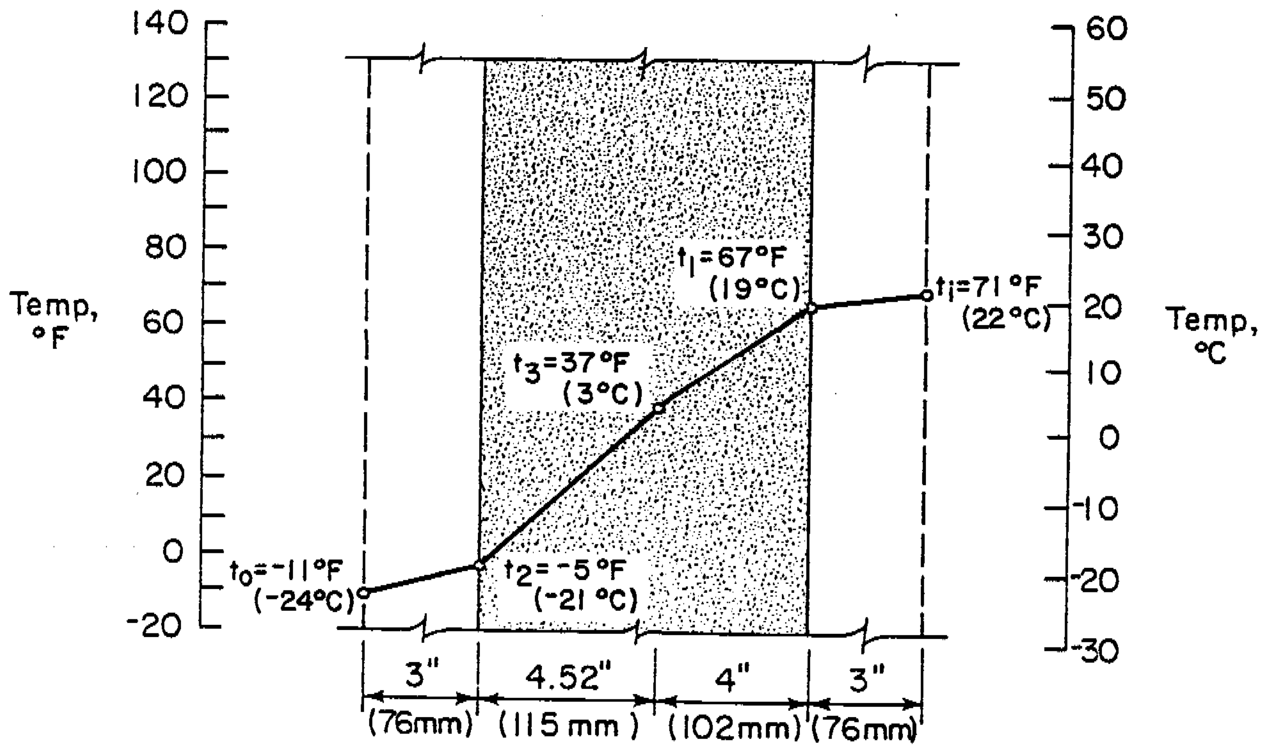


Fig. 21 Temperature Profile Across Wall C3, Mean Wall Temperature = 31°F (-1°C)

t_2 = wall surface temperature, outdoor side

t_o = outdoor chamber air temperature

Theoretically, the slope of the temperature profile line through a homogeneous wall should be constant. As can be seen from Fig. 19, the slopes of lines through Wall C3 joining t_2 to t_3 and t_3 to t_1 are not exactly equal. This may be due to thermocouple t_3 not being exactly 4 in. from the inside surface.

The maximum air to surface temperature differential was 6°F (3°C). This occurred during the test at a mean wall temperature of 31°F (-1°C).

THERMAL PROPERTIES OF CONCRETE UNDER DYNAMIC TEST CONDITIONS

Although steady-state tests provide a measure of resistance to heat flow, response of walls to temperature changes is a function of both thermal resistance and heat storage capacity. Dynamic tests are a means of evaluating thermal response under controlled conditions that simulate temperature changes actually encountered in building envelopes. These tests provide a comparative measure of response and also can be used to verify analytical models for transient heat flow.

Test Procedure

Dynamic tests were conducted by maintaining calibrated hot box indoor air temperatures constant while outdoor air temperatures were cycled over a predetermined time versus temperature relationship. Energy required to maintain a constant indoor air temperature was monitored as a function of time. The rate of heat flow through Wall C3 was determined using Eq. (1) for hourly averages of data.

Three 24-hour (diurnal) temperature cycles were used in this investigation. The first cycle applied to Wall C3 was 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.[20] It represents a large variation in outdoor temperature over a 24-hour period. The mean outdoor temperature of the cycle was approximately equal to the mean indoor temperature. This cycle, denoted NBS, was run to permit comparison of results with those from earlier tests.[1-3]

Two additional sol-air temperature cycles were run with mean outdoor temperatures approximately 10°F (6°C) above and 10°F (6°C) below the indoor temperature. The NBS+10 cycle was derived by increasing hourly outdoor temperatures of the NBS cycle by 10°F (6°C). The NBS-10 cycle was derived by decreasing hourly outdoor temperatures by 10°F (6°C).

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

*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.[10]

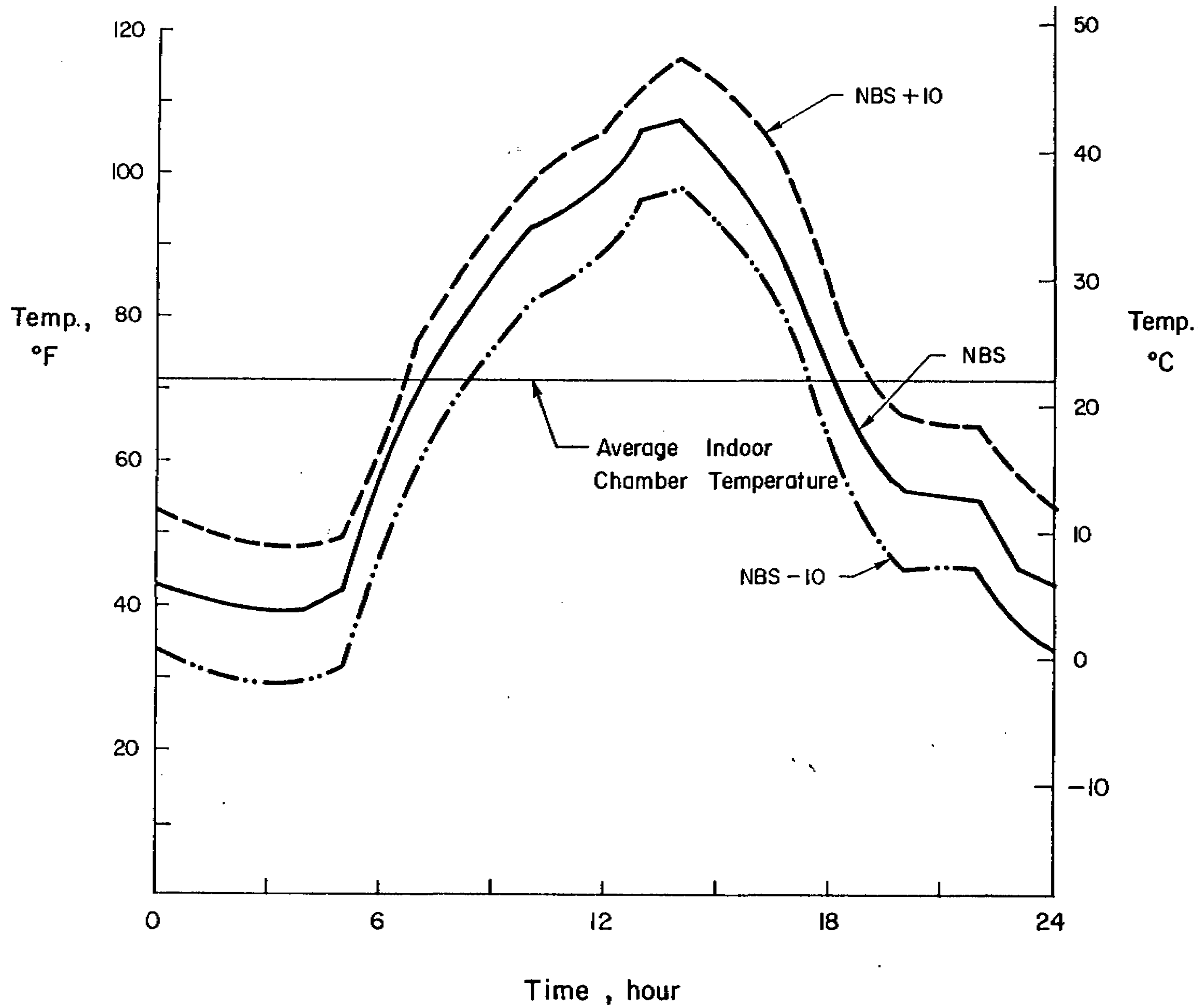


Fig. 22 Outdoor Chamber Air Temperatures for Dynamic Test Cycles

For all tests, dynamic cycles were repeated until conditions of equilibrium were obtained. Equilibrium conditions were evaluated by consistency of applied temperatures and measured energy response. Each test required approximately four to six days for completion. After equilibrium conditions were reached, the test was continued for a period of three days. Results are based on average readings for at least three consecutive 24-hour cycles.

