Portland Cement Association

Research & Development Information

PCA R&D Serial No. 0889

Condensation on Inside Surface of Multi-layer Concrete Walls with and Without Metal Ties

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

5420 Old Orchard Road
Skokie, Illinois 60077-1083
847.966.6200 Fax 847.966.9481

www.cement.org

PCA R&D Serial No. 0889

Report to

Portland Cement Association
Project No. HM-3400/4324

CONDENSATION ON INSIDE SURFACE OF MULTI-LAYER CONCRETE WALLS WITH AND WITHOUT METAL TIES

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

Report prepared by

CONSTRUCTION TECHNOLOGY LABORATORIES
A Division of the Portland Cement Association
5420 Old Orchard Road
Skokie, Illinois 60077

December 1986

WP ID NO. 1827D

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES
(Continued)

Page

CONDENSATION ON INSIDE SURFACE OF MULTI-LAYER CONCRETE WALLS WITH AND WITHOUT METAL TIES

by

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

SYNOPSIS

Tests were conducted to determine whether metal ties connecting layers of insulated concrete sandwich panel walls can increase the potential for condensation on the indoor wall surface. Two concrete sandwich panel walls were subjected to steady-state and dynamic temperature conditions using a calibrated hot box. The two tested walls consisted of 2-in. of extruded polystyrene insulation board between two 3-in. normal weight concrete layers. The first wall, a control wall, contained no ties. Concrete layers of the second wall were connected using stainless steel ties and anchors which passed through the insulation. A third wall, consisting of solid concrete, was also investigated to evaluate the potential for condensation at solid portions of multi-layer concrete walls.

Measured temperatures were used to evaluate indoor relative humidities at which condensation would be expected to occur on the indoor surface of test walls. Results of dynamic tests were compared to results of steady-state tests to determine the effect of thermal mass on indoor surface condensation.

The test results indicated that relative humidities required to potentially cause condensation on insulated concrete sandwich panel walls for selected winter temperature conditions are greater than 88%. Humidities of

*Respectively, Structural Engineer, Analytical Design Section, and Senior Research Engineer, Fire/Thermal Technology Section, Construction Technology Laboratories, a Division of the Portland Cement Association, 5420 Old Orchard Road, Skokie, Illinois 60077

this magnitude are significantly larger than those typically encountered inside residential and commercial buildings during winter. It can be concluded that condensation would not be a problem on indoor surfaces of insulated portions of this type of wall, with or without the type of metal ties considered in this investigation. The fact that these walls are well insulated allows the indoor surface temperature to remain close to indoor air temperatures. The influence of the metal ties appeared to be negligible, both on overall wall performance and on conditions at the location of a tie.

Relative humidities required to potentially cause condensation evaluated using dynamic tests were not significantly different than those determined from steady-state tests. Steady-state relative humidities ranged from 88 to 99% while results from dynamic tests ranged from 92 to 99%.

Solid portions of concrete sandwich panel walls will be more likely to experience condensation. Steady-state test results on the solid concrete wall indicate that condensation is likely to occur for relative humidities of 42 to 80%, depending on temperature conditions. For the one dynamic test considered, condensation would potentially occur at relative humidities of 75 to 85%. Because of the large thermal mass of the wall, indoor surface temperatures remain closer to indoor air temperatures, reducing the likelihood of condensation.

CONDENSATION ON INSIDE SURFACE OF MULTI-LAYER CONCRETE WALLS WITH AND WITHOUT METAL TIES

by

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

INTRODUCTION AND OBJECTIVES

Tests were conducted to determine whether metal ties connecting layers of insulated concrete sandwich panel walls can increase the potential for condensation on the indoor wall surface. For the condensation study, two walls were subjected to steady-state and dynamic temperature conditions using a calibrated hot box. The two tested walls consisted of 2 in. of extruded polystyrene insulation board between two 3-in. normal weight concrete layers as shown in Fig. 1. The first wall, a control wall, contained no ties. Concrete layers of the second wall were connected using stainless steel ties and anchors which passed through the insulation. Temperature measurements from previous calibrated hot box tests of an 8-in. thick normal weight concrete wall were used to determine relative humidities at which condensation is likely to occur on solid portions of concrete sandwich panel walls.

Average measured indoor surface temperatures were used to evaluate indoor relative humidities at which condensation would potentially occur on indoor surfaces of test walls. For sandwich panel walls, temperatures were also evaluated at the location of ties. Results of dynamic tests were compared to results of steady-state tests to determine the effect of thermal mass on indoor surface condensation.

---

*Respectively, Structural Engineer, Analytical Design Section, and Senior Research Engineer, Fire/Thermal Technology Section, Construction Technology Laboratories, a Division of the Portland Cement Association, 5420 Old Orchard Road, Skokie, Illinois 60077

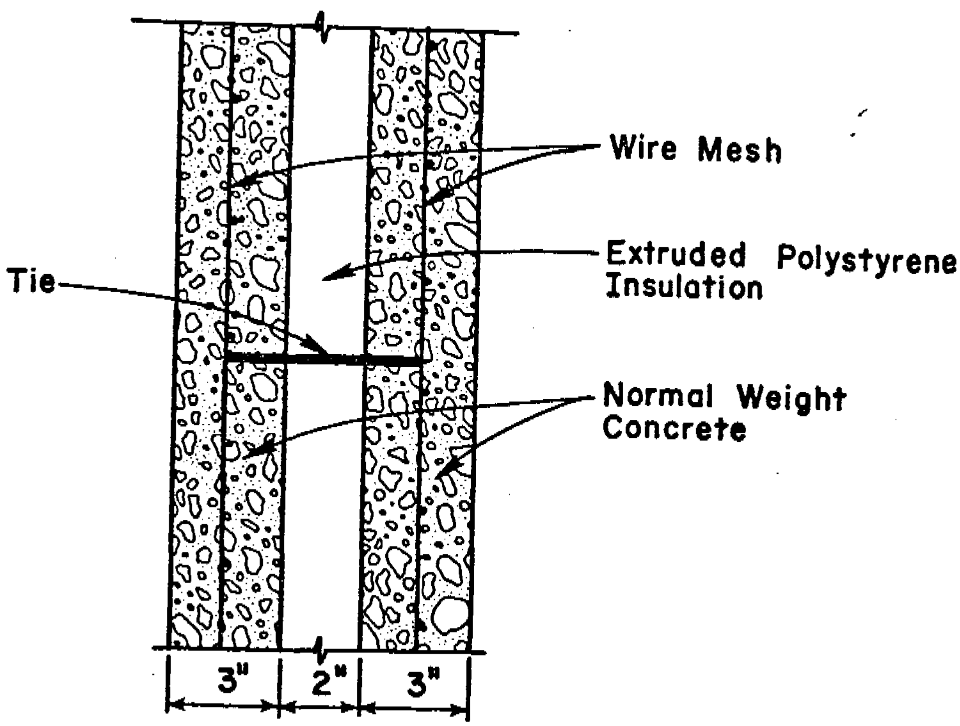


Fig. 1 Cross Section of Insulated Sandwich Panel Walls

The primary objective of calibrated hot box tests was to determine heat transfer characteristics of the walls described previously. Results for the two sandwich panel walls and the solid concrete wall are summarized in References 1 and 2, respectively. References 1 and 2 describe specimen construction, instrumentation, the calibrated hot box test program, and test results.

The test program was conducted at Construction Technology Laboratories (CTL). Work was authorized in the 1984 Work Program under Project No. HM-3210, in the 1985 Work Program under Project No. HM-3210 (changed to HM-3211 in June 1985), and in the 1986 Work Program under Project No. HM-3400.

SCOPE

The scope of work performed by Construction Technology Laboratories (CTL) consisted of the following tasks:

1. Selection of the tie system to be used in the concrete sandwich panel wall.
2. Construction of two insulated concrete sandwich panel wall specimens, one with stainless steel ties and one with no ties.
3. Instrumentation of the two concrete sandwich panel wall specimens.
4. Performance of calibrated hot box tests on the two concrete sandwich panel walls for steady-state and dynamic temperature conditions in accordance with ASTM Designation: C 976.[(3)*] The wall with no ties was subjected to two steady-state tests and three dynamic tests. The wall with ties was subjected to two steady-state tests and four dynamic tests.
5. Analysis of test results to determine indoor relative humidities that would be expected to cause condensation on insulated and uninsulated

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

inside surfaces of concrete sandwich panel walls. Test results for insulated portions of sandwich panel walls were from work performed in Item No. 4. Test results for uninsulated (solid concrete) portions of sandwich panel walls were from previous calibrated hot box tests performed on a solid concrete wall (Ref. 2).

6. Preparation of this report describing specimen test results and results of the analysis.

Item No's. 1, 2, 3, and 4 were performed in conjunction with work described in Reference 1.

BACKGROUND

Condensation may occur on indoor surfaces of exterior walls when the outdoor surface is exposed to cold air. Depending on thermal properties of the wall, and the outdoor and indoor air temperature history, the indoor wall surface temperature may be less than the indoor air temperature. If the indoor surface temperature is at or below the dewpoint of the indoor air, condensation would be expected to occur on the indoor surface. This can lead to moisture damage to the wall and its finishes.

It has been hypothesized that the thermal bridge caused by penetration of a metal tie through insulation can result in condensation concentrated at tie locations. The high thermal conductivity of the steel relative to the surrounding insulation may cause localized heat flow through the wall, as shown in Fig. 2. This may result in a lower indoor surface temperature at the location of the metal tie. Condensation would be expected to occur at any point on the wall where the surface temperature is less than the dewpoint of the indoor air.

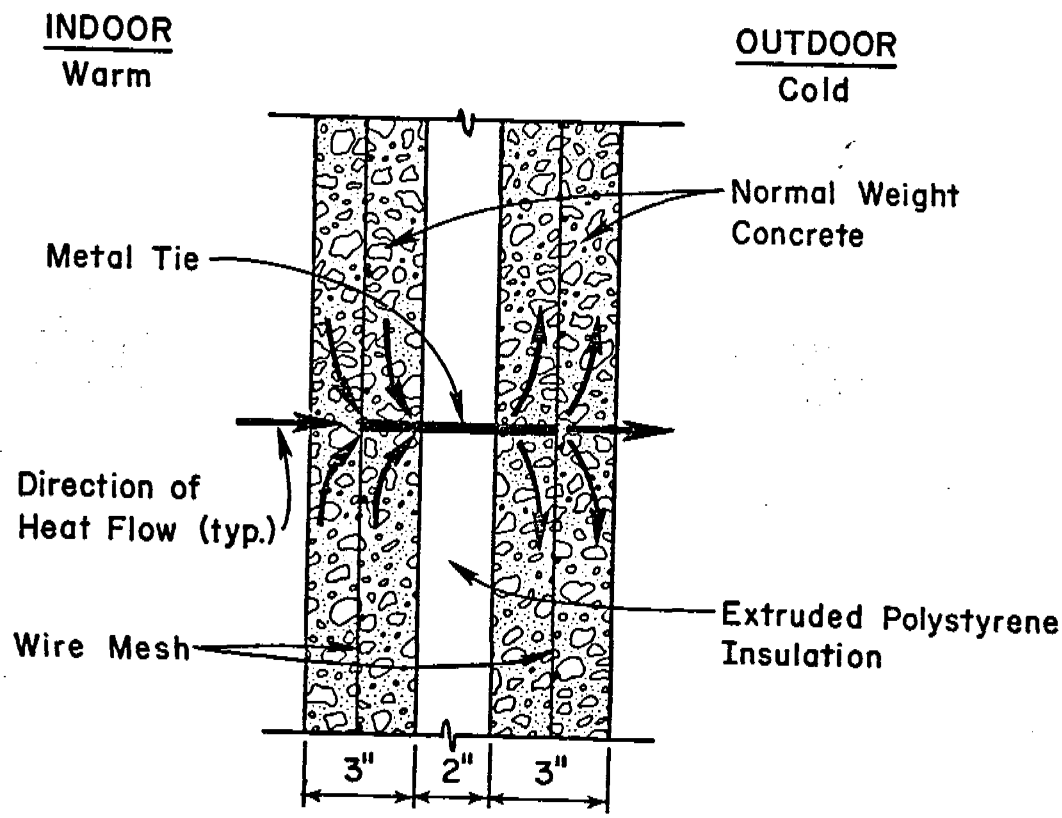


Fig. 2 Thermal Bridge Due to Metal Tie
Penetrating Insulation

TEST SPECIMENS

Two insulated concrete sandwich panel walls were constructed by CTL and subsequently tested in a calibrated hot box. Walls consisted of extruded polystyrene board insulation sandwiched between normal weight concrete layers as shown in Fig. 1. Overall nominal dimensions of each wall were 103x103 in. Nominal thicknesses of concrete and insulation layers were 3 and 2 in., respectively. Walls were reinforced with a single layer of 6x6-in. W1.4xW1.4 welded wire fabric located at midthickness of each 3-in. concrete layer.