Dynamic Test Results

Results for the three diurnal tests are given in Tables 13 through 16 and Figs. 23 through 31. Tables 13 through 15 and Figs. 23, 26, and 29 give measured air, surface, and internal wall temperatures. Air-to-air, surface-to-surface, and surface-to-air temperature differentials are illustrated in Figs. 24, 27, and 30. Notation used to designate average measured temperatures is repeated here for reference.

t_i = indoor chamber air temperature

t_1 = wall surface temperature, indoor side

t_3 = internal wall temperature at approximate midthickness

t_2 = wall surface temperature, outdoor side

t_o = outdoor chamber air temperature

Table 16 and Figs. 25, 28, and 31 present Q_w, measured heat flow rates through Wall C3, calculated from Eq. (1). Heat flow rates measured by heat flow meters mounted on the indoor surface of Wall C3, Q_{hfm}, and on the outdoor wall surface, Q'_{hfm}, are also shown. Heat flow rates predicted by steady-state analysis

TABLE 13 - MEASURED TEMPERATURES OF WALL C3 FOR NBS TEST CYCLE

Time, hr	Outdoor Chamber Air Temperature, t_o		Outdoor Surface Temperature of Wall, t_2		Internal Wall Temperature, t_3		Indoor Surface Temperature of Wall, t_1		Indoor Chamber Air Temperature, t_i	
	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C
1	41.60	5.33	46.88	8.27	70.88	21.60	72.78	22.66	72.43	22.46
2	40.17	4.54	45.23	7.35	69.99	21.11	72.66	22.59	72.39	22.44
3	39.84	4.36	44.58	6.99	69.06	20.59	72.56	22.53	72.36	22.42
4	39.71	4.28	44.18	6.77	68.18	20.10	72.42	22.46	72.32	22.40
5	44.13	6.74	46.66	8.14	67.37	19.65	72.28	22.38	72.32	22.40
6	58.09	14.49	56.98	13.88	66.63	19.24	72.18	22.32	72.32	22.40
7	68.01	20.00	65.67	18.71	66.06	18.92	72.07	22.26	72.33	22.35
8	77.66	25.37	74.37	22.54	65.49	18.86	71.97	22.21	72.25	22.36
9	84.48	29.16	80.55	26.97	66.13	18.96	71.87	22.15	72.19	22.33
10	89.96	32.20	85.91	29.95	66.63	19.24	71.80	22.11	72.19	22.33
11	92.08	33.38	88.45	31.36	67.42	19.68	71.78	22.10	72.17	22.32
12	97.33	36.29	92.77	33.76	68.27	20.15	71.82	22.12	72.16	22.31
13	103.44	39.69	98.40	36.89	69.31	20.73	71.89	22.16	72.22	22.34
14	103.15	39.53	99.47	37.48	70.39	21.33	71.99	22.22	72.25	22.36
15	98.34	36.86	96.50	35.83	71.46	21.92	72.11	22.28	72.22	22.34
16	91.00	32.78	90.99	32.77	72.65	22.58	72.27	22.37	72.33	22.41
17	79.07	26.15	81.95	27.75	73.61	23.12	72.43	22.46	72.38	22.43
18	66.45	19.14	71.22	21.79	74.21	23.40	72.60	22.56	72.42	22.46
19	59.49	15.27	64.41	18.01	74.37	23.54	72.75	22.64	72.41	22.45
20	56.67	13.71	60.95	16.08	74.19	23.44	72.86	22.70	72.46	22.48
21	56.22	13.46	59.85	15.47	73.74	23.19	72.93	22.74	72.45	22.47
22	52.22	11.23	57.00	13.89	73.15	22.86	72.94	22.74	72.48	22.49
23	44.82	7.12	50.80	10.44	72.48	22.49	72.92	22.73	72.46	22.48
24	43.32	6.29	48.65	9.25	71.73	22.07	72.85	22.69	72.44	22.47

TABLE 14 - MEASURED TEMPERATURES OF WALL C3 FOR NBS+10 TEST CYCLE

Time, hr	Outdoor Chamber Air Temperature, t_o		Outdoor Surface Temperature of Wall, t_2		Internal Wall Temperature, t_3		Indoor Surface Temperature of Wall, t_1		Indoor Chamber Air Temperature, t_i	
	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C
1	52.13	11.18	56.81	13.78	75.25	24.03	73.48	23.04	72.65	22.58
2	50.21	10.12	54.80	12.67	74.42	23.57	73.39	22.99	72.65	22.58
3*	49.08	9.49	53.52	11.96	73.53	23.07	73.32	22.96	72.66	22.59
4	49.29	9.61	53.20	11.78	72.67	22.59	73.19	22.88	72.58	22.54
5	50.26	10.14	53.68	12.04	71.81	22.12	73.08	22.82	72.61	22.56
6	59.34	15.19	59.36	15.20	71.00	21.67	72.94	22.74	72.58	22.54
7	72.87	22.71	70.29	21.27	70.28	21.27	72.83	22.68	72.55	22.53
8	81.93	27.74	78.48	25.82	69.32	20.73	72.58	22.54	72.44	22.47
9	88.52	31.40	84.61	29.23	69.37	20.76	72.45	21.47	72.40	22.44
10	95.40	35.22	90.69	32.61	69.76	20.98	72.34	21.41	72.35	22.42
11	99.70	37.61	95.28	35.16	70.23	21.24	72.29	22.38	72.33	22.41
12	102.59	39.22	98.19	36.77	71.26	21.81	72.36	22.42	72.38	22.43
13	108.58	42.54	103.32	39.62	72.21	22.34	72.41	22.45	72.33	22.41
14	112.02	44.46	107.22	41.79	73.28	22.93	72.50	22.50	72.41	22.45
15	109.95	43.31	106.59	41.44	74.45	23.58	72.62	22.57	72.47	22.48
16	105.79	41.00	103.71	39.84	75.62	24.23	72.74	22.63	72.50	22.50
17	97.25	36.25	97.42	36.34	76.67	24.82	72.94	22.74	72.53	22.52
18*	82.77	28.21	86.12	30.07	77.49	25.27	73.10	22.83	72.60	22.56
19	71.93	22.18	76.44	24.69	77.96	25.53	73.30	22.94	72.67	22.59
20	67.32	19.62	71.43	21.91	78.24	25.69	73.46	23.03	72.74	22.63
21	65.69	18.72	69.04	20.58	77.88	25.49	73.55	23.08	72.79	22.66
22	64.99	18.33	68.03	20.02	77.33	25.18	73.60	23.11	72.76	22.64
23	58.10	14.50	63.00	17.22	76.70	24.83	73.58	23.10	72.68	22.60
24	54.58	12.54	59.11	15.06	76.04	24.47	73.55	23.08	72.70	22.61

*Data for these hours are 2-day hourly averages.

TABLE 15 - MEASURED TEMPERATURES OF WALL C3 FOR NBS-10 TEST CYCLE

Time, hr	Outdoor Chamber Air Temperature, t_o		Outdoor Surface Temperature of Wall, t_2		Internal Wall Temperature, t_3		Indoor Surface Temperature of Wall, t_1		Indoor Chamber Air Temperature, t_i	
	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C
1	33.55	0.86	39.46	4.14	67.50	19.72	72.22	22.34	72.21	22.34
2	31.38	-0.34	37.23	2.91	66.65	19.25	72.12	22.29	72.20	22.33
3	30.44	-0.87	35.98	2.21	65.76	18.76	72.01	22.23	72.16	22.31
4	30.34	-0.92	35.54	1.97	64.87	18.26	71.90	22.17	72.14	22.30
5	31.34	-0.36	35.87	2.15	64.03	17.79	71.78	22.10	72.10	22.28
6	40.88	4.93	42.17	5.65	63.21	17.34	71.65	22.03	72.10	22.28
7	53.90	12.17	52.69	11.50	62.54	16.97	71.53	21.96	72.07	22.26
8	63.18	17.32	60.89	16.05	62.12	16.73	71.39	21.88	72.04	22.24
9	70.12	21.18	67.31	19.62	62.06	16.70	71.28	21.82	72.02	22.23
10	77.47	25.26	73.96	23.31	62.61	17.00	71.27	21.82	72.07	22.26
11	81.09	27.27	77.95	25.53	63.21	17.34	71.24	21.80	72.08	22.27
12	84.25	29.03	80.90	27.17	63.99	17.77	71.25	21.81	72.07	22.26
13	91.33	32.96	86.67	30.37	64.82	18.23	71.30	21.83	72.06	22.26
14	94.48	34.71	90.47	32.48	65.86	18.81	71.36	21.87	72.09	22.27
15	92.55	33.64	89.96	32.20	66.92	19.40	71.46	21.92	72.07	22.26
16	87.14	30.63	86.24	30.13	68.06	20.03	71.59	21.99	72.12	22.29
17	79.12	26.18	80.33	26.85	69.15	20.64	71.74	22.08	72.18	22.32
18	64.73	18.18	69.27	20.71	69.97	21.09	71.88	22.16	72.21	22.34
19	54.48	12.49	59.95	15.53	70.40	21.33	72.08	22.27	72.20	22.33
20	48.47	9.15	54.10	12.28	70.52	21.40	72.19	22.33	72.24	22.36
21	46.78	8.21	51.67	10.93	70.17	21.21	72.28	22.38	72.19	22.33
22	46.18	7.88	50.65	10.36	69.60	20.89	72.32	22.40	72.24	22.36
23	39.24	4.02	45.55	7.53	68.94	20.52	72.32	22.40	72.22	22.34
24	35.65	2.03	41.58	5.32	68.28	20.16	72.27	22.37	72.24	22.36

TABLE 16 - RATE OF HEAT FLOW THROUGH WALL C3

Time, hr	Rate of Heat Flow Through Wall, W·hr/hr					
	NBS		NBS+10		NBS-10	
	Measured Q_w	Steady-State Q_{ss}	Measured Q_w	Steady-State Q_{ss}	Measured Q_w	Steady-State Q_{ss}
1	20	-92	52	-60	-6	-116
2	11	-97	47	-67	-12	-123
3	7	-99	37	-71	-15	-126
4	4	-100	30	-72	-22	-127
5	-6	-91	23	-69	-32	-125
6	-20	-54	-14	-49	-44	-104
7	-30	-23	2	-10	-51	-67
8	-41	9	-10	21	-58	-38
9	-39	32	-16	45	-68	-15
10	-45	52	-17	68	-71	10
11	-45	62	-24	87	-75	24
12	-49	79	-24	97	-76	36
13	-45	100	-20	117	-77	57
14	-35	104	-12	132	-74	71
15	-27	91	-6	129	-61	69
16	-20	70	4	118	-53	54
17	-7	35	9	92	-41	32
18	8	-5	22	49	-30	-10
19	18	30	29	12	-19	-44
20	23	-43	41	-8	-11	-65
21	22	-47	49	-17	-6	-74
22	23	-57	49	-20	-2	-78
23	29	-79	52	-39	-1	-95
24	27	-87	52	-52	-4	-108
Mean	-9	-11	16	18	-38	-40

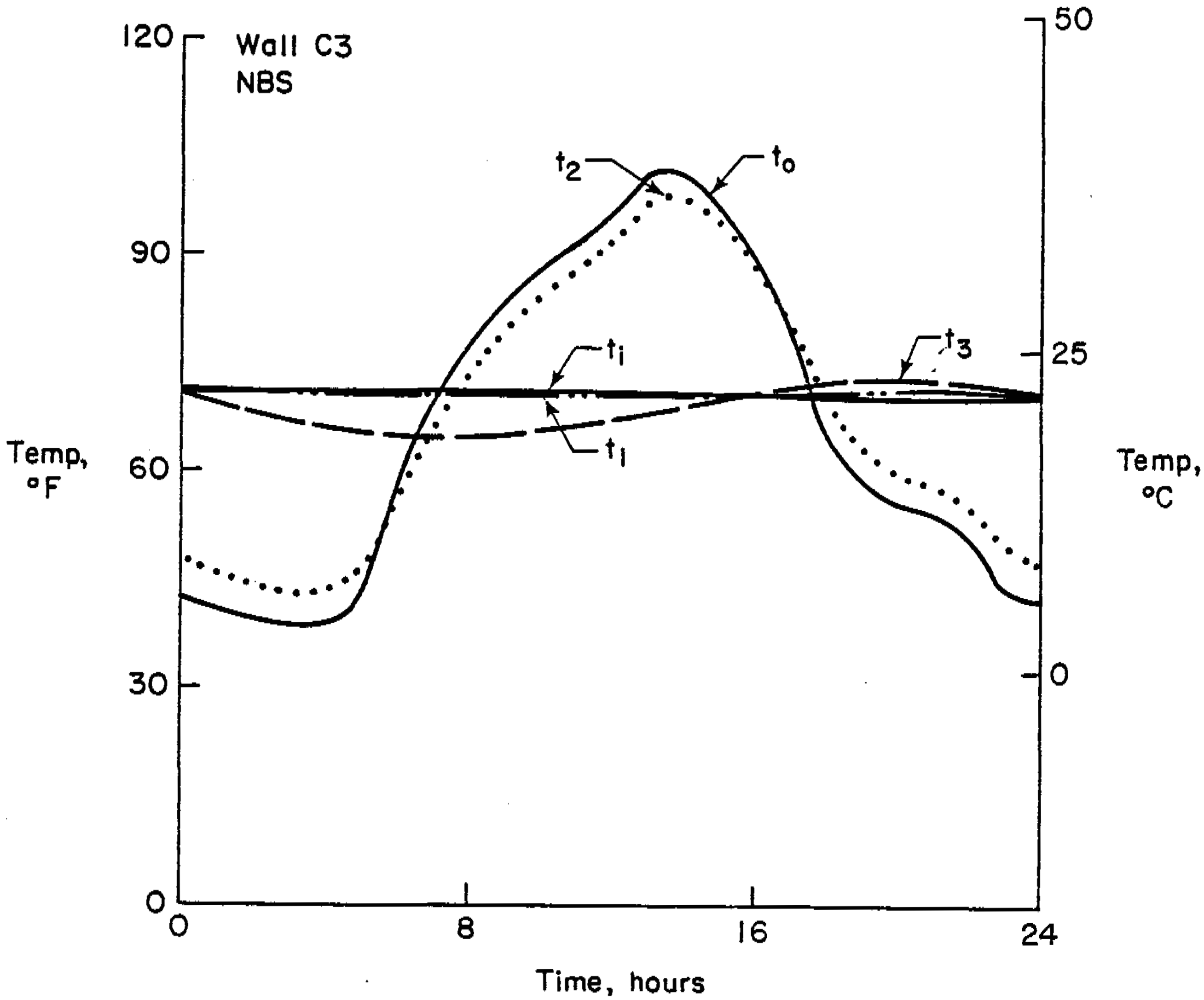


Fig. 23 Measured Temperatures of Wall C3 for NBS Test Cycle

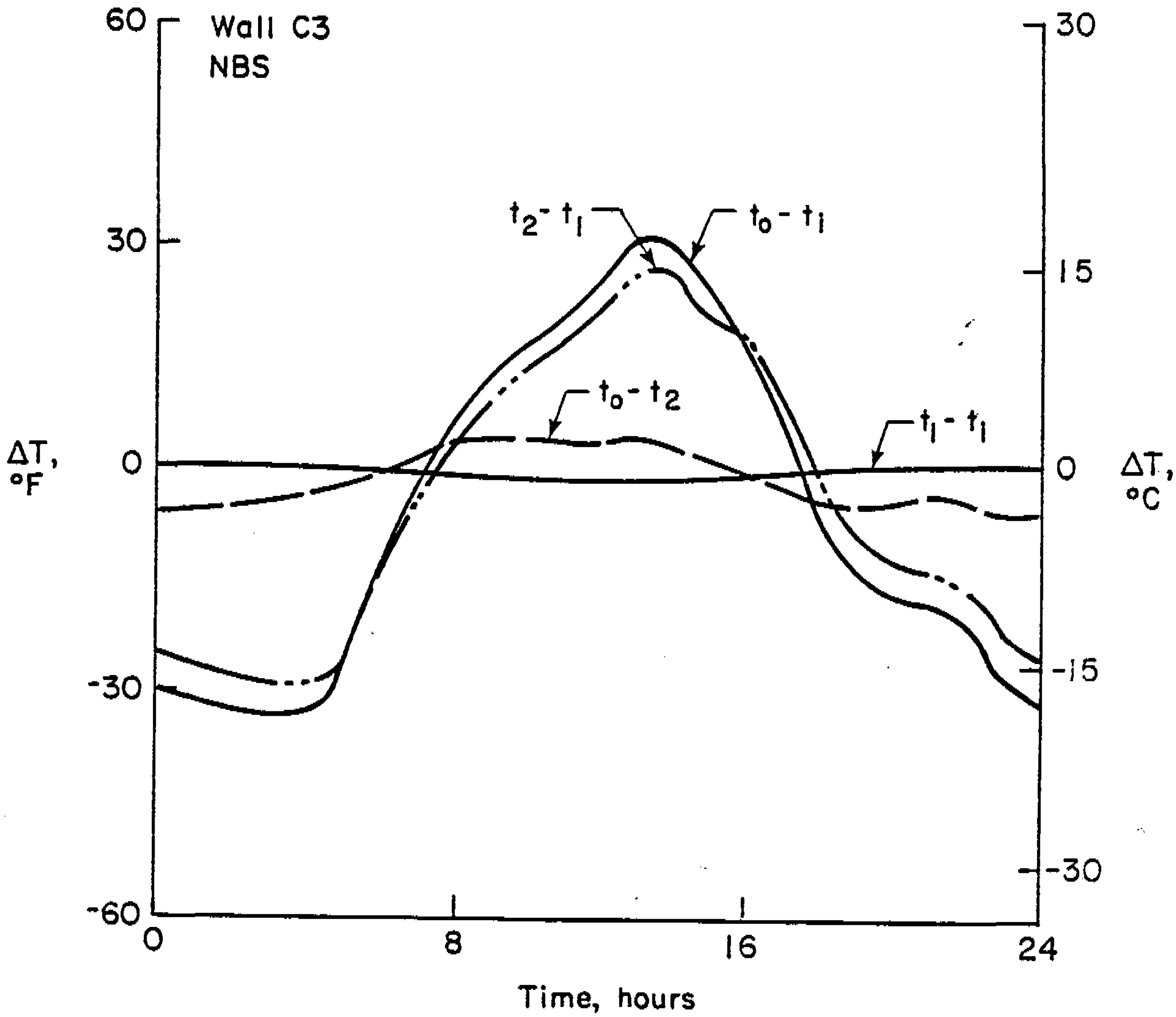


Fig. 24 Measured Temperature Differentials of Wall C3 for NBS Test Cycle

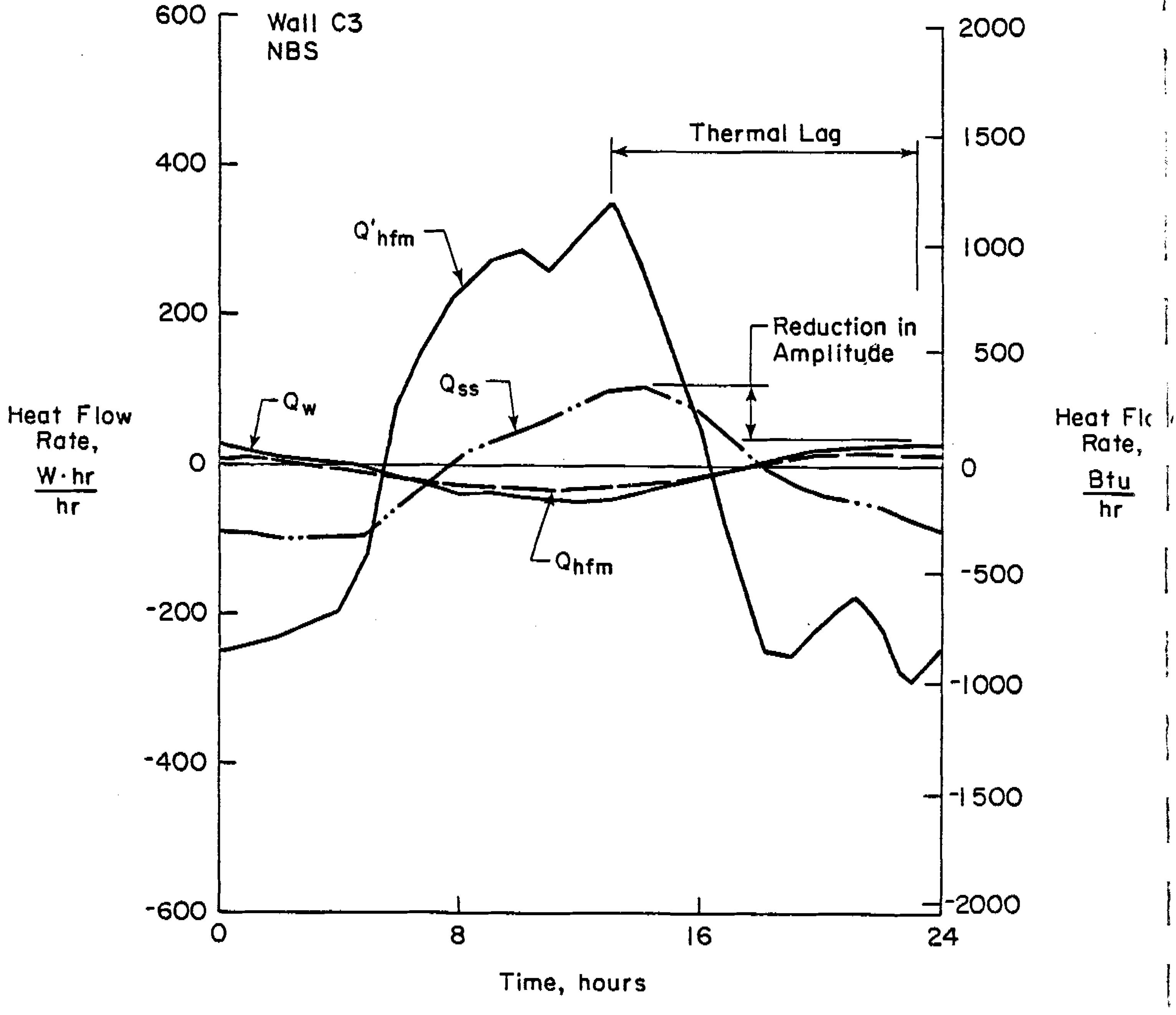


Fig. 25 Rate of Heat Flow Through Wall C3 for NBS Test Cycle

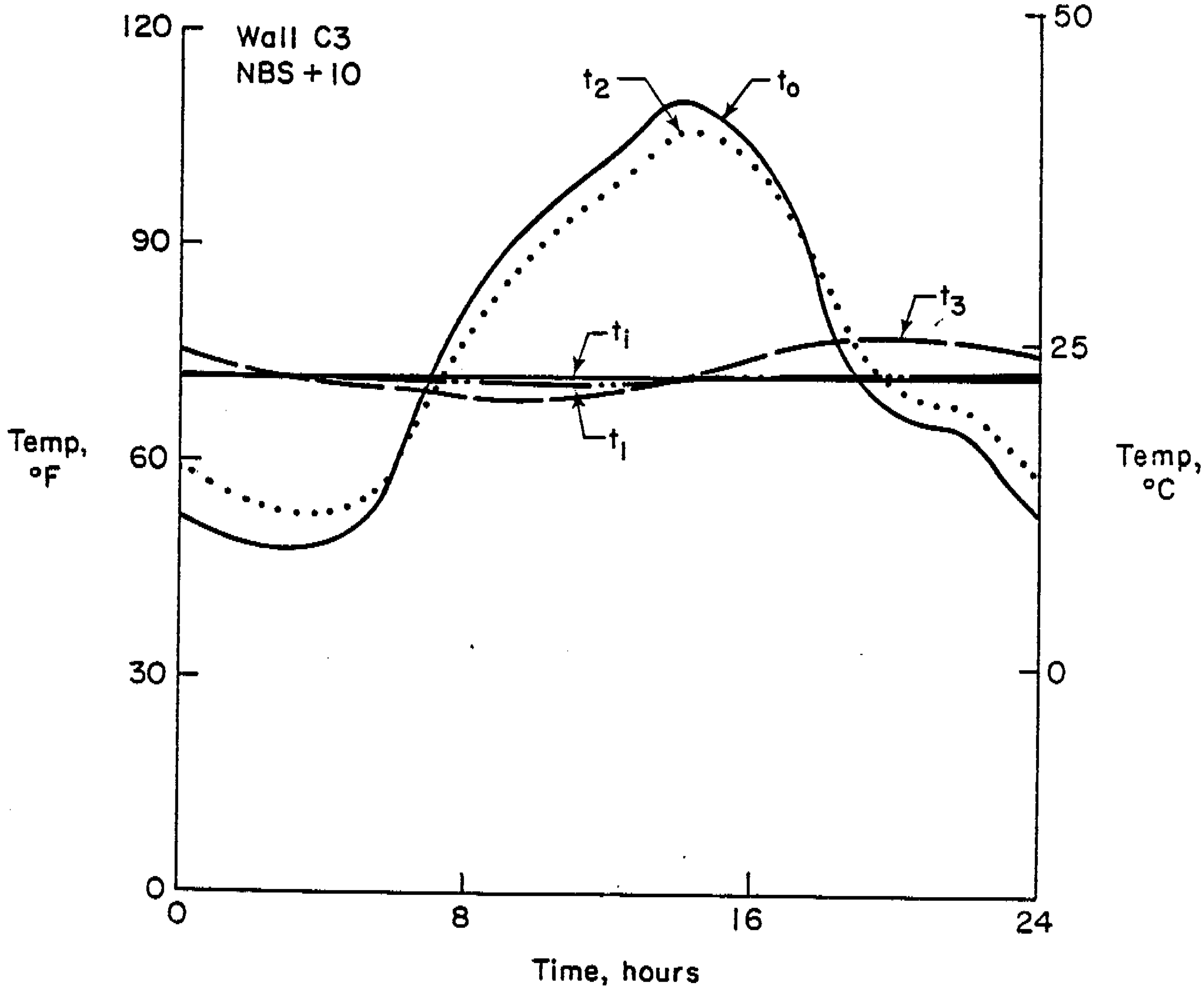


Fig. 26 Measured Temperatures of Wall C3 for NBS+10 Test Cycle

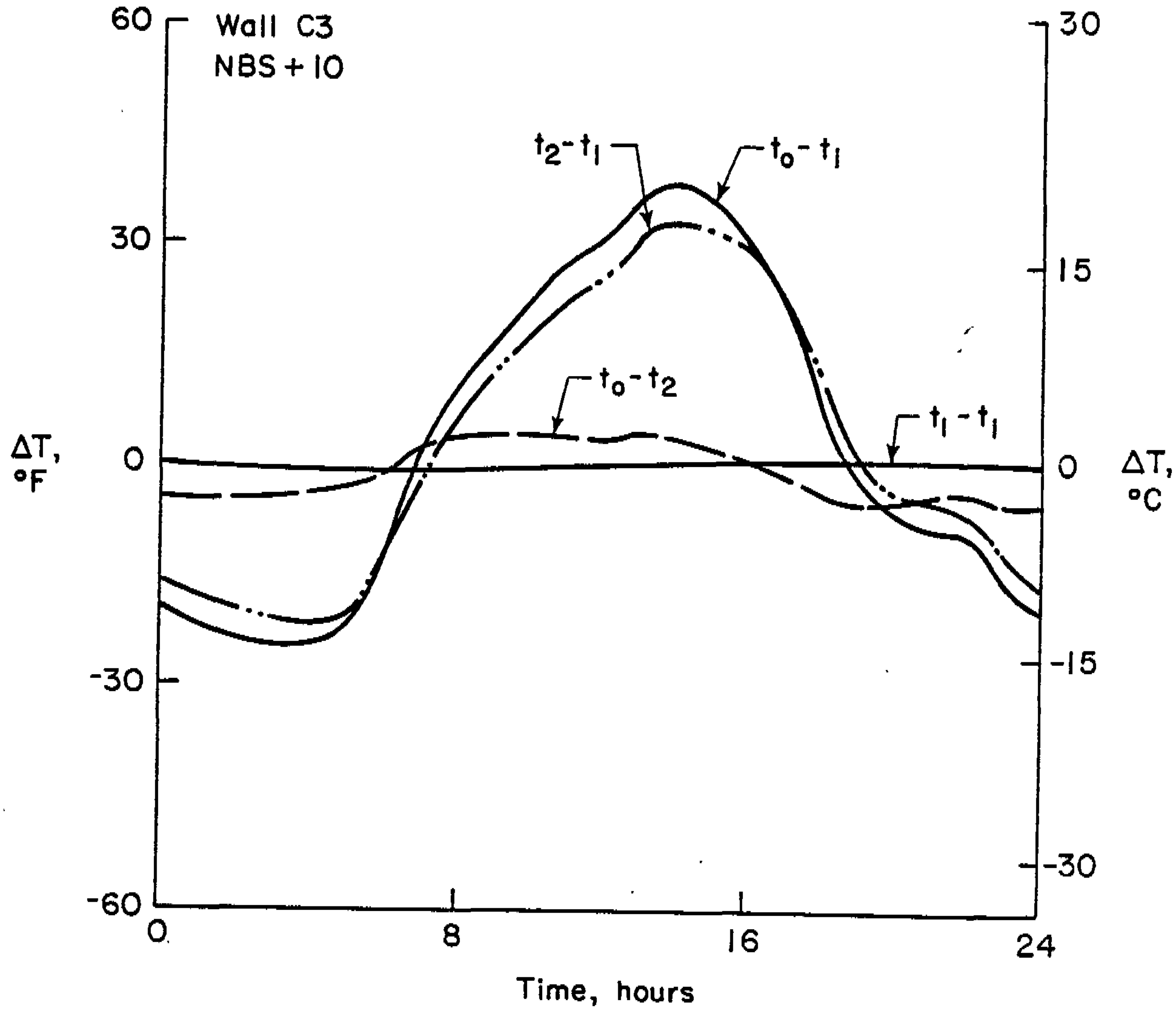


Fig. 27 Measured Temperature Differentials of Wall C3 for NBS+10 Test Cycle

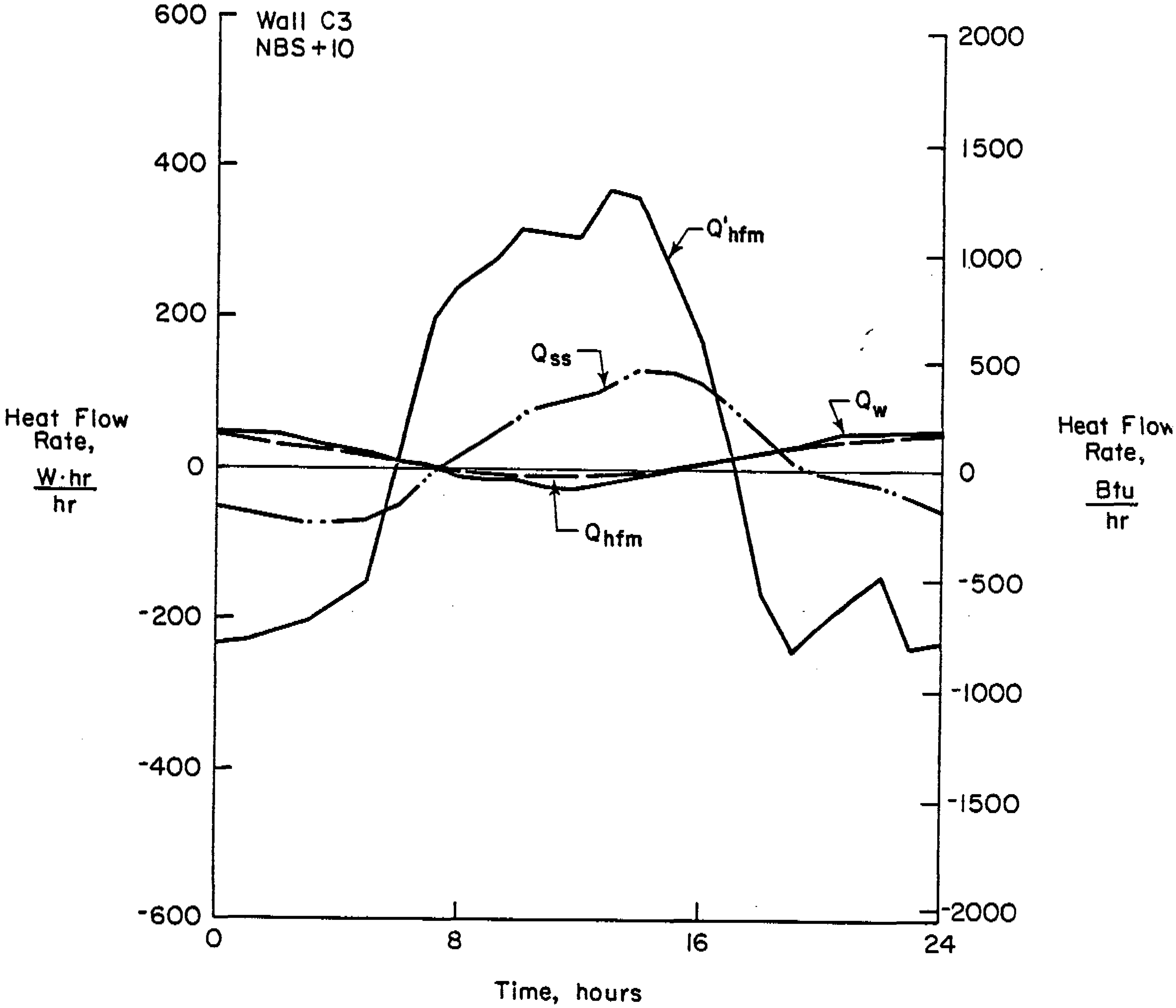


Fig. 28 Rate of Heat Flow Through Wall C3 for NBS+10 Test Cycle

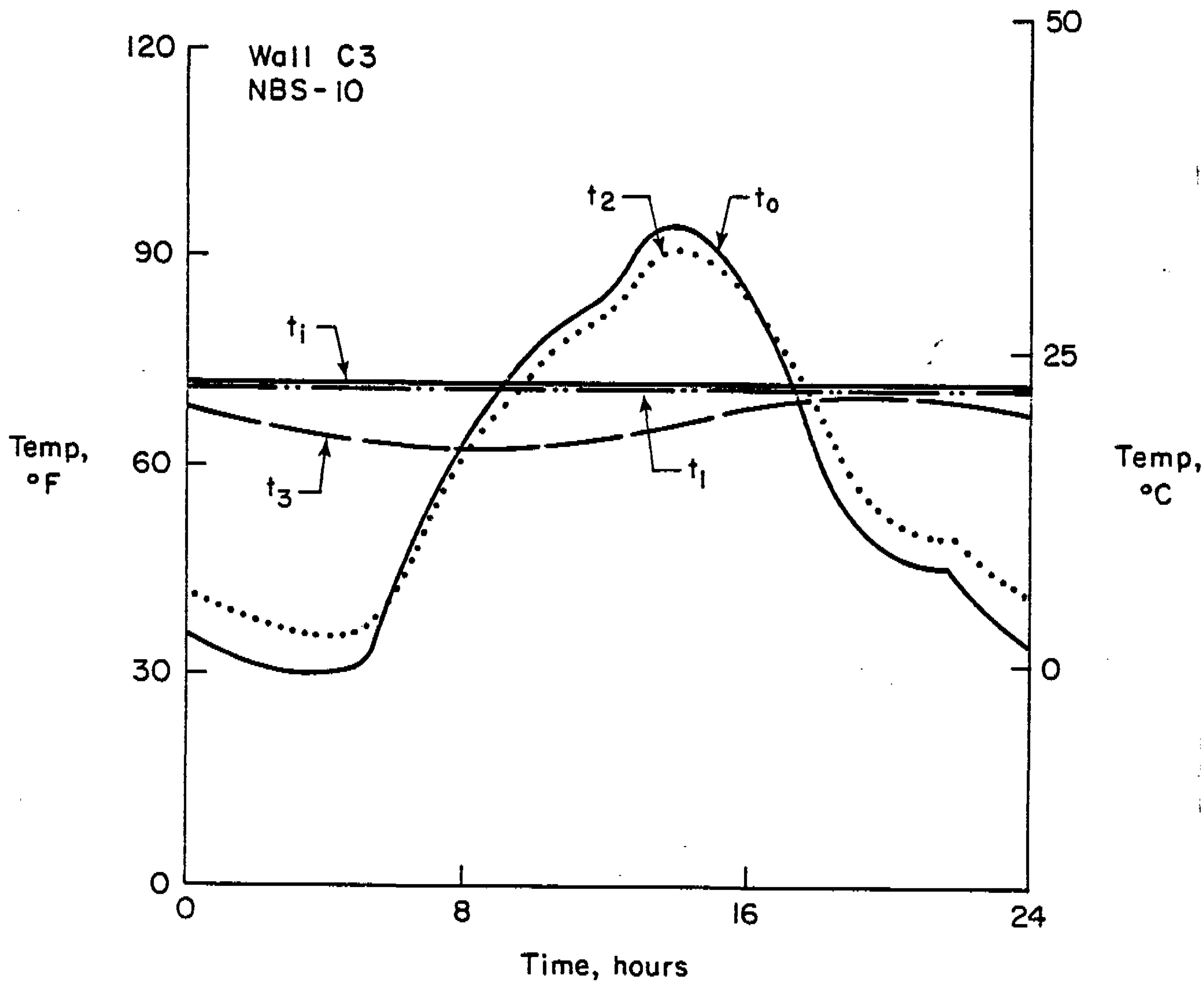


Fig. 29 Measured Temperatures of Wall C3 for NBS-10 Test Cycle

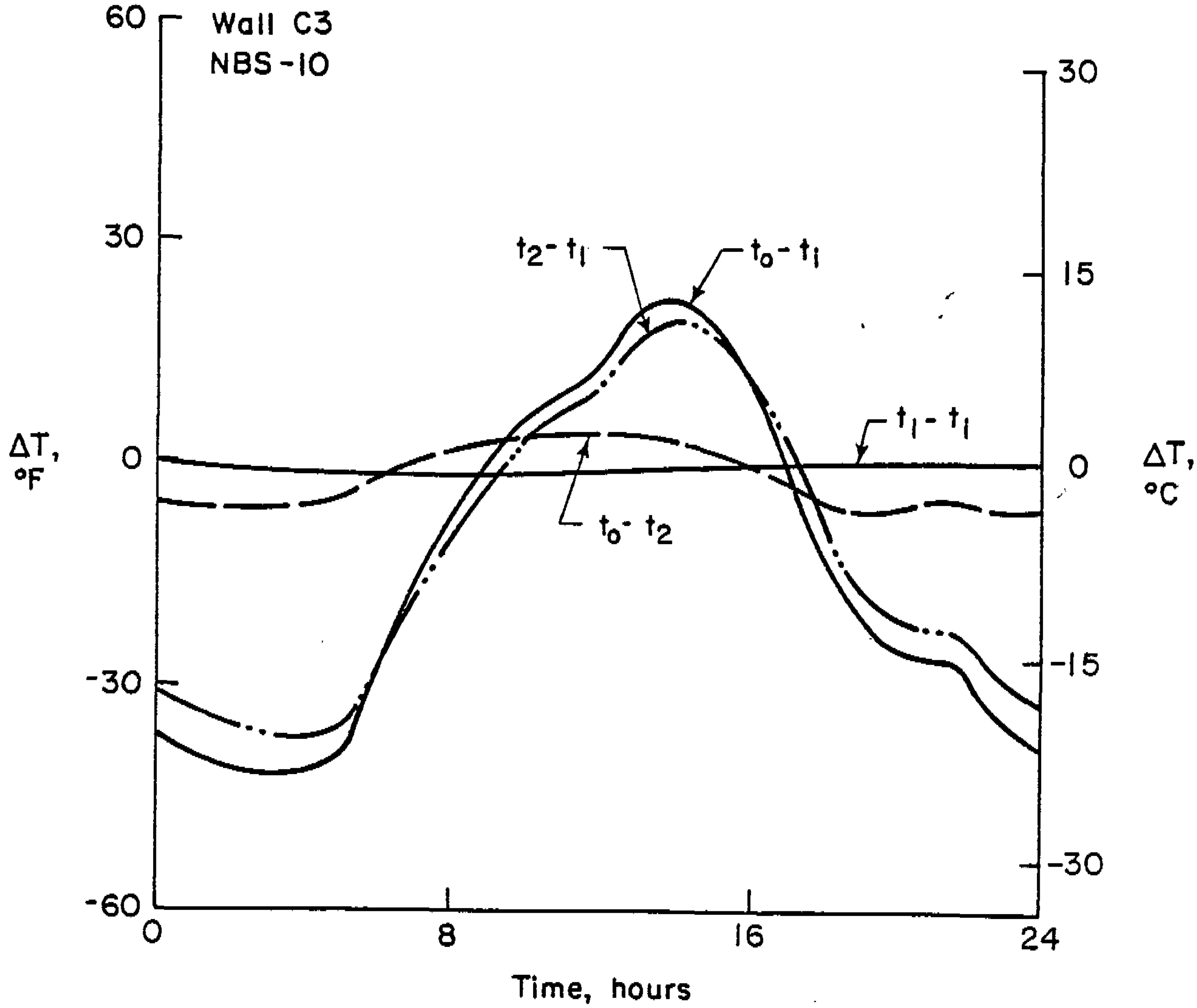


Fig. 30 Measured Temperature Differentials of Wall C3 for NBS-10 Test Cycle

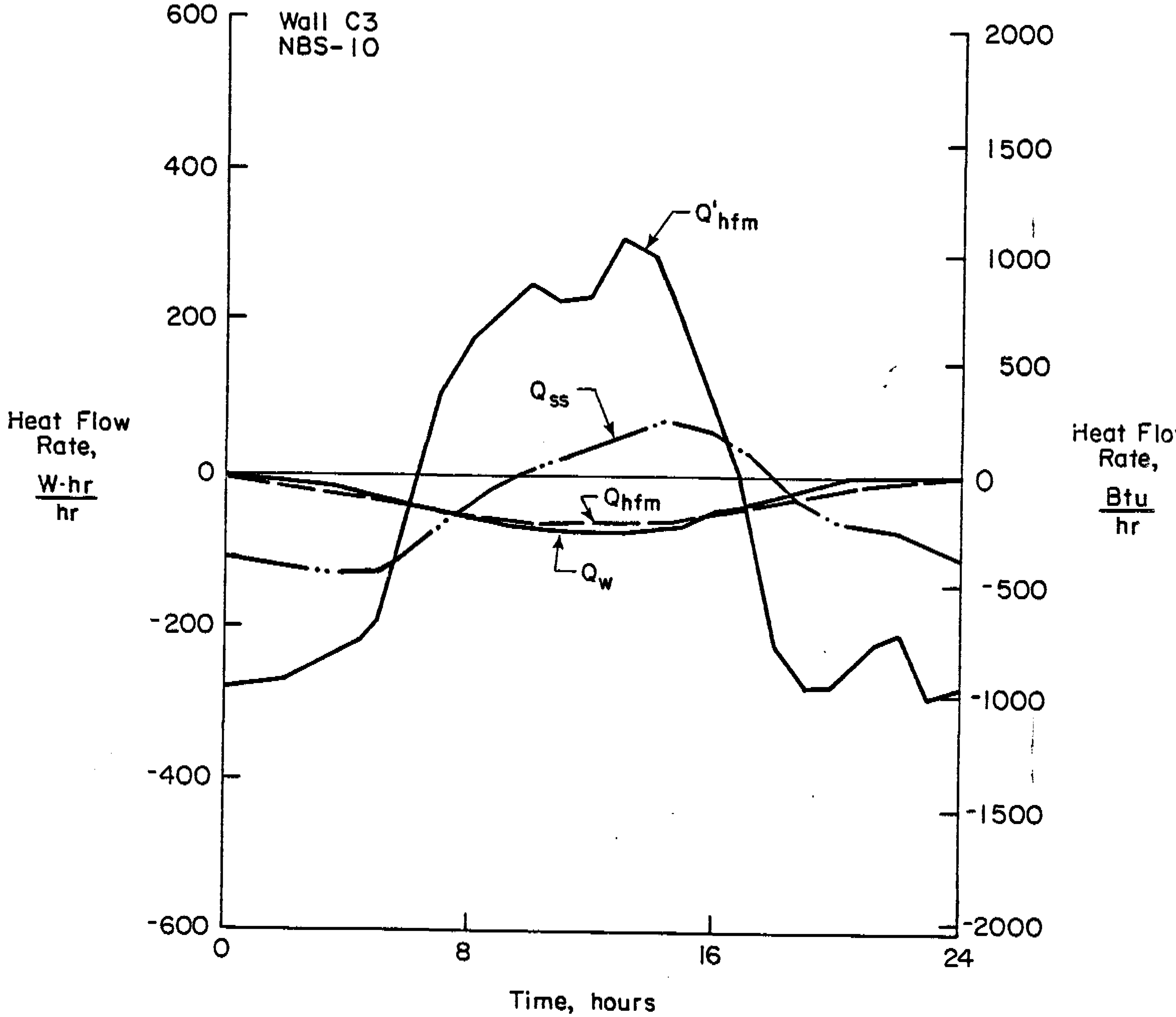


Fig. 31 Rate of Heat Flow Through Wall C3 for NBS-10 Test Cycle

are shown by the curve designated Q_{ss}. Positive values represent heat flow from the outdoor to the indoor side of the wall. All data represent averages from three consecutive 24-hour cycles.

Heat flow meter data were calibrated using results from steady-state calibrated hot box tests of Wall C3. Heat flow meter readings were plotted against measured heat flow rates, Q_w, for the three steady-state tests. The slope of the line through the three points was used as a calibration factor.

Heat flow rates predicted by steady-state analysis were calculated on an hourly basis from wall surface temperatures using Eq. (3). Peaks in the Q_{ss} curve occur where differences in temperature between the outdoor and indoor wall surfaces are the greatest.