The first wall, designated Wall P1, was constructed without any ties bridging between the two concrete layers.

The second wall, designated Wall P2, was constructed with stainless steel ties and torsion anchors connecting the two concrete layers. Locations of the four torsion anchors and sixteen metal ties are shown in Fig. 3. A Type A-3 Tie consists of a 0.118-in. diameter bar with a nominal length of 5 in. Torsion anchors are described more thoroughly in Reference 1. Ties and torsion anchors were manufactured by The Burke Company and were installed per manufacturer's instructions.

This report evaluates temperatures at the location of ties rather than torsion anchors because of the relative prevalence of ties.

The sandwich panel walls were constructed horizontally. First, the lower concrete panel was cast with wire mesh, ties, and torsion anchors in place. Figure 4 shows a tie attached directly to the wire mesh of the lower layer before concrete was placed.

Sections of insulation were cut out at tie locations. Insulation was placed over the bottom concrete layer. Figure 5 shows insulation in place with a tie penetrating the cutout section. Cut-out sections were saved and replaced, as shown in Fig. 6, after insulation board was placed on the first concrete layer. Seams of cut-out sections were taped on the top surface using

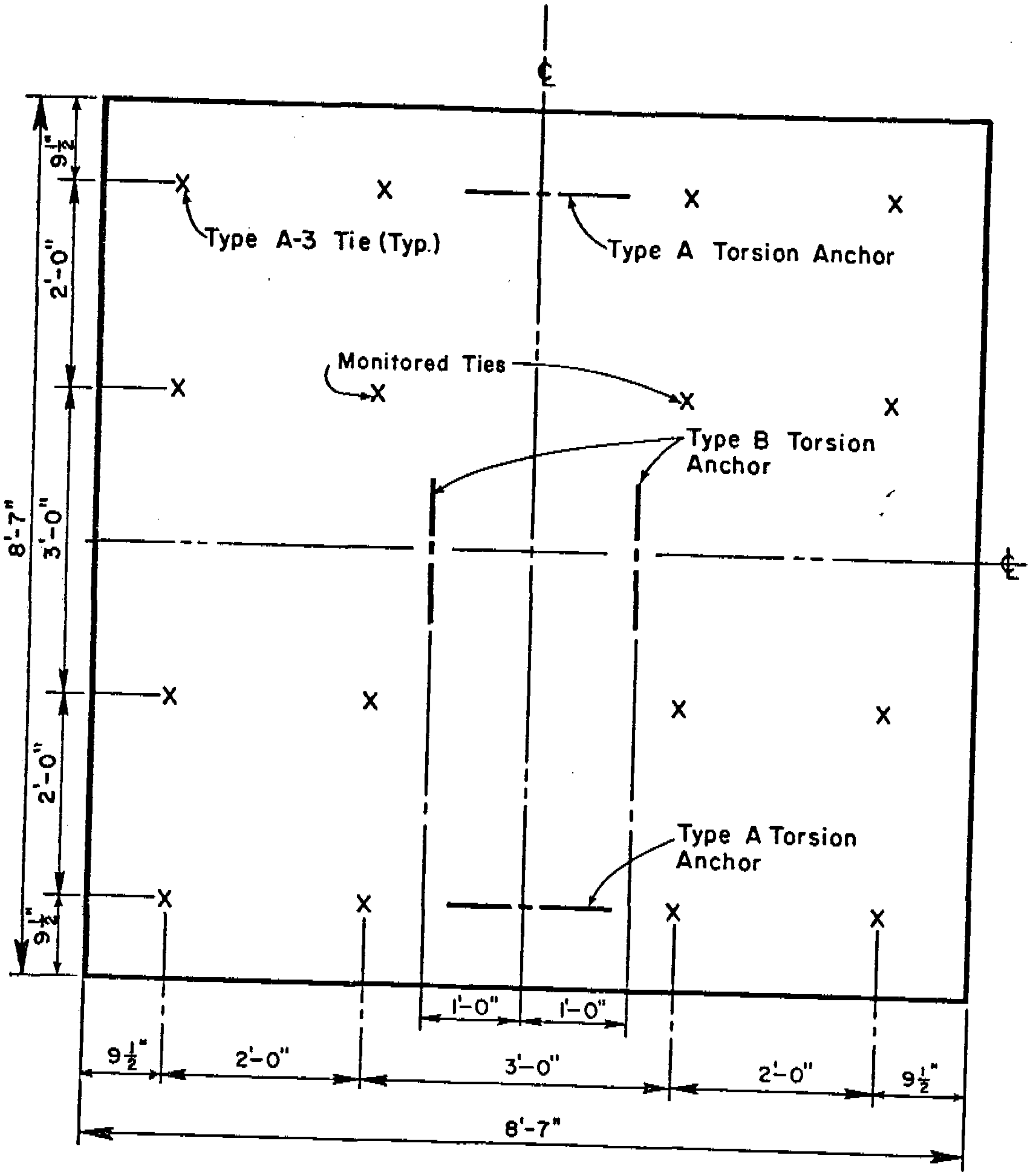


Fig. 3 Location of Stainless Steel Torsion Anchors and Ties in Wall P2

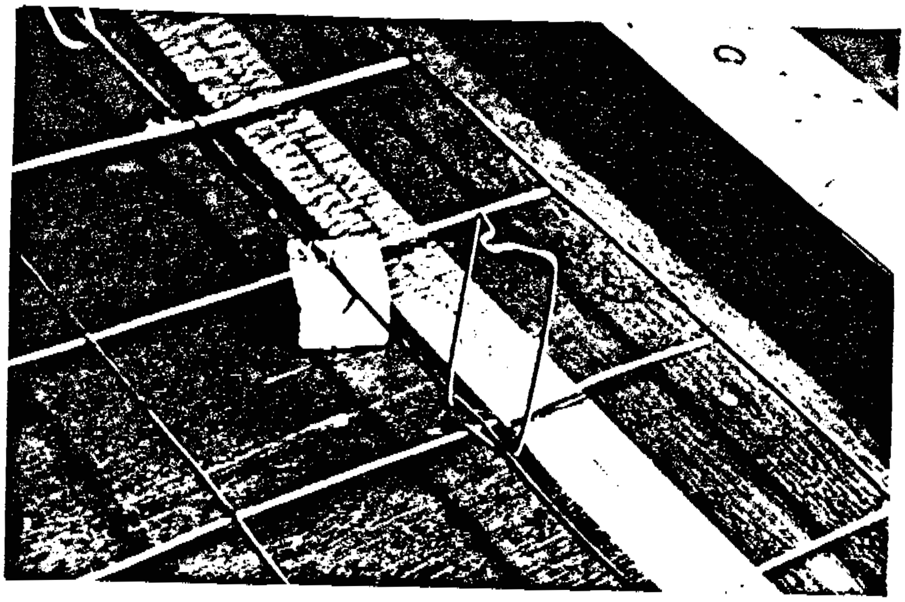


Fig. 4 Mounting of Type A-3 Metal Tie to Wire Mesh for Wall P2

Fig. 5 Insulation Cut-Out for Wall P2 to Allow Penetration of Metal Tie

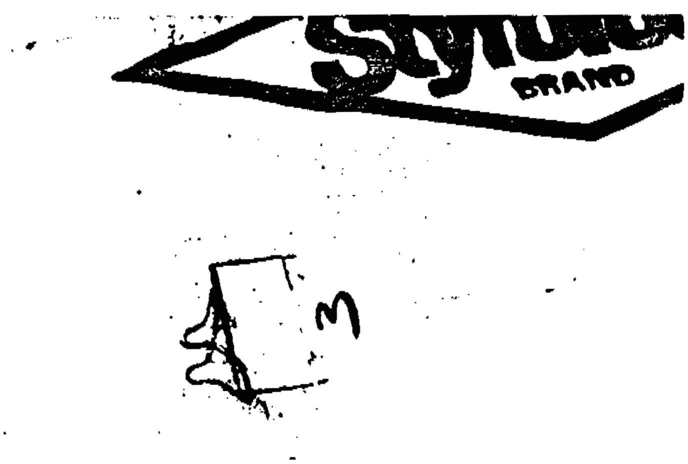


Fig. 6 Insulation Replaced Around Metal Tie

duct tape. Wire mesh reinforcement for the top concrete layer was placed on the insulation and tied to protruding ties and torsion anchors. The top concrete layer was then cast over the insulation. These procedures are recommended by the tie manufacturer, and are detailed in the manufacturer's installation procedures.

Detailed descriptions of construction of Walls P1 and P2 are given in Ref. 1. Properties of Walls P1 and P2 are given in Table 1.

The solid concrete wall, designated Wall C1, was constructed and tested in the calibrated hot box at CTL in 1981. Wall C1 was an 8-in. thick normal weight concrete wall. It was reinforced with a single layer of No. 5 bars spaced 12-in. center-to-center in each direction. Bars were located at the approximate midthickness of the wall. Figure 7 shows details of reinforcement for Wall C1. Faces of the wall were coated with a cementitious waterproofing and sealing material and then painted. Detailed descriptions of construction and calibrated hot box testing of Wall C1 are given in Ref. 2. Properties of Wall C1 are given in Table 1.

INSTRUMENTATION

Ninety-six thermocouples, corresponding to ASTM Designation: E230, "Standard Temperature-Electromotive Force (EMF) Tables for Thermocouples,"[3] Type T, were used to measure temperatures during thermal testing of the concrete sandwich panel walls. For Walls P1 and P2, 16 thermocouples were located in the air space on each side of the test specimen, 16 on each face of the test wall, and 16 at each of the two concrete/insulation interfaces. The 16 thermocouples in each plane were spaced 20-3/5-in. apart in a 4x4 grid over the wall area.

TABLE 1 - SUMMARY OF PROPERTIES FOR WALLS P1, P2, AND C1[1,2]

Property	Measured Value		
	Wall P1	Wall P2	Wall C1
Wall Thermal Resistance,[1] hr•ft^2•°F/Btu	9.7	9.1	1.56
Unit Weight of Wall, psf	77.1[2]	74.5[3]	99.7[3]
Average Wall Thickness, in.	8.2	8.2	8.3
Wall Area, ft^2	73.90	73.94	73.64
Insulation Thermal Resistance,[4] hr•ft^2•°F/Btu	8.9	8.9	--
Insulation Thickness, in.	2	2	--
Insulation Density, pcf	1.87	1.86	--

Notes:

(1) Thermal resistance calculated using heat flow measured by calibrated hot box and standard surface resistance coefficients of 0.68 hr•ft^2•°F/Btu for outdoor surfaces and 0.17 hr•ft^2•°F/Btu for indoor surfaces. Values listed are at a 75°F wall mean temperature.

(2) Measured after calibrated hot box tests were completed.

(3) Measured before calibrated hot box testing.

(4) Values are for a 75°F mean temperature and were measured in accordance with ASTM Designation: C177.