Peaks in the measured heat flow curve, Q_w, have smaller amplitudes and occur at a later time than those on the Q_{ss} curve. The reduction in amplitude and thermal lag are due to the storage capacity of low density concrete.

Thermal Lag

Thermal lag is a measure of the response of both inside and outside surface temperatures and heat flow to fluctuations in outdoor temperature. Lag is indicative of both thermal resistance and heat storage capacity of the test specimen, since both of these factors influence the rate of heat flow.

Thermal lag is quantified by two measures in Table 17. In one measure, lag was calculated as the time required for the

TABLE 17 - SUMMARY OF DYNAMIC TEST RESULTS FOR WALL C3

Test Cycle	Thermal Lag, hrs					Reduction in Amplitude, percent			Total Energy, W·hr			Net Energy, W·hr		
	t_o vs t_1		Q_{ss} vs Q_w		Avg.									
	@ Max	@ Min	@ Max	@ Min		@ Max	@ Min	Avg.	Q'_a	Q'_b	Q'_a/Q'_b	Measured	Calculated	Meas./Calc.
NBS	9	7	9	8	8.5	66	56	61	601	1538	0.39	-217	-270	0.80
NBS+10	8	8	10	8	8.5	69	55	62	641	1501	0.43	383	433	0.88
NBS-10	8.5	7	9	9	8.5	66	56	61	909	1668	0.54	-909	-962	0.94

maximum or minimum indoor surface temperature to be reached after the maximum or minimum outdoor air temperature was attained. In the second measure, lag was 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}, was attained. This is illustrated in Fig. 25. As can be seen from Table 17, both measures gave similar results. Results were also similar for each of the test cycles. Average lag for each cycle was 8.5 hours. Therefore, Wall C3 delayed peak heat flows by 8.5 hours.

Data from the heat flow meter mounted on the indoor surface of Wall C3, denoted Q_{hfm} in the figures, consistently show the same lag time as measured heat flow, Q_w.