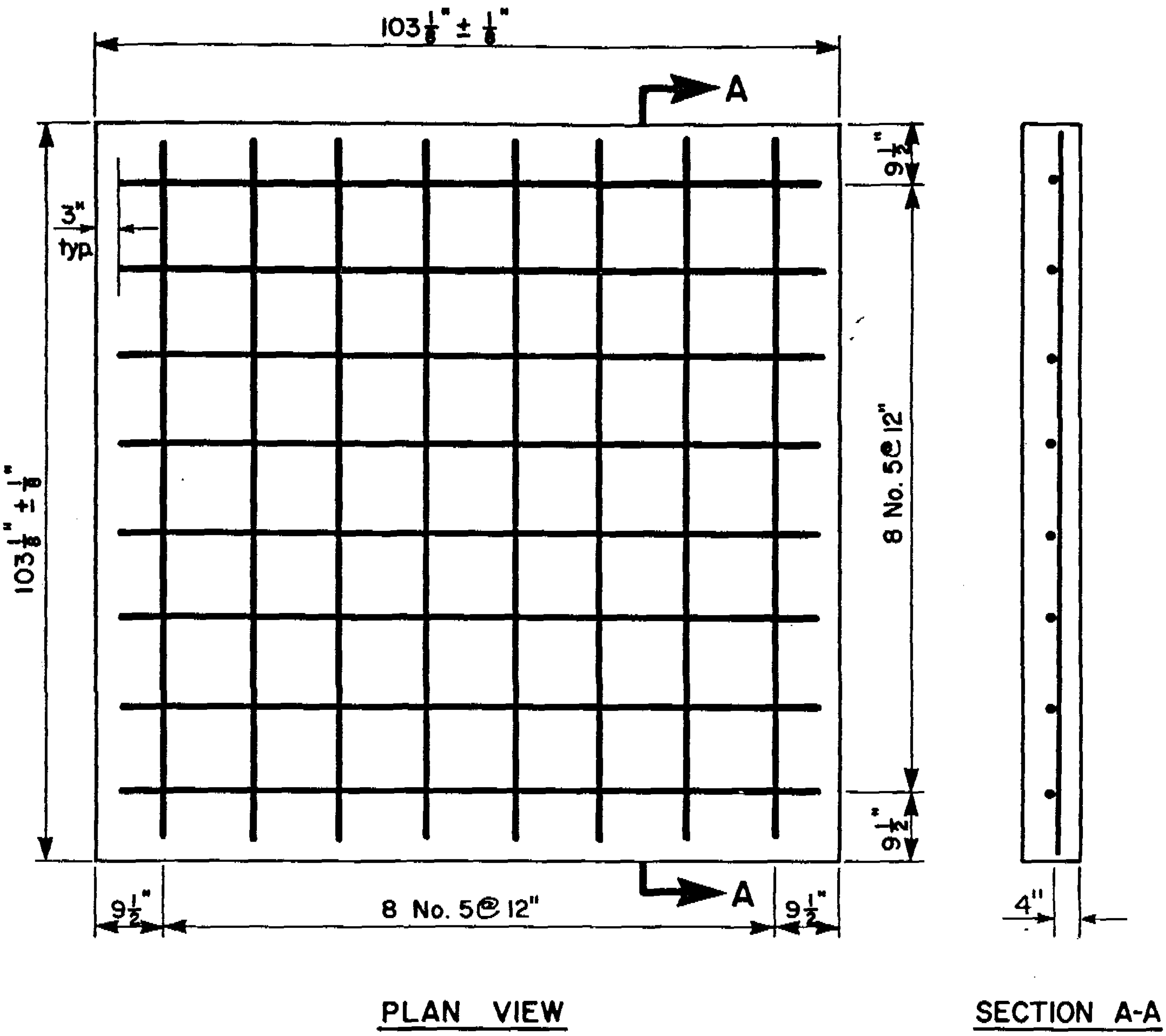


Fig. 7 Reinforcement Details for Normal-Weight Concrete Wall C1

Thermocouples measuring temperatures in the air space of each chamber of the calibrated hot box were located approximately 3 in. from the face of the test wall.

Surface thermocouples were securely attached to the wall with duct tape for a length of approximately 4 in. The tape covering the sensors was painted the same color as the test wall surface. Thermocouples attached to indoor and outdoor surfaces of Wall P1 are shown in Figs 8 and 9, respectively.

Additional thermocouples were also used to monitor temperatures on and near ties for Wall P2. Two stainless steel ties were monitored. Each instrumented tie was located 2-ft 9-1/2 in. from the top of the wall and 2-ft 9-1/2 in. from the side of the wall. Monitored tie locations are shown in Fig. 3. Thermocouple locations in a typical cross-section of the wall are shown in Fig. 10. Thermocouple sensors were taped to each end of monitored ties, on concrete surfaces directly across from monitored ties, and on concrete surfaces 6 in. and 12 in. above monitored ties. The thermocouples located 12 in. above monitored ties are midway between two ties. Reported temperatures are average readings of two similarly located thermocouples at the monitored ties.

Thermocouples were placed in Wall P1 at the same locations as those placed in Wall P2. Comparisons of measurements from companion thermocouples on Walls P1 and P2 show effects of ties on concrete temperatures and indoor surface condensation.

For calibrated hot box tests on Wall C1, 16 thermocouples were located in the air space on each side of the wall, 16 on each face of the specimen, and 16 at the approximate midthickness of the wall. The 16 thermocouples in each plane were spaced 20-3/5-in. apart in a 4x4 grid over the wall area. Air and surface thermocouples were mounted in the same manner as described above for

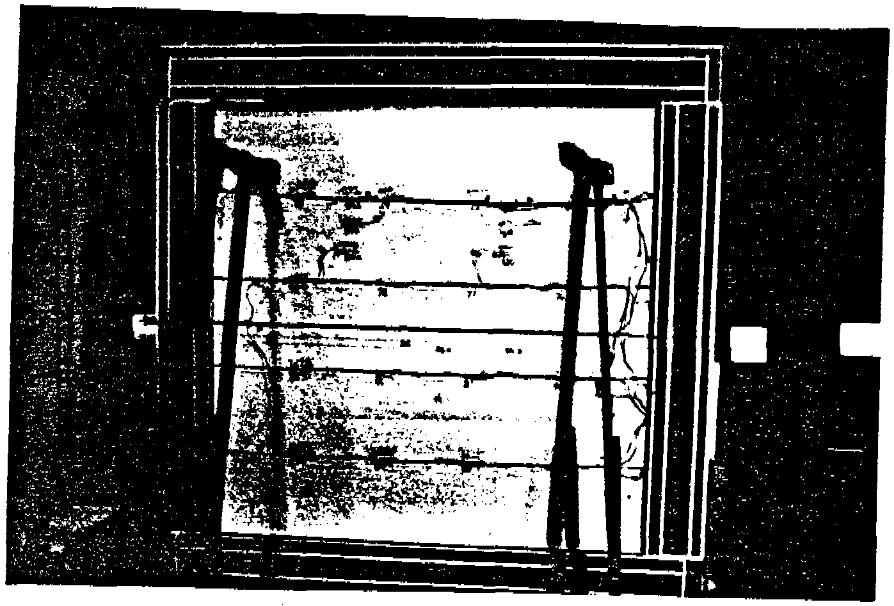


Fig. 8 Indoor Surface of Wall P1 Before Calibrated Hot Box Testing

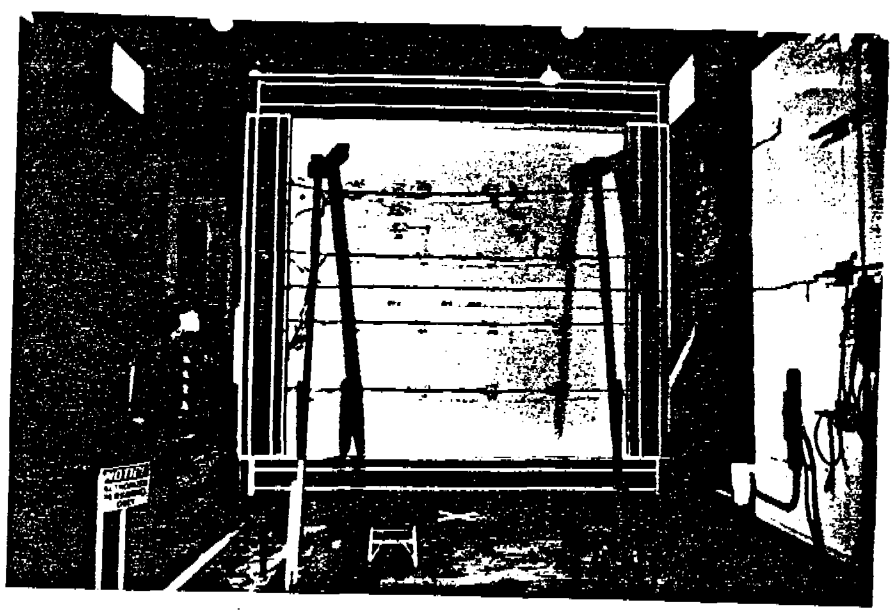


Fig. 9 Outdoor Surface of Wall P1 Before Calibrated Hot Box Testing

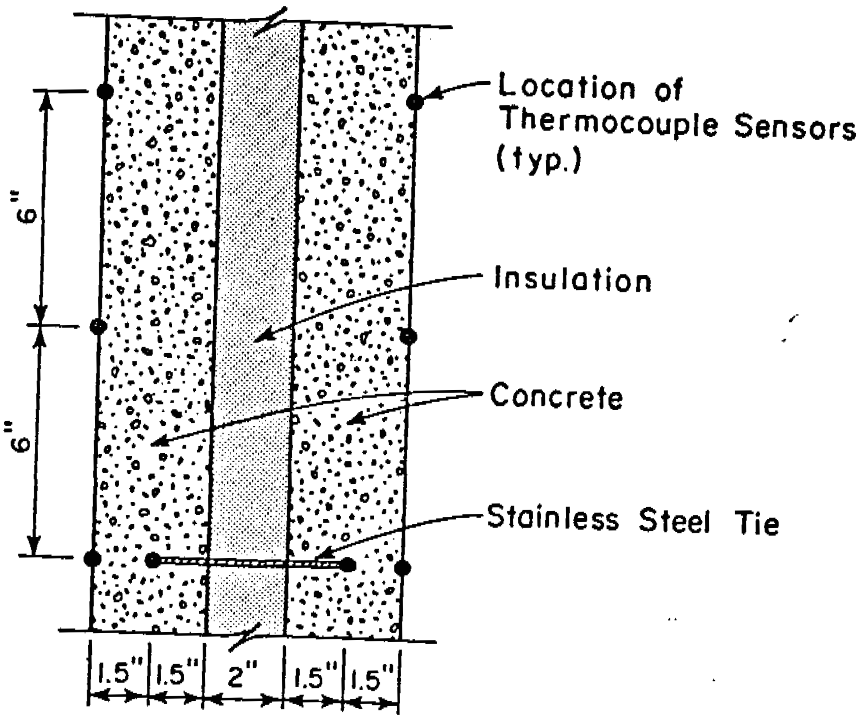


Fig. 10 Locations of Thermocouples in Vicinity
of Stainless Steel Tie

Walls P1 and P2. Internal thermocouples were attached to reinforcement to secure their location at the wall midthickness. Further details on the instrumentation of Wall C1 can be found in Reference 2.

CALIBRATED HOT BOX TEST FACILITY

Tests were conducted in the calibrated hot box facility shown in Figs. 11 and 12. Tests were performed in accordance with ASTM Designation: C 976, "Thermal Performance of Building Assemblies by Means of Calibrated Hot Box."[3]

A calibrated hot box is generally used to measure heat flow through building components. Heat flow through Walls P1 and P2 for steady-state and dynamic temperature conditions is reported in Reference 1. Heat flow through Wall C1 for steady-state and dynamic temperature conditions is reported in Reference 2. This report presents indoor relative humidities at which condensation would be expected to occur on indoor wall surfaces, determined using temperatures measured during calibrated hot box tests.

The following is a brief description of the calibrated hot box. Instrumentation and calibration details are described in References 1, 2, and and 4.

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

The outdoor (climatic) chamber can be held at a constant temperature or cycled within the range -15 to 130°F. Temperatures can be programmed for a

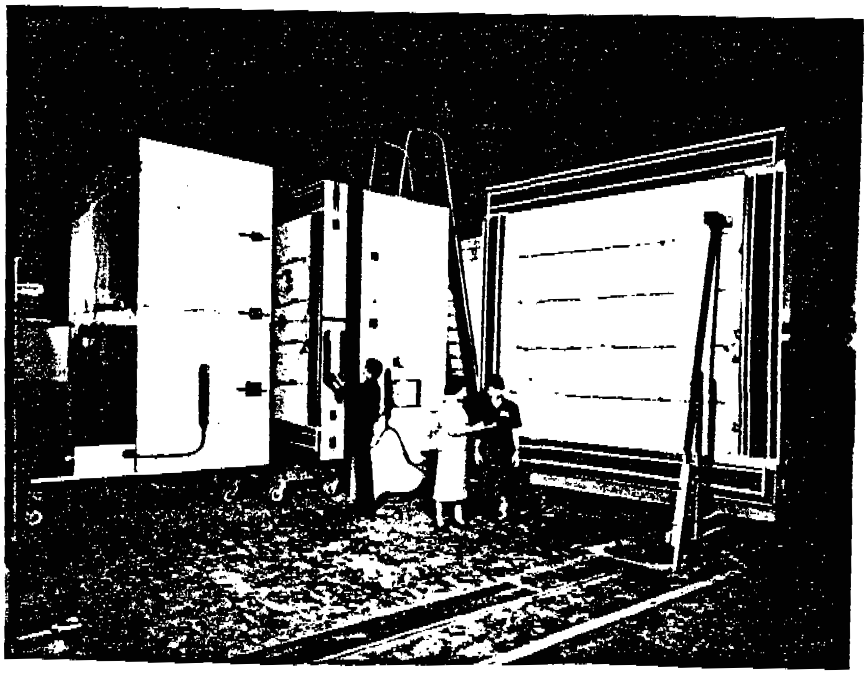


Fig. 11 Calibrated Hot Box Test Facility

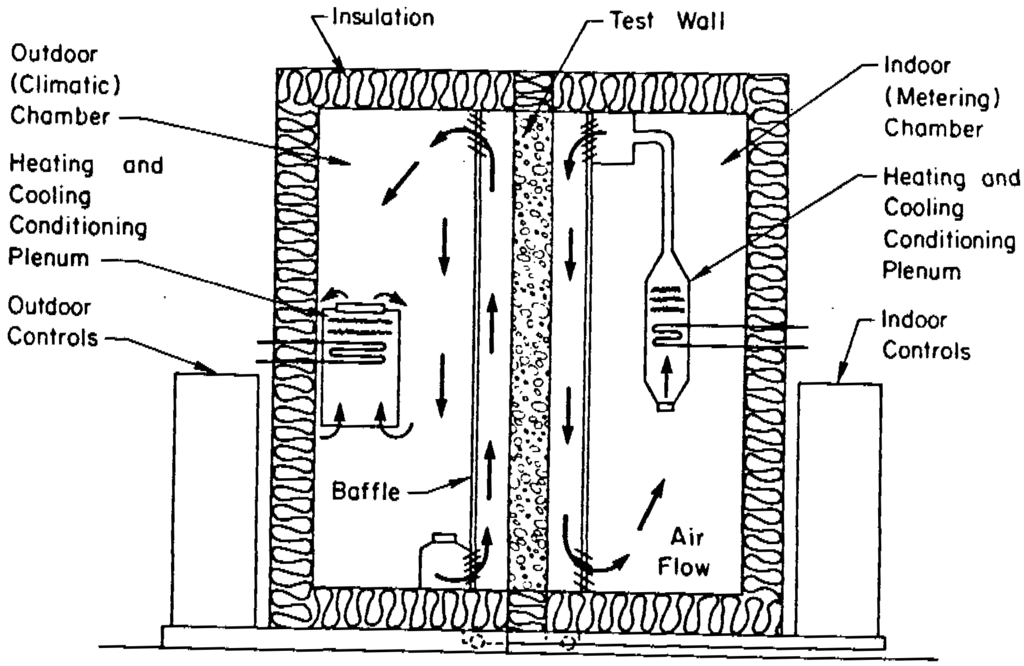


Fig. 12 Schematic of Calibrated Hot Box

24-hour cycle to obtain the desired temperature-time relationship. The indoor (metering) chamber, which simulates an indoor environment, can be maintained at a constant room temperature between 65 and 80°F.

STEADY-STATE TEMPERATURE CONDITIONS

Steady-State Test Procedures

Steady-state calibrated hot box tests were conducted by maintaining constant indoor and outdoor chamber temperatures. Results are presented for data collected when specimen temperatures reached equilibrium and the rate of heat flow through the test wall was constant. Steady-state tests used for the condensation study were run at two temperature differentials.

In the first case for Walls P1 and P2, indoor air temperature was maintained at approximately 71°F while outdoor air temperature was maintained at approximately -5°F. This provided a nominal temperature differential of approximately 76°F and mean wall temperature (t_m) of approximately 34°F. In the second case for Walls P1 and P2, indoor air temperature was maintained at approximately 72°F, while outdoor air temperature was maintained at approximately 38°F. This provided a nominal temperature differential of 34°F and a mean wall temperature (t_m) of approximately 56°F.

For the first steady-state test on Wall C1, indoor air temperature was maintained at approximately 69°F while outdoor air temperature was maintained at approximately -2°F. This provided a nominal temperature differential of approximately 71°F and a mean wall temperature (t_m) of approximately 37°F. In the second test on Wall C1, indoor air temperature was maintained at approximately 71°F, while outdoor air temperature was maintained at approximately 34°F. This provided a nominal temperature differential of 37°F and a mean wall temperature (t_m) of approximately 55°F.

Measured Temperatures

Measured temperatures and relative humidities from steady-state calibrated hot box tests on Walls P1, P2, and C1 are summarized in Table 2. Data are averages for 16 consecutive hours of testing.

The first four rows of Table 2 list air and surface temperatures measured during each steady-state test. Temperatures are averages of measurements from 16 thermocouples uniformly distributed in a 4x4 grid on the wall. Figures 13, 14, and 15, respectively, are temperature profiles for the steady-state tests performed on Walls P1, P2, and C1. Average measured temperatures for Wall P1 are within 0.8°F of those for Wall P2 for corresponding steady-state tests.

Figures 16 and 17 show temperatures in the vicinity of monitored tie locations for the two steady-state tests applied to Walls P1 and P2. The minimum and average of the three indoor wall surface temperatures monitored near the tie locations are given in Table 2. Indoor surface temperatures at monitored ties are within 1.2°F of average indoor surface temperatures measured by the 16 thermocouples in a 4x4 grid. Indoor surface temperatures at tie locations are warmer than the average surface temperature. This may be due to the fact that the monitored ties are located towards the top of the wall, where wall temperatures tend to be warmer.

Measured relative humidities within the indoor and outdoor chambers of the calibrated hot box are also listed in Table 2.

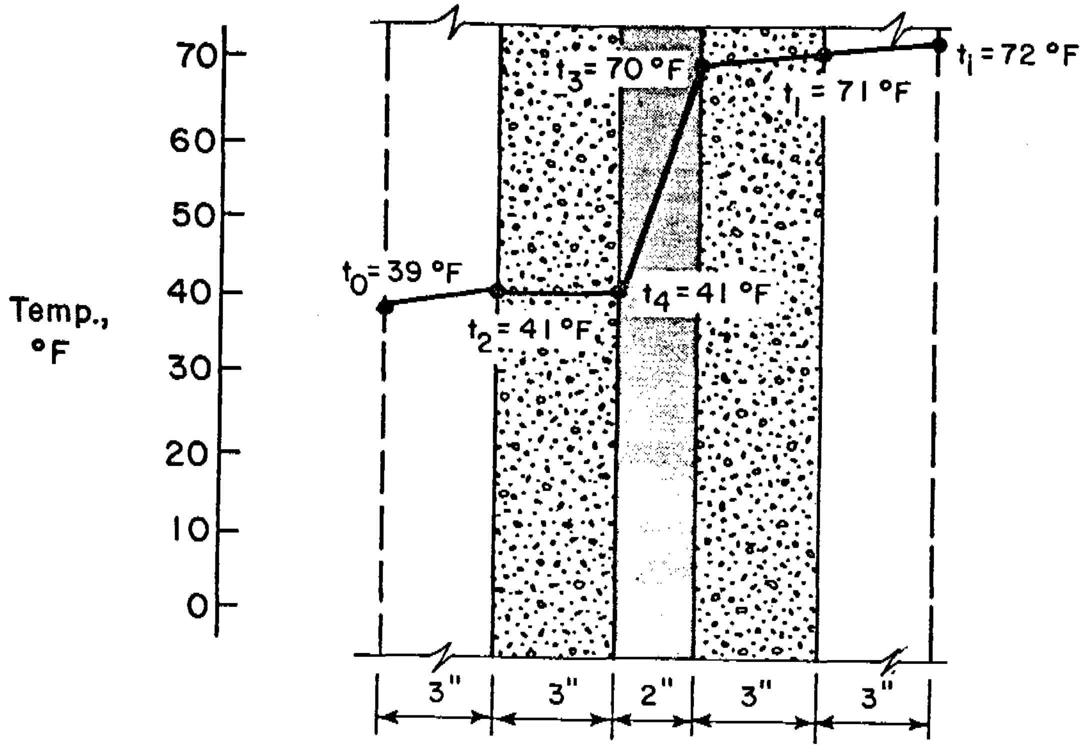
Use of Psychrometric Chart

A psychrometric chart,[5] shown in Fig. 18, can be used to determine temperature and relative humidity conditions that can result in condensation. The chart contains relationships between air temperature and moisture content at a specific total pressure. The psychrometric chart in Fig. 18 is based on

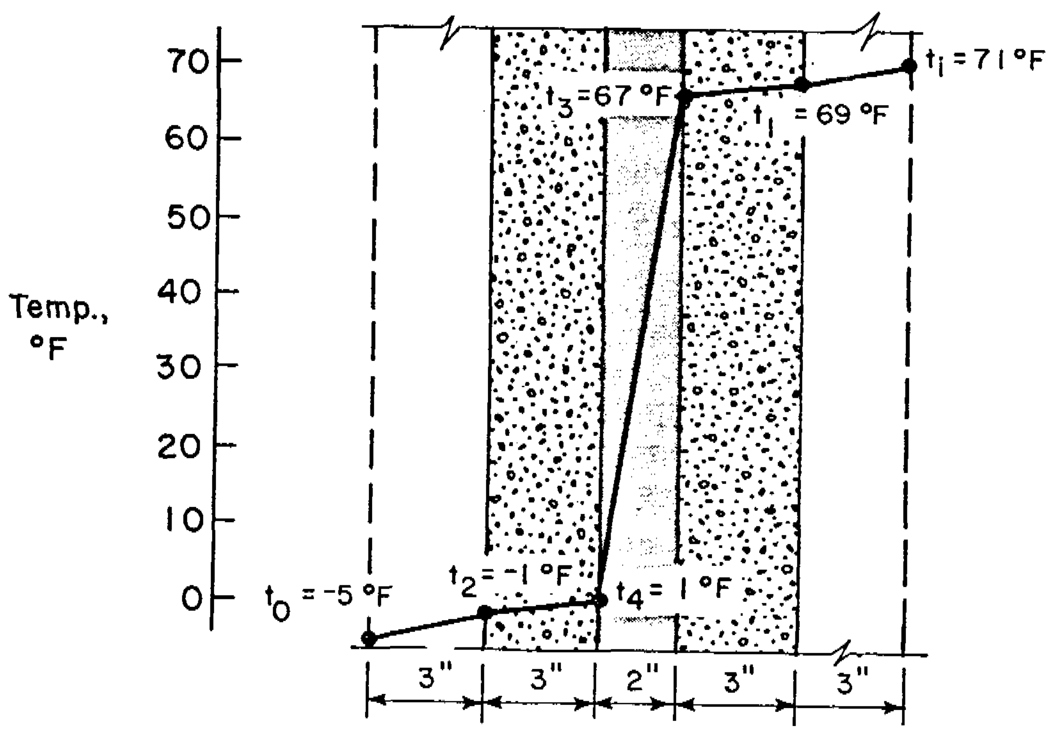
TABLE 2 - MEASURED TEMPERATURES AND RELATIVE HUMIDITIES FROM STEADY-STATE CALIBRATED HOT BOX TESTS(1,2)

Measured Property	Wall P1		Wall P2		Wall C1	
	Test Condition		Test Condition		Test Condition	
	t_m* = 34°F	t_m = 56°F	t_m = 34°F	t_m = 56°F	t_m = 37°F	t_m = 55°F
Outdoor Air Temp., t_o (°F)	-5.5	38.6	-5.3	37.8	-2.4	34.5
Outdoor Surface Temp., t_2 (°F)	-1.5	40.9	-1.2	40.1	18.5	45.6
Indoor Surface Temp., t_1 (°F)	69.3	71.0	69.2	71.1	55.4	64.2
Indoor Air Temp., t_i (°F)	71.4	71.8	71.3	71.8	69.1	70.7
Minimum Indoor Surface Temp. Monitored Near Tie (°F)	70.5	71.5	70.2	71.5	—	—
Average of Indoor Surface Temps. Monitored Near Tie (°F)	70.7	71.7	70.4	71.7	—	—
Indoor Chamber Relative Humidity, %	23	24	37	38	26	31
Outdoor Chamber Relative Humidity, %	22	21	23	19	22	19