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

The reduction in amplitude, or damping, is influenced by the same factors as thermal lag. Both thermal resistance and heat storage capacity affect damping. The damping effect can be defined as shown in Fig. 25.

Values for percent reduction in amplitude listed in Table 17 were calculated using the following equation:

$$A = [1 - (Q_w' - \bar{Q}_w)/(Q_{ss}' - \bar{Q}_w)] \cdot 100 \qquad (11)$$

where:

A = percent reduction in amplitude

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

Q'_w = maximum or minimum measured heat flow through wall

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

As shown in Table 17, average reduction in amplitude for the three cycles was between 61 and 62%.

Actual maximum heat flow through a wall is important in determining the peak energy load for a building envelope. If peak heat flows are reduced, peak energy demands will decrease. Storage capacity, as well as thermal transmittance of each wall in a building envelope, influences peak energy requirements.

Amplitudes for indoor surface heat flow meter data, Q_{hfm}, are less than amplitudes for measured heat flow, Q_w. This occurs for all dynamic cycles and is illustrated in Figs. 25, 28, and 31. Amplitudes for Q_{hfm} and Q_w differ because of the physical effect of a heat flow meter mounted on a wall. Heat flow paths are altered at the location of the heat flow meter. Heat flow meter calibration using steady-state results does not correct for effects of the meter on dynamic measurements.

Measured Energy