*Mean wall temperature

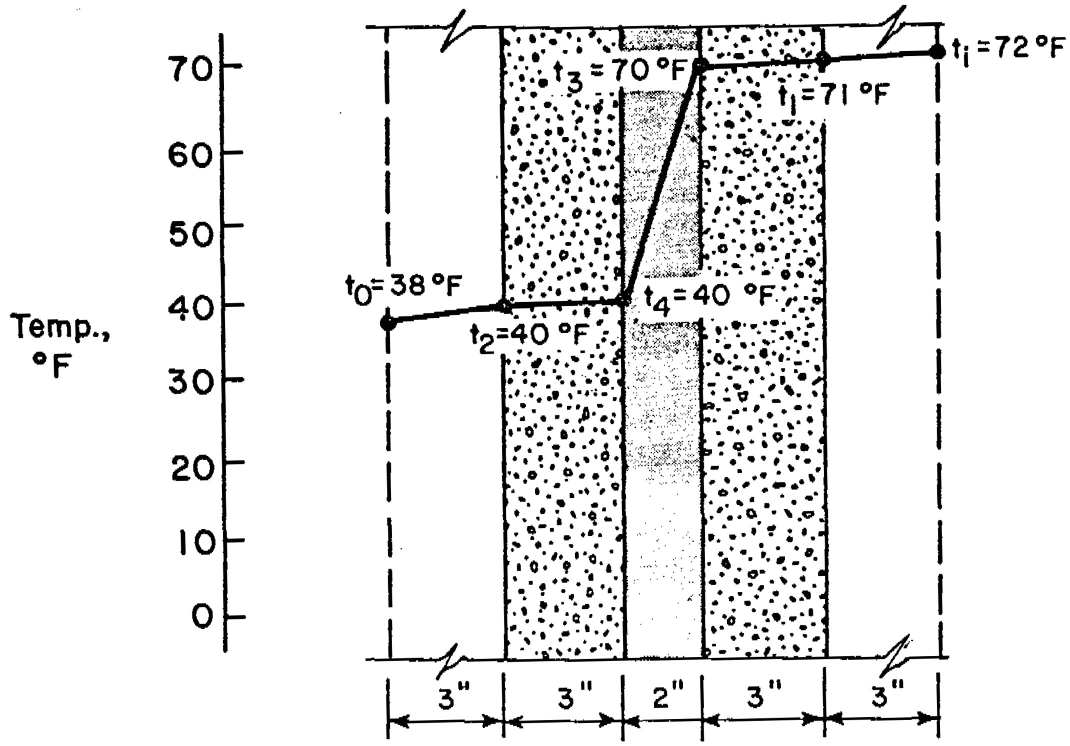


(a) Mean Wall Temperature = 56°F

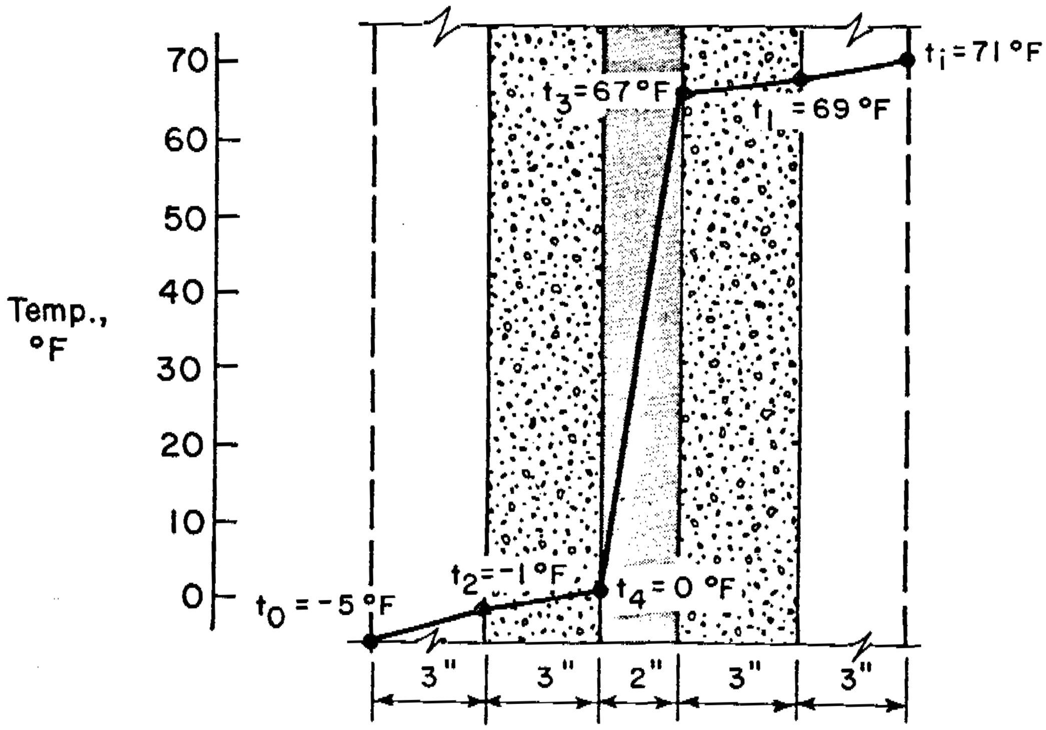


(b) Mean Wall Temperature = 34°F

Fig. 13 Steady-State Temperature Profiles Across Wall P1

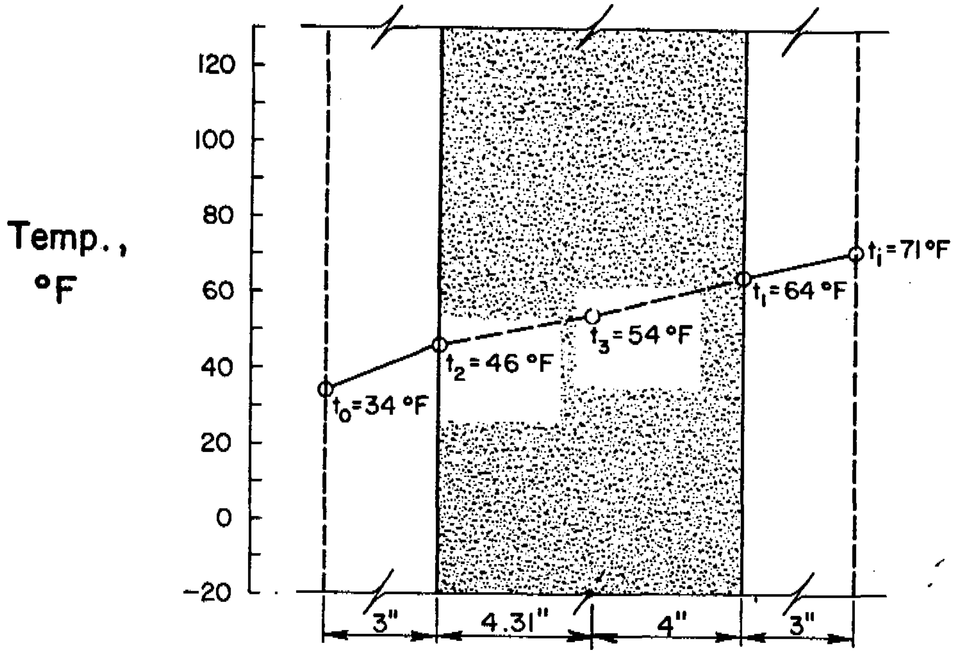


(a) Mean Wall Temperature = 56°F

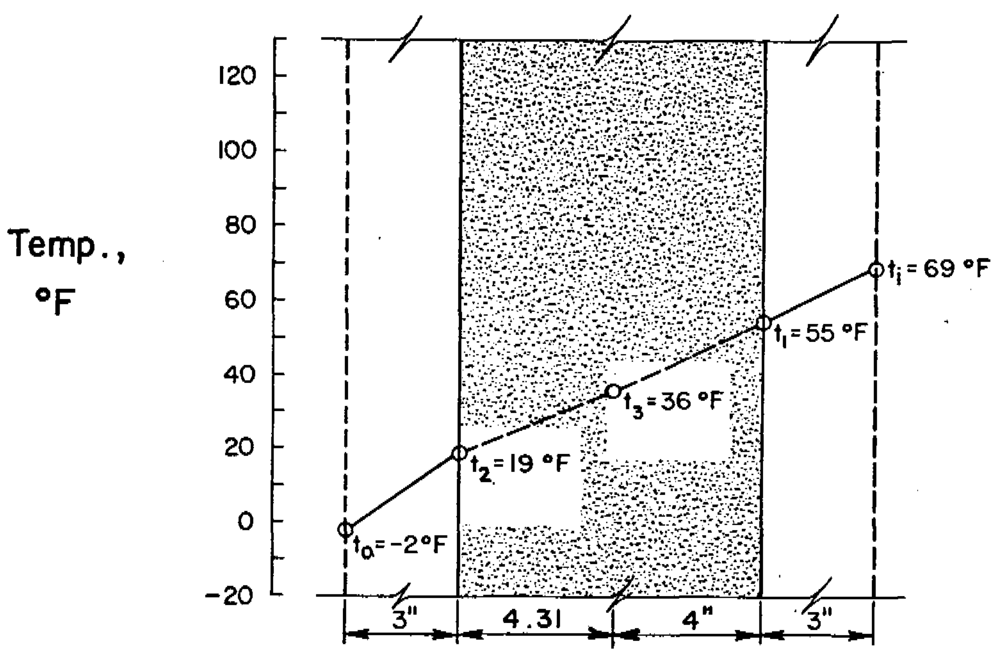


(b) Mean Wall Temperature = 34°F

Fig. 14 Steady-State Temperature Profiles Across Wall P2

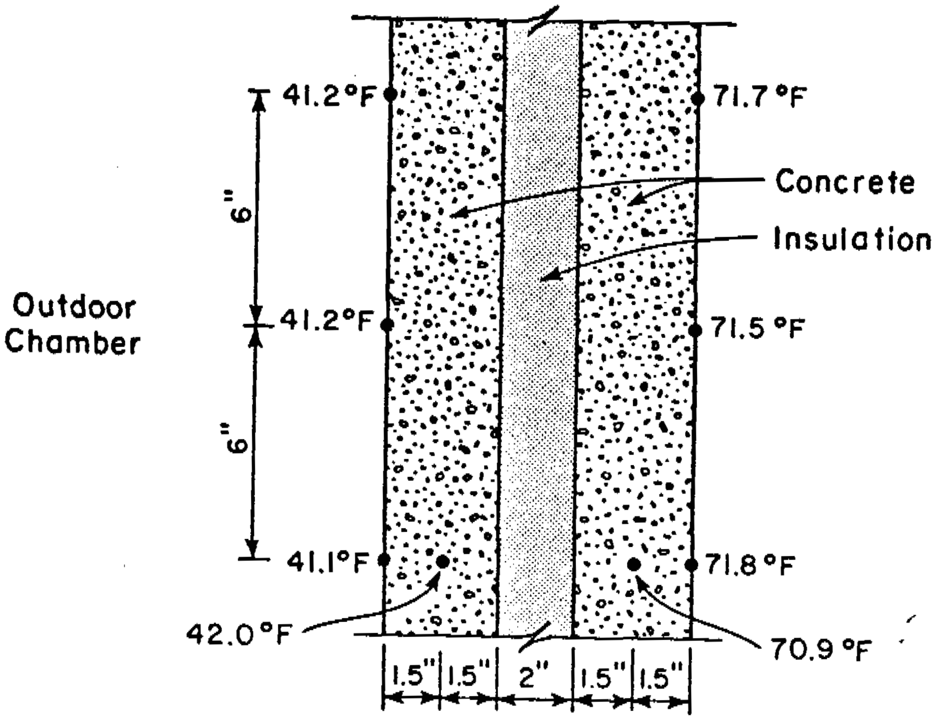


(a) Mean Wall Temperature = 55°F

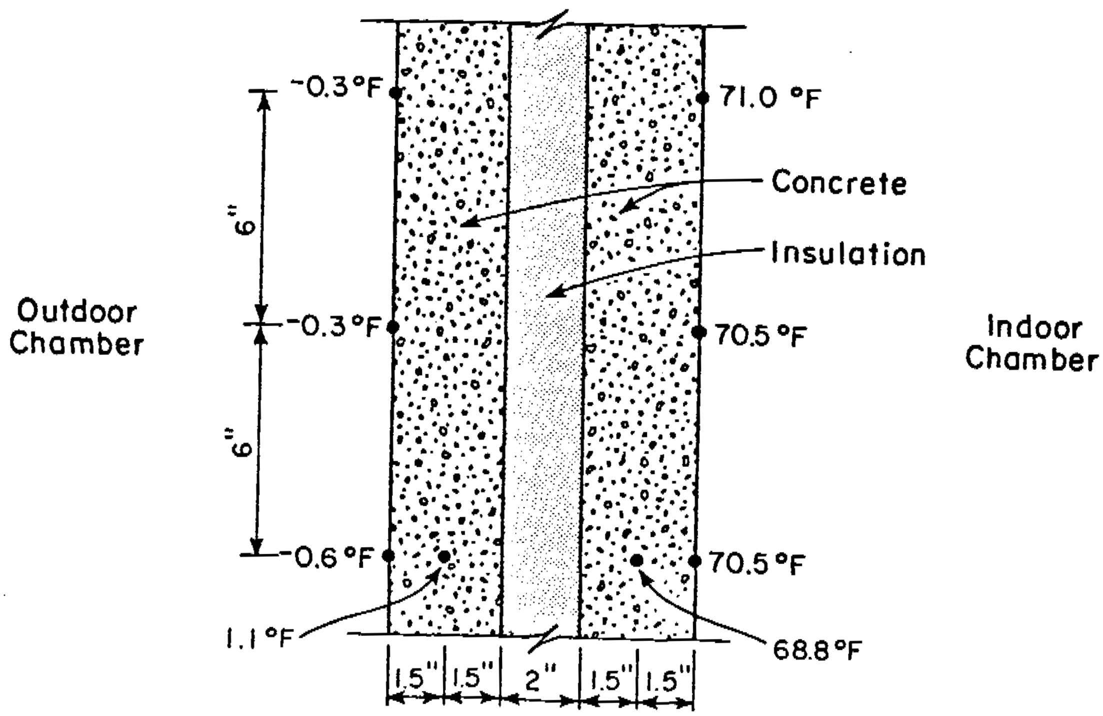


(b) Mean Wall Temperature = 37°F

Fig. 15 Steady-State Temperature Profiles Across Wall C1

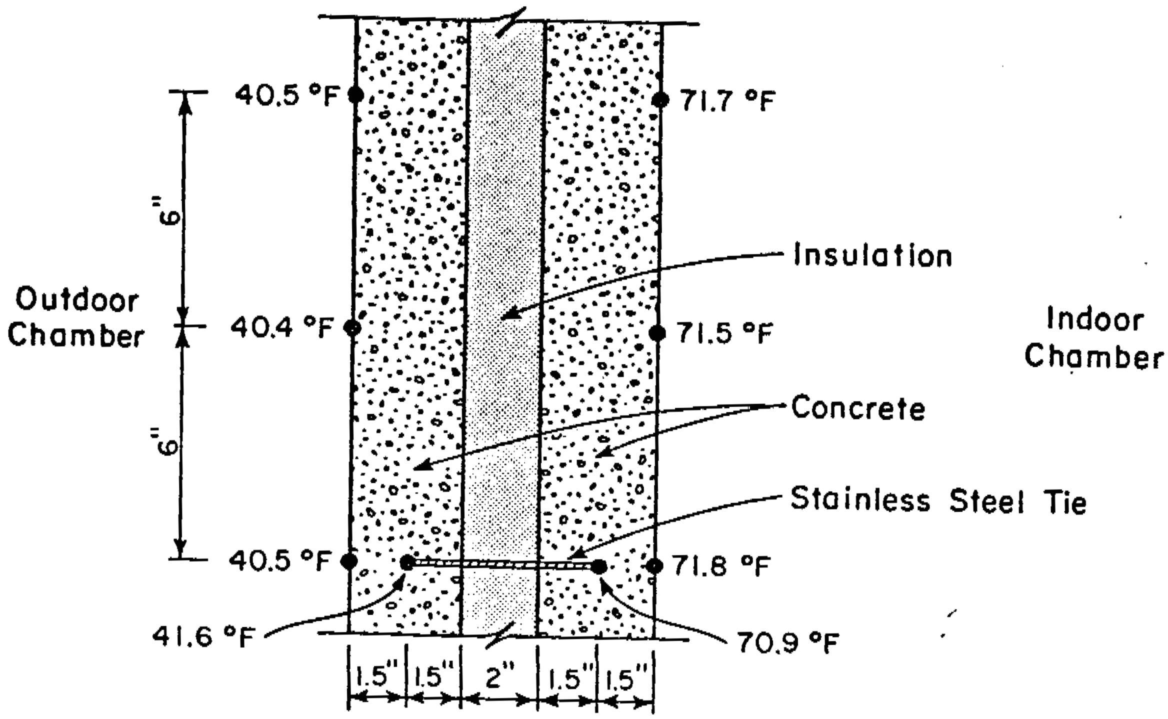


(a) Mean Wall Temperature = 56°F

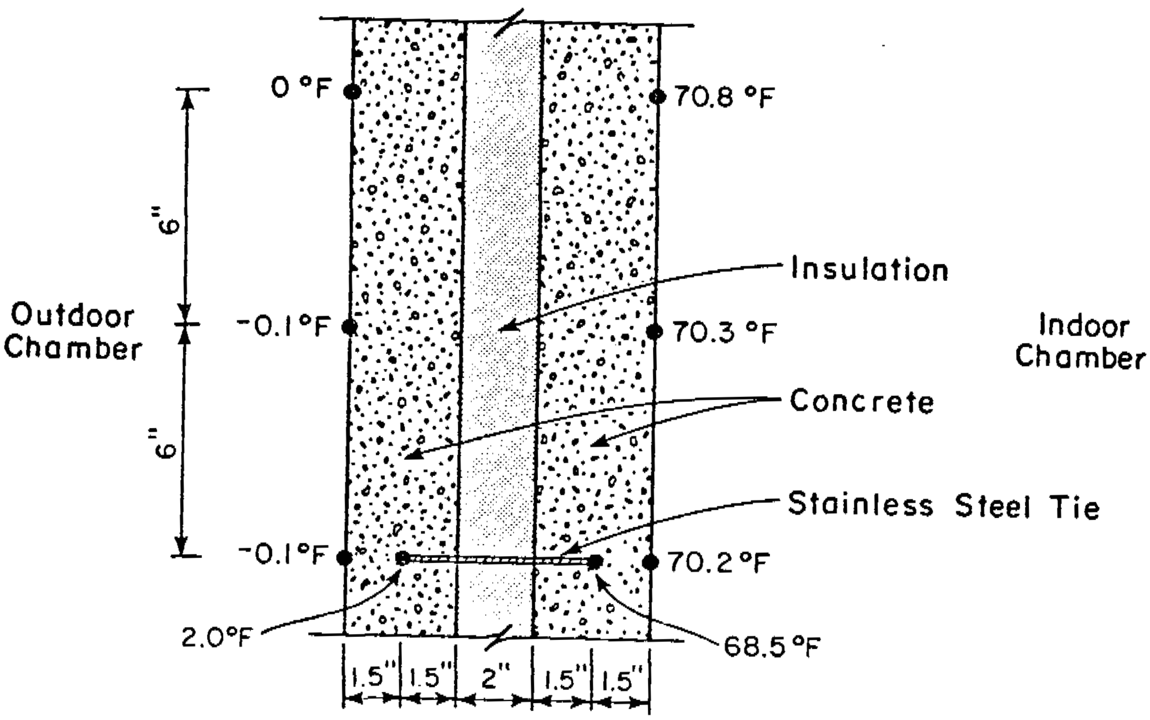


(b) Mean Wall Temperature = 34°F

Fig. 16 Temperatures at Thermocouples in Vicinity of Ties for Wall P1



(a) Mean Wall Temperature = 56°F



(b) Mean Wall Temperature = 34°F

Fig.17 Temperatures at Thermocouples in Vicinity of Ties for Wall P2

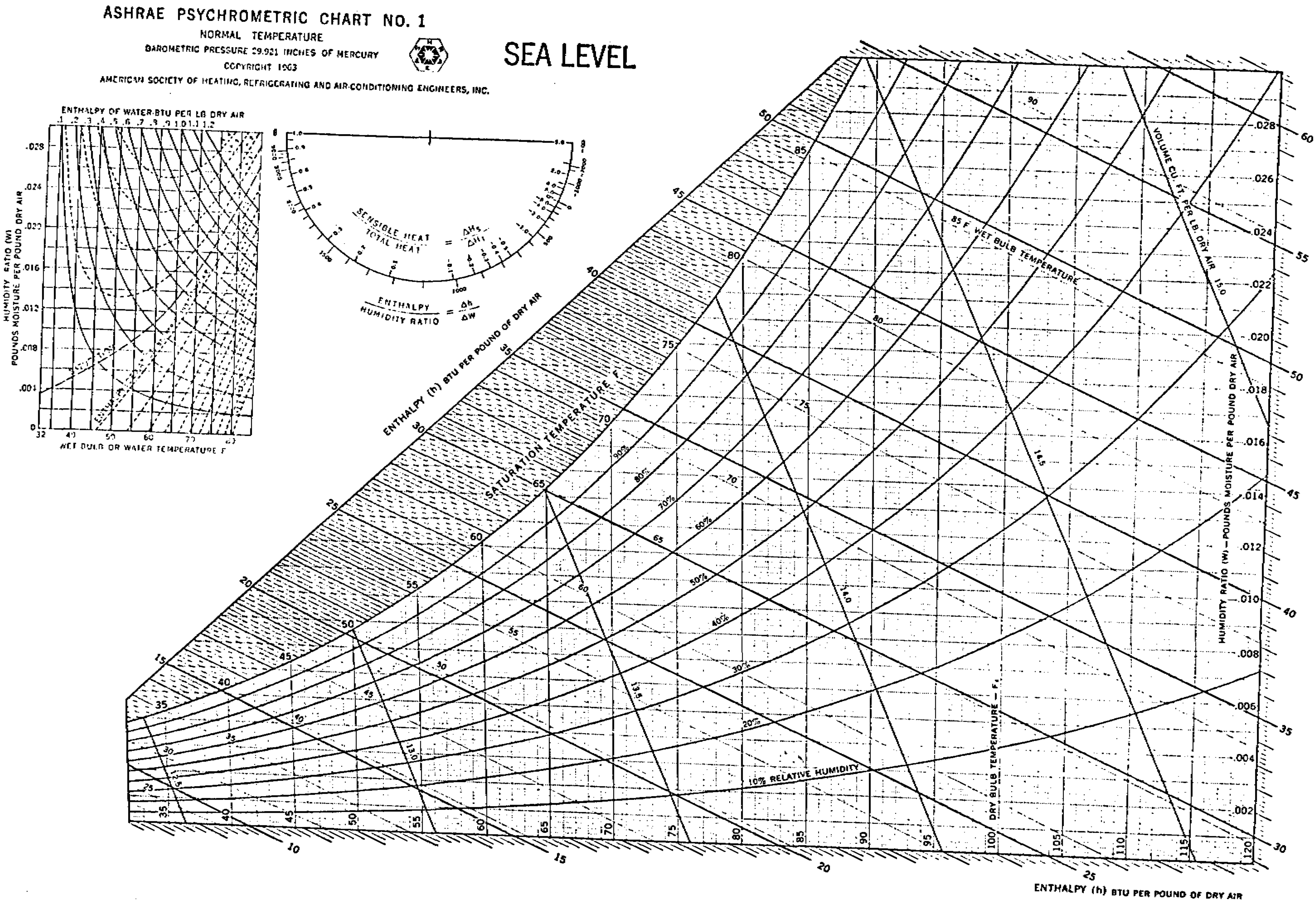


Fig. 18 Psychrometric Chart(5)

a total pressure of one standard atmosphere at sea level. The horizontal axis gives dry bulb temperatures. The uppermost curve gives wet bulb or dew point temperatures. Wet bulb temperatures are generally obtained from measurements using a thermometer with a moist wick around the bulb and sufficient air movement to cause evaporation. The difference between dry bulb and wet bulb temperatures is used to determine relative humidity. The curves that extend from the lower left corner to the upper right side of the chart represent constant relative humidity.

For this study, a psychrometric chart was used to determine the relative humidity at which condensation would be expected to occur on a wall with a known surface temperature in contact with air of a known temperature. An example of the use of the psychrometric chart is shown in Fig. 18. For a wall temperature of 65°F and an air temperature of 80°F, a relative humidity of 60% or higher will cause condensation to occur on the wall. To determine relative humidity, vertical lines are extended up from the dry bulb air temperature and the wall surface temperature on the horizontal axis. A horizontal line is extended from the point where the wall surface temperature, or dew point temperature, intersects the 100% relative humidity curve. The intersection of the horizontal line and the vertical air temperature line gives the relative humidity of the indoor air at which condensation would occur on the wall surface. Relative humidities determined with this method do not take into account local conditions such as air movement which may influence condensation.

Condensation

Table 3 lists relative humidities at which indoor wall surface condensation would be expected to occur for steady-state tests on Walls P1, P2, and C1.

TABLE 3 - RELATIVE HUMIDITIES AT WHICH CONDENSATION WOULD BE EXPECTED TO OCCUR FOR STEADY-STATE TESTS

Surface Temp. Measurement	Wall	Test Condition	Indoor Air Temp., °F	Indoor Surface Temp., °F	Calc. RH, %
Average of 16 Thermocouples	P1	t_m* = 34°F	71.4	69.3	93
		t_m = 56°F	71.8	71.0	97
	P2	t_m = 34°F	71.3	69.2	93
		t_m = 56°F	71.8	71.1	98
	C1	t_m = 37°F	69.1	55.4	61
		t_m = 55°F	70.7	64.2	80
Average of 4 T.C.'s in Bottom Row	P1	t_m = 34°F	71.4	68.0	88
		t_m = 56°F	71.8	70.5	96
	P2	t_m = 34°F	71.3	67.9	88
		t_m = 56°F	71.8	70.5	96
	C1	t_m = 37°F	69.1	44.9	42
		t_m = 55°F	70.7	59.1	68
Minimum Temperature Near Tie	P1	t_m = 34°F	71.4	70.5	96
		t_m = 56°F	71.8	71.5	99
	P2	t_m = 34°F	71.3	70.2	95
		t_m = 56°F	71.8	71.5	99

*Mean wall temperature

Values were determined from the psychrometric chart described previously using indoor air and wall surface temperatures measured during steady-state calibrated hot box tests.

Relative humidities were determined for two indoor wall surface temperatures for each steady-state test on the three wall specimens. The first was average readings of 16 thermocouples uniformly distributed in a 4x4 grid over the wall area. The second surface temperature used was the average reading of the four thermocouples in the bottom row of the 4x4 grid. This measure shows the effect of cooler temperatures near the bottom of the wall. For Walls P1 and P2, a third relative humidity was determined using the minimum indoor surface temperature measured by thermocouples in the vicinity of monitored ties. Indoor air temperature for all cases was the average of 16 thermocouples uniformly distributed over the wall area.

Relative humidities determined for the two steady-state temperature conditions on Walls P1 and P2 are nearly identical. This suggests that the metal ties in Wall P2 have a negligible effect on the potential for condensation at the inside surface of the wall.

Relative humidities which could potentially cause condensation on the indoor surface of the solid concrete wall were significantly lower than those for the insulated sandwich panel walls. For the average of 16 thermocouples, calculated relative humidities range from 18 to 34% lower for similar steady-state tests on Wall C1 compared to Walls P1 and P2. For the average of 4 bottom row thermocouples, calculated relative humidities range from 19 to 52% lower for Wall C1 compared to Walls P1 and P2. This is to be expected since the uninsulated concrete wall has a much lower thermal resistance than the insulated concrete sandwich panel wall. As a result, more heat escapes through the solid concrete wall and indoor surface temperatures are decreased.

As expected for each wall, temperatures from the bottom (coolest) row of thermocouples give the lowest relative humidities at which condensation is likely to occur.

DYNAMIC TEMPERATURE CONDITIONS

Exterior building walls are seldom subjected to steady-state thermal conditions. 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.

Dynamic Test Procedures

Dynamic tests of Walls P1, P2, and C1 were conducted in the CTL calibrated hot box. For these tests, calibrated hot box indoor air temperatures were held constant while outdoor air temperatures were cycled over a predetermined temperature versus time relationship.

Three 24-hour (diurnal) temperature cycles were used on Walls P1, P2, and C1. The first cycle, denoted the NBS Test Cycle, has been used in previous studies using the CTL calibrated hot box. This periodic 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.[6]

*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.[7]

Two additional sol-air temperature cycles were run with mean outdoor temperatures approximately 10°F above and 10°F below the indoor temperature. The test cycle designated "NBS+10" was derived by increasing hourly outdoor temperatures of the NBS Test Cycle by 10°F. The test cycle designated "NBS-10" was derived by decreasing hourly outdoor temperatures by 10°F. Average indoor air temperature over the 24-hour period for each cycle was approximately 72°F.

Reference 1 contains detailed heat transfer test results for the three dynamic cycles applied to Walls P1 and P2. Reference 2 contains detailed heat transfer test results for the three dynamic cycles applied to Wall C1. The coldest of the three dynamic cycles, NBS-10, will be considered in this report.

An additional dynamic temperature cycle which was not reported in Ref. 1 was applied to Wall P2. This cycle represented average temperature conditions for Denver, Colorado for the month of January. Twenty-year-average hourly air temperatures were obtained from the Colorado Climate Center at Fort Collins for the month of January. Sol-air temperatures were calculated from average air temperature data using procedures described in the ASHRAE Handbook - 1985 Fundamentals.(7) Sol-air temperatures were averaged for north, northeast, east, southeast, south, southwest, west, and northwest orientations. Indoor air temperature was maintained at 72°F while the January Denver Temperature Cycle was applied to Wall P2.

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

Measured Temperatures

Measured temperatures and temperature differentials for the NBS-10 Temperature Cycle applied to Walls P1, P2, and C1 are available in Refs. 1 and 2. Measured temperatures for the January Denver Test Cycle applied to Wall P2 are presented in Appendix A. Indoor air and surface temperatures for dynamic tests on the walls are summarized in this section.

Hourly temperatures measured on the indoor surface of Walls P1 and P2 in the vicinity of the monitored ties are given in Tables 4 through 6. Tables 4 and 5 list values for the NBS-10 Test Cycle applied to Walls P1 and P2, respectively. Table 6 lists values for the January Denver Test Cycle applied to Wall P2. Figures 19, 20, and 21, respectively, present plots of temperatures listed in Tables 4, 5, and 6.

Temperatures designated t_{tie} are average measurements of thermocouples located on the indoor wall surface at the monitored ties. Temperatures designated t_6 and t_{12}, respectively, are average measurements from thermocouples on the indoor surface of the wall located 6 and 12 in. above the monitored ties. Average indoor wall surface temperatures, t_1, and indoor air temperatures, t_i, are included for comparison.

Table 7 lists average indoor surface, t_1, and average indoor air temperatures, t_i, for the NBS-10 Test Cycle applied to Wall C1. Figure 22 presents a plot of temperatures listed in Table 7.

Condensation

Table 8 lists relative humidities at which indoor wall surface condensation would be expected to occur during dynamic tests considered for this study. Values were determined from the psychrometric chart described

TABLE 4 - MEASURED INDOOR AIR AND SURFACE TEMPERATURES FOR NBS-10 TEST CYCLE APPLIED TO WALL P1

Time, hr	Measured Temperatures, °F				
	t1 Average Indoor Surface	t(tie) Indoor Surf. @ Tie	t(6) Indoor Surf. 6 in. from Tie	t(12) Indoor Surf. 12 in. from Tie	ti Average Indoor Air
1	72.1	72.7	72.2	72.3	72.1
2	72.0	72.6	72.1	72.2	72.1
3	71.9	72.5	72.1	72.1	72.0
4	71.8	72.5	72.0	72.1	72.0
5	71.7	72.4	71.9	72.0	72.0
6	71.6	72.3	71.9	72.0	72.0
7	71.5	72.2	71.8	71.9	71.9
8	71.5	72.2	71.8	71.9	71.9
9	71.5	72.2	71.8	71.9	71.9
10	71.5	72.2	71.8	71.9	71.8
11	71.6	72.2	71.8	71.9	71.9
12	71.6	72.2	71.9	72.0	71.9
13	71.8	72.3	71.9	72.1	72.0
14	71.9	72.4	72.1	72.2	72.0
15	72.1	72.6	72.1	72.2	72.1
16	72.2	72.7	72.2	72.3	72.1
17	72.3	72.8	72.3	72.5	72.2
18	72.4	73.0	72.4	72.5	72.2
19	72.5	73.0	72.5	72.5	72.2
20	72.5	73.0	72.5	72.5	72.2
21	72.5	73.0	72.5	72.5	72.2
22	72.4	72.9	72.4	72.4	72.2
23	72.3	72.9	72.3	72.4	72.1
24	72.2	72.8	72.3	72.3	72.1
Mean	72.0	72.6	72.1	72.2	72.0

Note: Maximum and minimum outdoor air temperatures were 91.7 and 34.7°F, respectively, for the NBS-10 Test Cycle applied to Wall P1.

TABLE 5 - MEASURED INDOOR AIR AND SURFACE TEMPERATURES FOR NBS-10 TEST CYCLE APPLIED TO WALL P2

Time, hr	Measured Temperatures, °F				
	t1 Average Indoor Surface	t(tie) Indoor Surf. @ Tie	t(6) Indoor Surf. 6 in. from Tie	t(12) Indoor Surf. 12 in. from Tie	ti Average Indoor Air
1	72.0	72.6	72.1	72.2	72.1
2	72.0	72.5	72.1	72.2	72.1
3	71.8	72.4	72.0	72.1	72.0
4	71.7	72.3	72.0	72.0	72.0
5	71.7	72.3	71.9	72.0	72.0
6	71.6	72.2	71.9	72.0	72.0
7	71.5	72.1	71.8	71.9	71.9
8	71.5	72.1	71.8	71.9	71.9
9	71.5	72.1	71.8	71.9	71.9
10	71.5	72.1	71.8	71.9	71.9
11	71.6	72.2	71.8	72.0	71.9
12	71.7	72.2	71.9	72.0	72.0
13	71.8	72.3	72.0	72.1	72.0
14	71.9	72.5	72.1	72.2	72.0
15	72.1	72.6	72.2	72.3	72.1
16	72.2	72.7	72.3	72.3	72.1
17	72.3	72.8	72.4	72.4	72.1
18	72.4	72.9	72.5	72.5	72.2
19	72.4	72.9	72.5	72.5	72.2
20	72.4	73.0	72.5	72.5	72.2
21	72.4	72.9	72.4	72.4	72.2
22	72.4	72.8	72.4	72.4	72.2
23	72.3	72.8	72.3	72.4	72.1
24	72.2	72.7	72.3	72.3	72.1
Mean	72.0	72.5	72.1	72.2	72.1

Note: Maximum and minimum outdoor air temperatures were 94.2 and 36.9°F, respectively, for the NBS-10 Test Cycle applied to Wall P2.

TABLE 6 - MEASURED INDOOR AIR AND SURFACE TEMPERATURES FOR JANUARY DENVER TEST CYCLE APPLIED TO WALL P2

Time, hr	Measured Temperatures, °F				
	t1 Average Indoor Surface	t(tie) Indoor Surf. @ Tie	t(6) Indoor Surf. 6 in. from Tie	t(12) Indoor Surf. 12 in. from Tie	ti Average Indoor Air
1	70.8	71.6	71.3	71.5	71.7
2	70.7	71.6	71.3	71.5	71.7
3	70.7	71.5	71.2	71.5	71.7
4	70.6	71.4	71.2	71.5	71.7
5	70.6	71.4	71.2	71.4	71.7
6	70.5	71.4	71.2	71.4	71.6
7	70.5	71.3	71.1	71.4	71.6
8	70.4	71.3	71.1	71.4	71.6
9	70.4	71.3	71.1	71.4	71.6
10	70.5	71.3	71.1	71.4	71.6
11	70.5	71.3	71.1	71.4	71.6
12	70.5	71.3	71.1	71.4	71.6
13	70.5	71.3	71.1	71.4	71.6
14	70.6	71.4	71.1	71.4	71.6
15	70.7	71.5	71.2	71.5	71.6
16	70.7	71.5	71.3	71.5	71.6
17	70.8	71.6	71.3	71.6	71.6
18	70.9	71.7	71.3	71.6	71.7
19	70.9	71.7	71.4	71.6	71.7
20	70.9	71.7	71.4	71.7	71.7
21	70.9	71.7	71.4	71.6	71.7
22	70.9	71.7	71.4	71.6	71.7
23	70.8	71.6	71.3	71.6	71.7
24	70.8	71.6	71.4	71.6	71.7
Mean	70.7	71.5	71.2	71.5	71.7

Note: Maximum and minimum outdoor air temperatures were 56.4 and 23.7°F, respectively, for the January Denver Test Cycle applied to Wall P2