Results of dynamic tests were also compared using measures of energy expended in maintaining constant indoor temperature while outdoor temperatures were varied. Energy expended is a measure of heat flow through the test wall. It should be noted that comparison of measured energy values for the test walls is limited to specimens and dynamic cycles evaluated in this program. Results are for these diurnal test cycles and should not be arbitrarily assumed to represent annual heating and cooling loads. In addition, results are for individual opaque wall assemblies. As such, they are representative of only one component of the building envelope.

Two parameters were derived as measures of energy expended, or heat flow through the test walls, during dynamic cycles. These are illustrated in Fig. 32. The curve marked "Q_w" is a measure of heat flow through the test wall. Results were corrected for heat extracted by indoor cooling and for heat transfer to laboratory space using Eq. (1), as previously described.

Areas within "loops" of the measured energy curves were used to provide an indication of total energy expended. These areas are denoted as Q'_{a+} and Q'_{a-} in Fig. 32. The sum of the absolute values of positive and negative areas is taken to represent total energy over a 24-hr period. This value is denoted as Q'_a in Table 17.

A similar procedure is used to calculate total energy based on steady-state predictions over a 24-hr period. This value, denoted Q'_b in Table 17, is the sum of the absolute values of positive and negative areas under a steady-state curve.

Values of Q'_a, Q'_b, and Q'_a/Q'_b for each test cycle are listed in Table 17. For all three test cycles, total measured energy, Q'_a, was considerably less than total energy based on steady-state predictions, Q'_b.

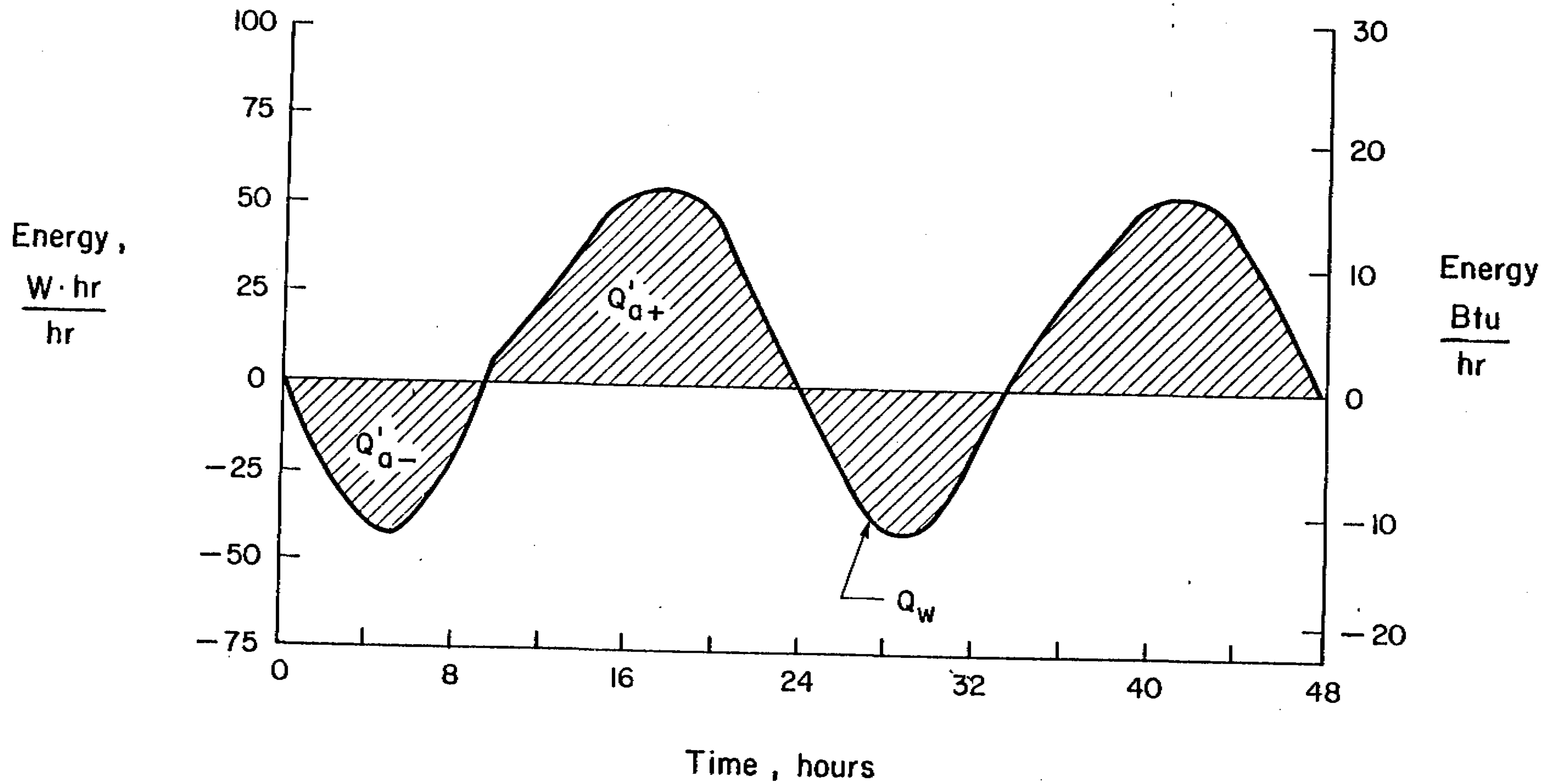


Fig. 32 Definition of Measured Energy

Measured net energy theoretically should be equal to net energy based on steady-state predictions. Measured net energy for a 24-hr periodic cycle is equal to the sum of hourly measured rates of heat flow. These values can be found by totalling values of "Q_w" in columns of Table 16. Steady-state net energy was calculated according to the following equation:

$$Q_n = \frac{C \cdot A \cdot (t_1^m - t_2^m) \cdot 24}{3.413} \qquad (12)$$

where:

Q_n = net energy based on steady-state predictions

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

t_1^m = mean temperature of inside wall surface over 24-hr cycle, °F

t_2^m = mean temperature of outside wall surface over 24-hr cycle, °F

3.413 = conversion factor from W·hr/hr to Btu/hr

C = average measured thermal conductance, $Btu/hr \cdot ft^2 \cdot °F$

The value Q_n can also be found by summing values of "Q_{ss}" in columns of Table 16.

A comparison of calculated and measured net energy data is given in Table 17. Measured and calculated values agree to within 20%.

Cycles with net heat flow close to zero have greater total energy savings. For example, Q_a'/Q_b' is smallest for the NBS cycle. This is also the cycle with net heat flow through Wall C3 closest to zero.

THERMAL PROPERTIES OF CONCRETE UNDER TRANSIENT TEST CONDITIONS

Time required for a wall to reach steady-state conditions 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, the outdoor chamber temperature setting is changed. The transient test continues until the wall reaches an equilibrium for the new outdoor chamber air temperature.

For Wall C3, energy required to maintain a constant indoor temperature was monitored as a function of time. The rate of heat flow through Wall C3 was determined using Eq. (1) for hourly averages of data.

Transient Test Results

Transient test results, illustrated in Figs. 33, 34, and 35, are for initial and final wall mean temperatures of 72.7°F (22.6°C) and 31.0°F (-0.5°C), respectively. Figure 33 gives measured air, surface, and internal wall temperatures. Air-to-air, surface-to-surface, and surface-to-air temperature differentials are illustrated in Fig. 34.

Figure 35 presents Q_W, measured heat flow, and Q_{SS}, heat flow predicted by steady-state analysis. Heat flow rates measured by a heat flow meter mounted on the indoor surface of

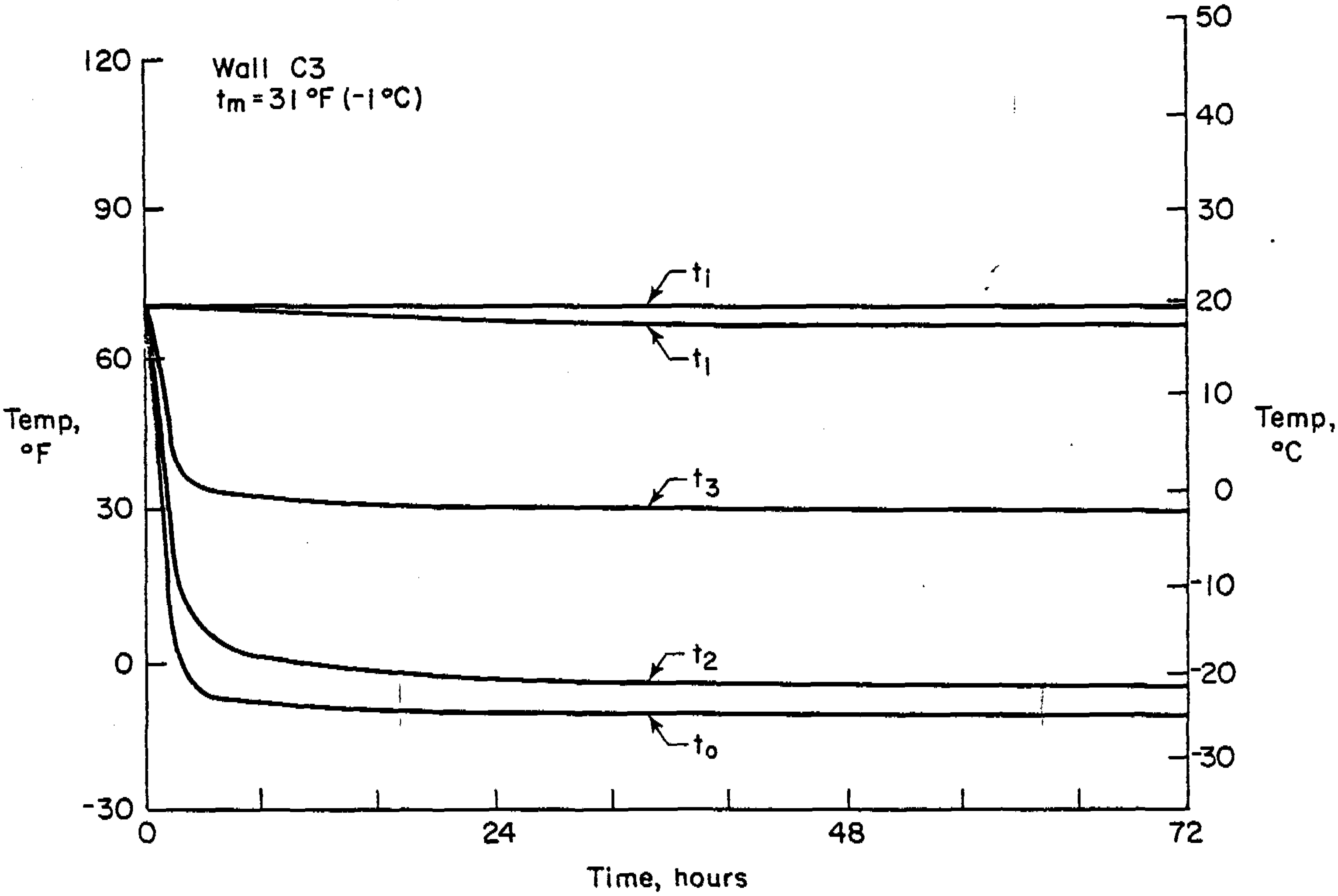


Fig. 33 Measured Temperatures of Wall C3 for Transient Test

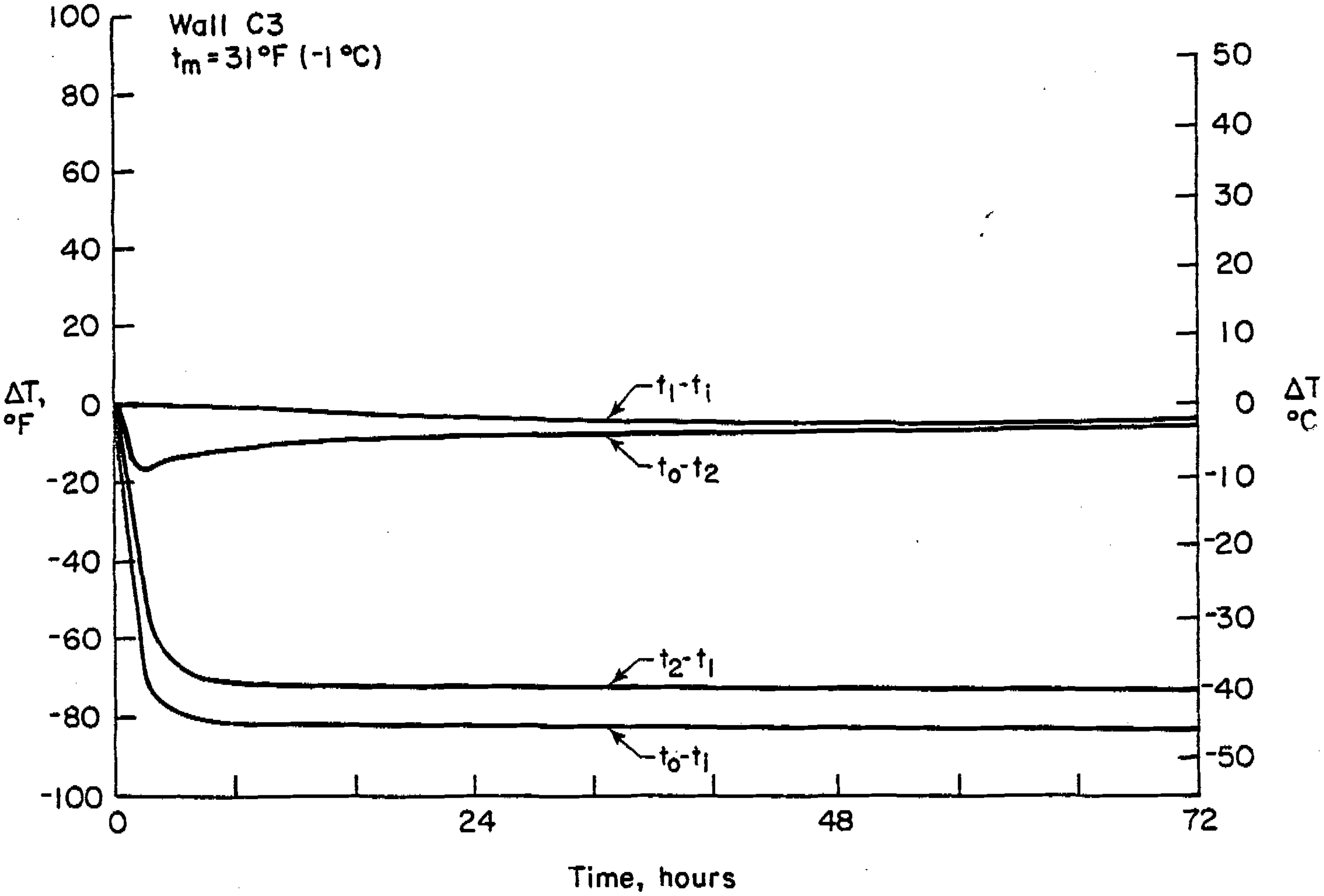


Fig. 34 Measured Temperature Differentials of Wall C3 for Transient Test

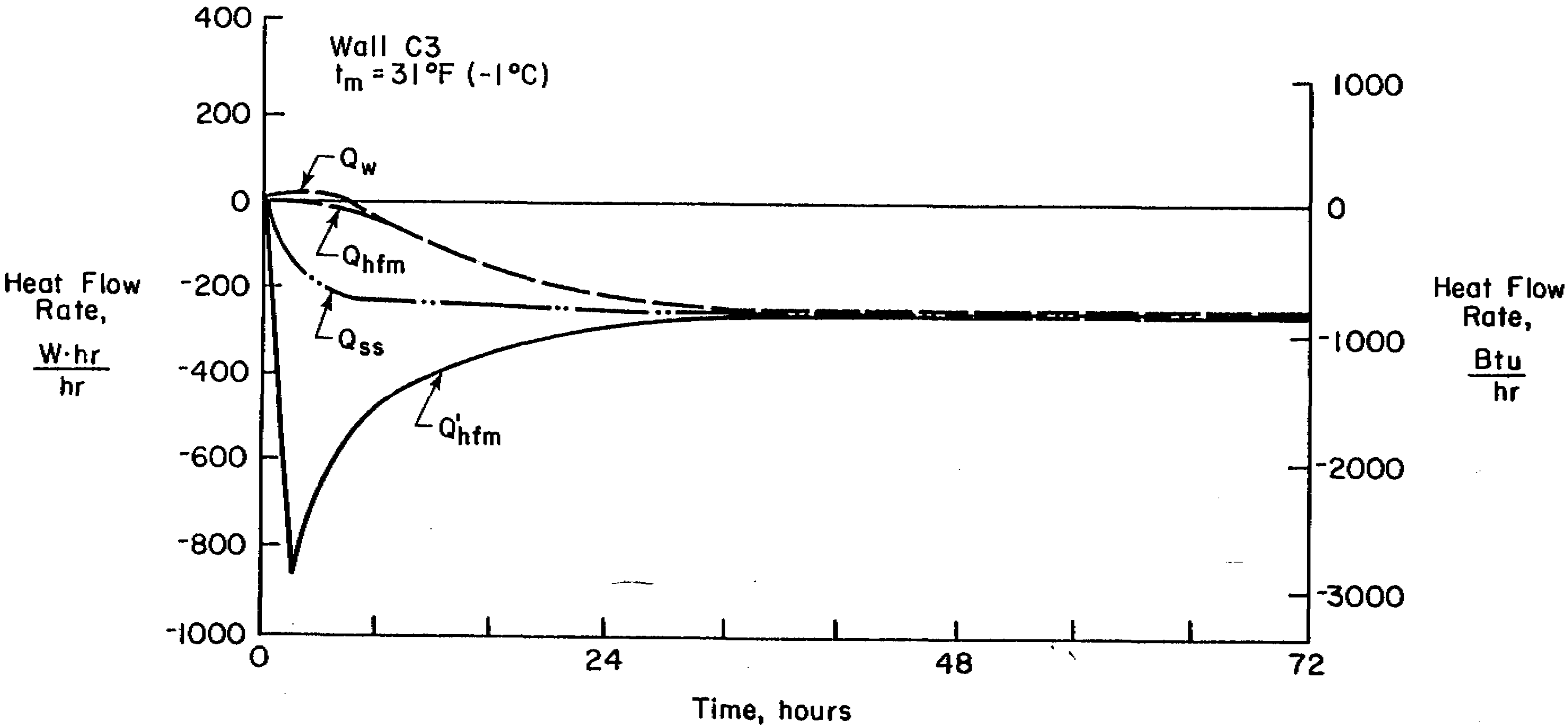


Fig. 35 Rate of Heat Flow Through Wall C3 for Transient Test

Wall C3, Q_{hfm}, and on the outdoor wall surface, Q'_{hfm}, are also shown. Values of Q_{ss} were calculated on an hourly basis from wall surface temperatures using Eq. (3). Heat flow meter data were calibrated using results of steady-state calibrated hot box tests. The values of Q_{ss} and Q_w are equivalent after 67 hours of testing. However, Q_{ss} approached the final heat flow rate more rapidly than Q_w.

Results of this transient test are summarized in Table 18. Calibrated hot box test results show that Wall C3 reached 95% of the final heat flow rate after 47 hours. Heat flow rates based on steady-state analysis predicted 95% of the final heat flow rate would be reached after 5 hours. Similarly, 90% of the final heat flow rate was measured as occurring after 35 hours, and was predicted to occur after 4 hours. The amount of time required for Wall C3 to reach 90% of the final heat flow rate was nine times greater than steady-state predictions.

This delayed response time of Wall C3 when compared to predicted response based on steady-state analysis is similar to the effect of thermal lag. Transient test results show that Wall C3 prolonged the consequences of a sudden change in outdoor chamber air temperature.

SUMMARY AND CONCLUSIONS

This report presents results of an experimental investigation of heat transmission characteristics for a low density concrete wall under steady-state and dynamic temperature conditions. Companion low density concrete control specimens were also tested to determine physical and thermal properties.

TABLE 18 - SUMMARY OF TRANSIENT TEST RESULTS FOR WALL C3

	Measured Q_W, W·hr/hr	Time Required to Reach Q_W, hr	Steady-State Q_{SS}, W·hr/hr	Time Required to Reach Q_{SS}, hr
Final Heat Flow Rate	- 260	67	- 242	9
95% of Final Heat Flow Rate	- 247	47	- 230	5
90% of Final Heat Flow Rate	- 234	35	- 218	4

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

1. Specific heat of Wall C3 was 0.179 Btu/lb·°F (750 J/kg·°K) at a moisture content of 9.5% relative to ovendry weight.
2. Apparent thermal conductivity of Wall C3 at 70°F (21°C) derived from steady-state calibrated hot box tests was 1.44 Btu·in./hr·ft^2·°F (0.207 W/m·°K).
3. Apparent thermal conductivity of ovendry concrete found using ASTM Designation: C177 with embedded thermocouples was 1.44 Btu·in./hr·ft^2·°F (0.207 W/m·°K).
4. Measured conductivity of air dry concrete determined from the hot wire method was 3.05 Btu·in./hr·ft^2·°F (0.440 W/m·°K). Moisture content of the concrete was 17.3% relative to ovendry weight.
5. Measured thermal diffusivity of a saturated specimen with the same mix design as Wall C3 was 0.00849 ft^2/hr (0.219 mm^2/s).
6. Total thermal resistance (R_T) and thermal transmittance (U) for Wall C3 at 70°F (21°C) were 6.8 hr·ft^2·°F/Btu (1.2 m^2·°K/W) and 0.15 Btu/hr·ft^2·°F (0.84 W/m^2·°K), respectively.
7. As indicated by thermal lag, heat storage capacity of Wall C3 delayed heat flow through the specimen. Average thermal lag for all three test cycles was 8.5 hours.

8. As indicated by the damping effect, heat storage capacity of Wall C3 reduced peak heat flows through the specimen. Average reductions in amplitude of Wall C3 for the three test cycles ranged from 61 to 62%.
9. For the three diurnal temperature cycles, energy requirements for a 24-hour period were less than would be predicted by steady-state anaylsis. Cycles with net heat flow closer to zero had greater total energy savings. Total measured heat flows over the 24-hour cycles tested ranged from 39 to 54% of those predicted by steady-state analysis. These reductions in total heat flow are attributed to effects of thermal mass.
10. Transient test results indicate that heat storage capacity of Wall C3 delayed heat flow through the specimen. The amount of time required for the specimen to reach a steady-state condition was approximately nine times greater than would be predicted by steady-state analysis.

Results described in this report provide data on thermal response of a low density concrete wall 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, the 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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