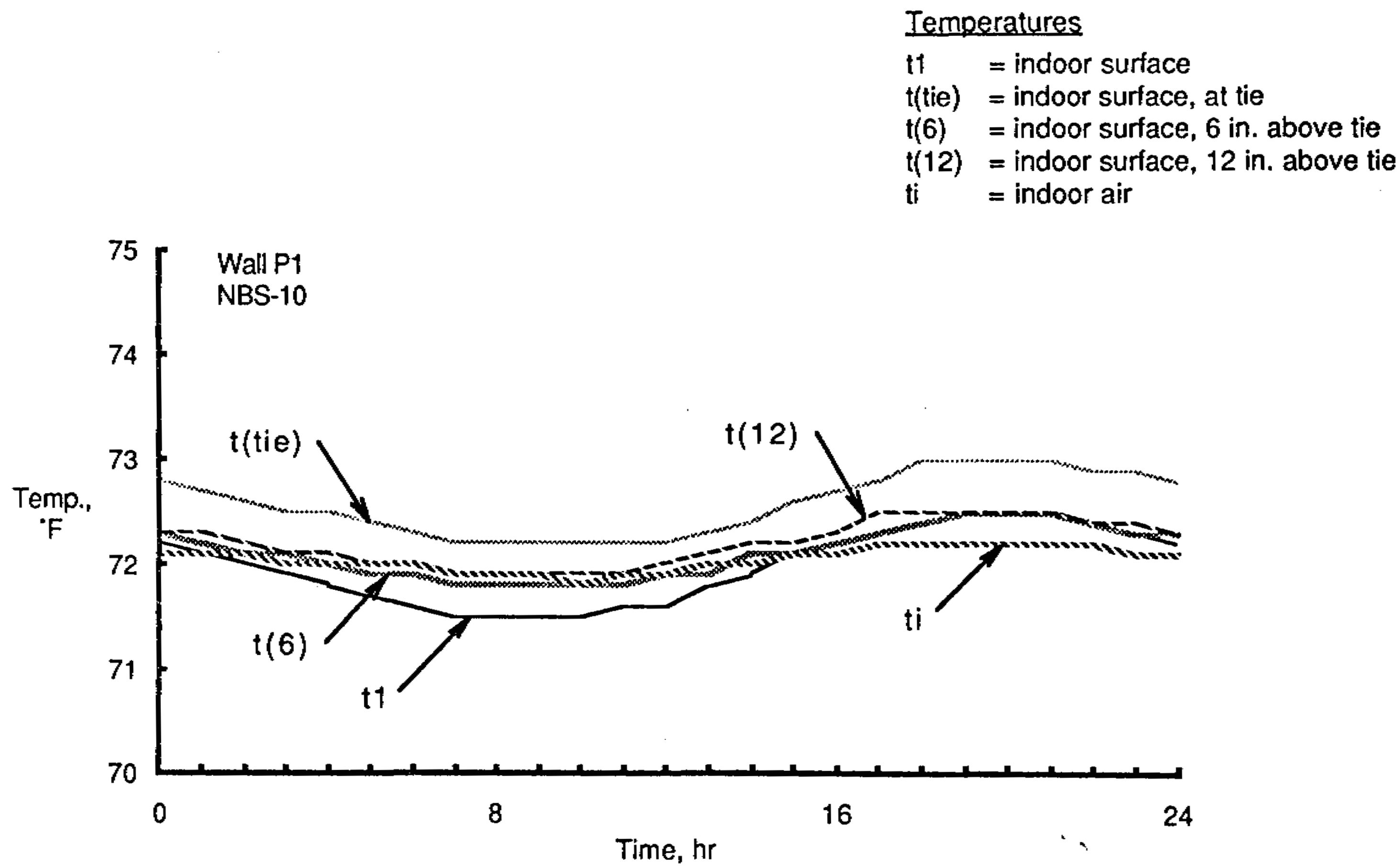


Fig. 19 Measured Indoor Air and Surface Temperatures for NBS-10 Test Cycle Applied to Wall P1

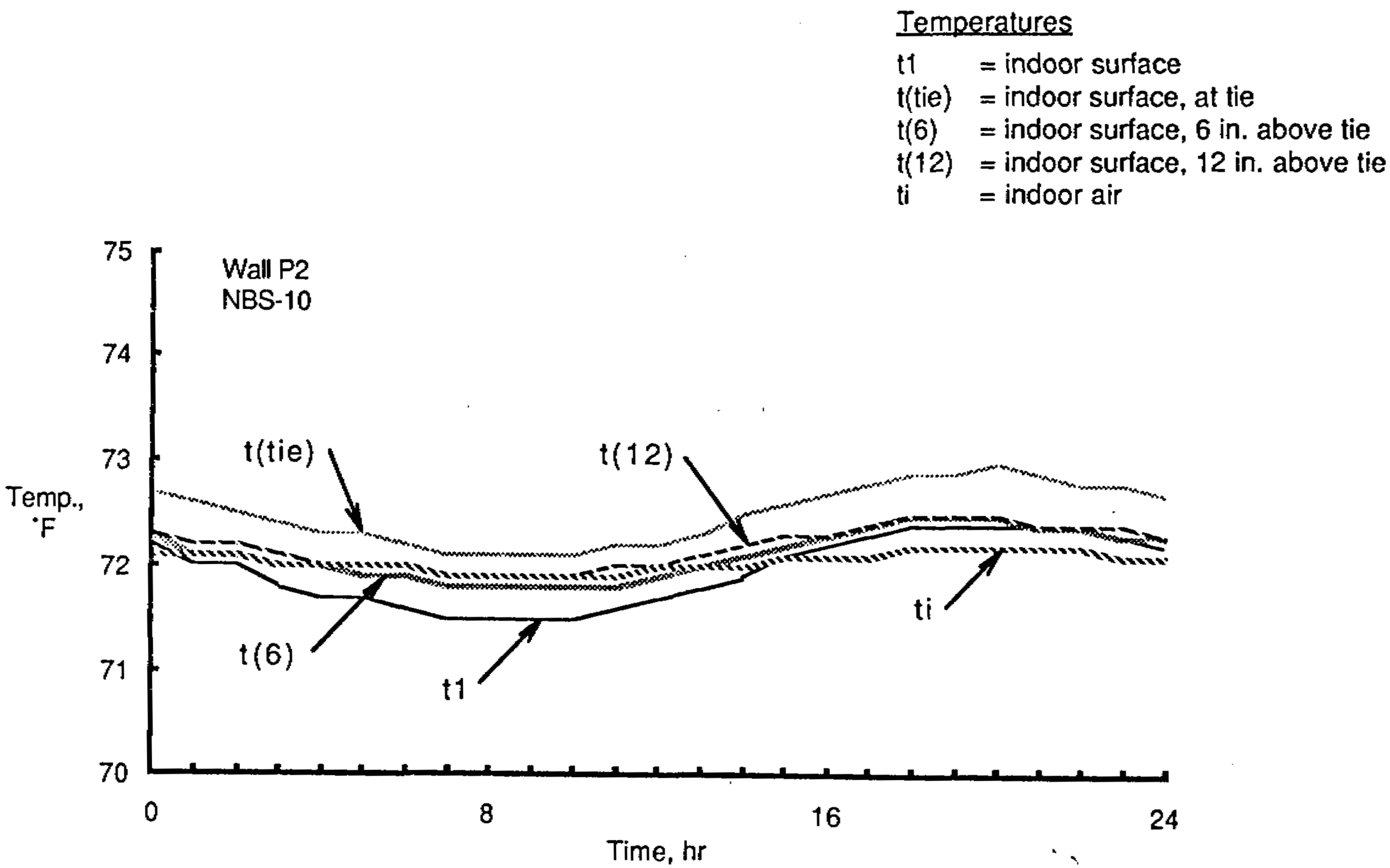


Fig. 20 Measured Indoor Air and Surface Temperatures for NBS-10 Test Cycle Applied to Wall P2

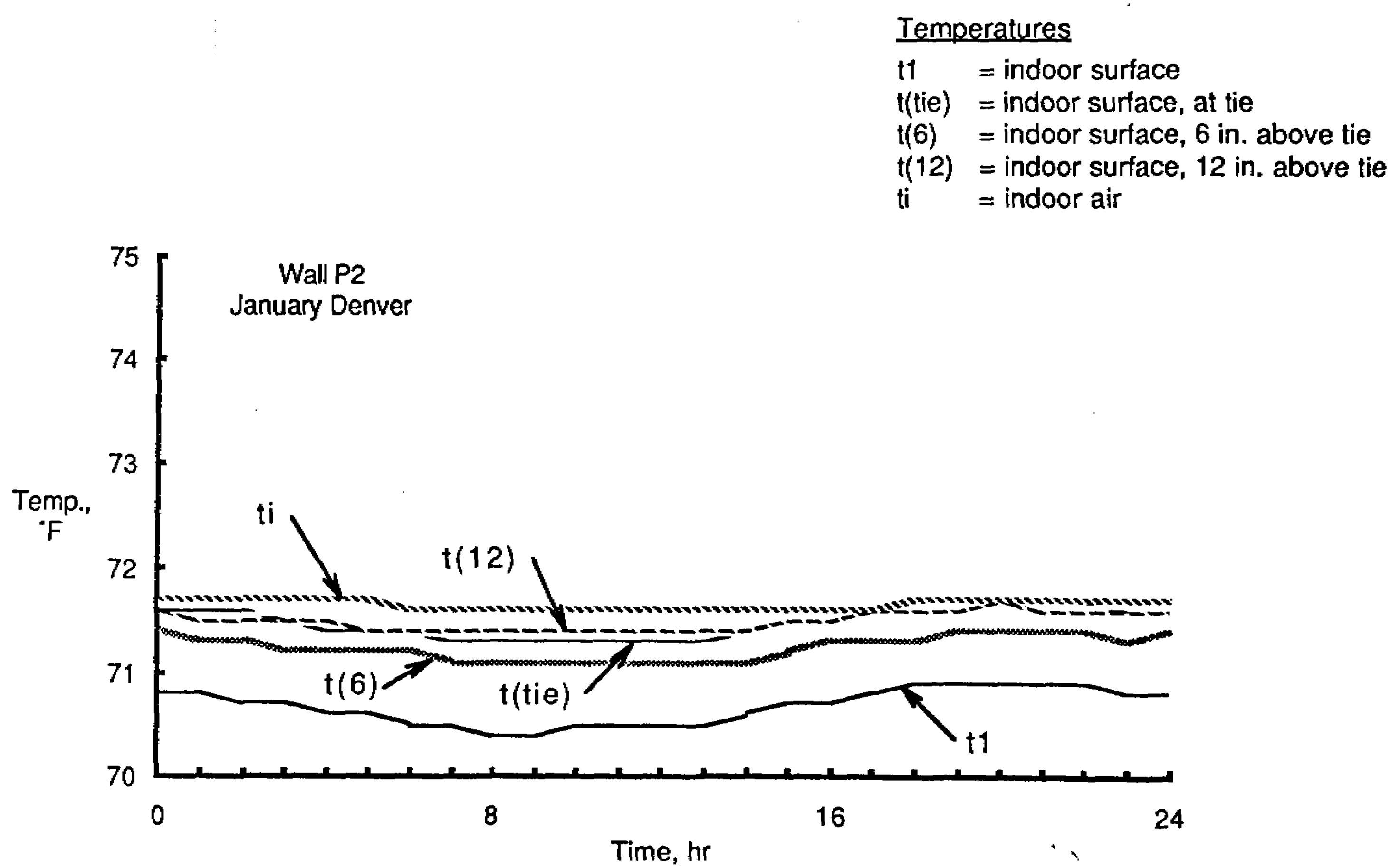


Fig. 21 Measured Indoor Air and Surface Temperatures for January Denver Test Cycle Applied to Wall P2

TABLE 7 - MEASURED INDOOR AIR AND SURFACE TEMPERATURES FOR NBS-10 TEST CYCLE APPLIED TO WALL C1

Time, hr	Measured Temperatures, °F	
	t1 Average Indoor Surface	ti Average Indoor Air
1	69.8	71.8
2	69.0	71.6
3	68.4	71.5
4	67.7	71.4
5	67.2	71.3
6	66.7	71.2
7	66.5	71.2
8	66.6	71.2
9	67.0	71.3
10	67.6	71.4
11	68.3	71.5
12	69.1	71.7
13	70.0	71.9
14	70.9	72.0
15	71.8	72.2
16	72.5	72.4
17	73.1	72.5
18	73.4	72.5
19	73.4	72.6
20	73.0	72.5
21	72.5	72.4
22	71.8	72.2
23	71.1	72.1
24	70.5	71.9
Mean	69.9	71.8

Note: Maximum and minimum outdoor air temperatures were 90.7 and 34.4 °F, respectively, for the NBS-10 Test Cycle applied to Wall C1.

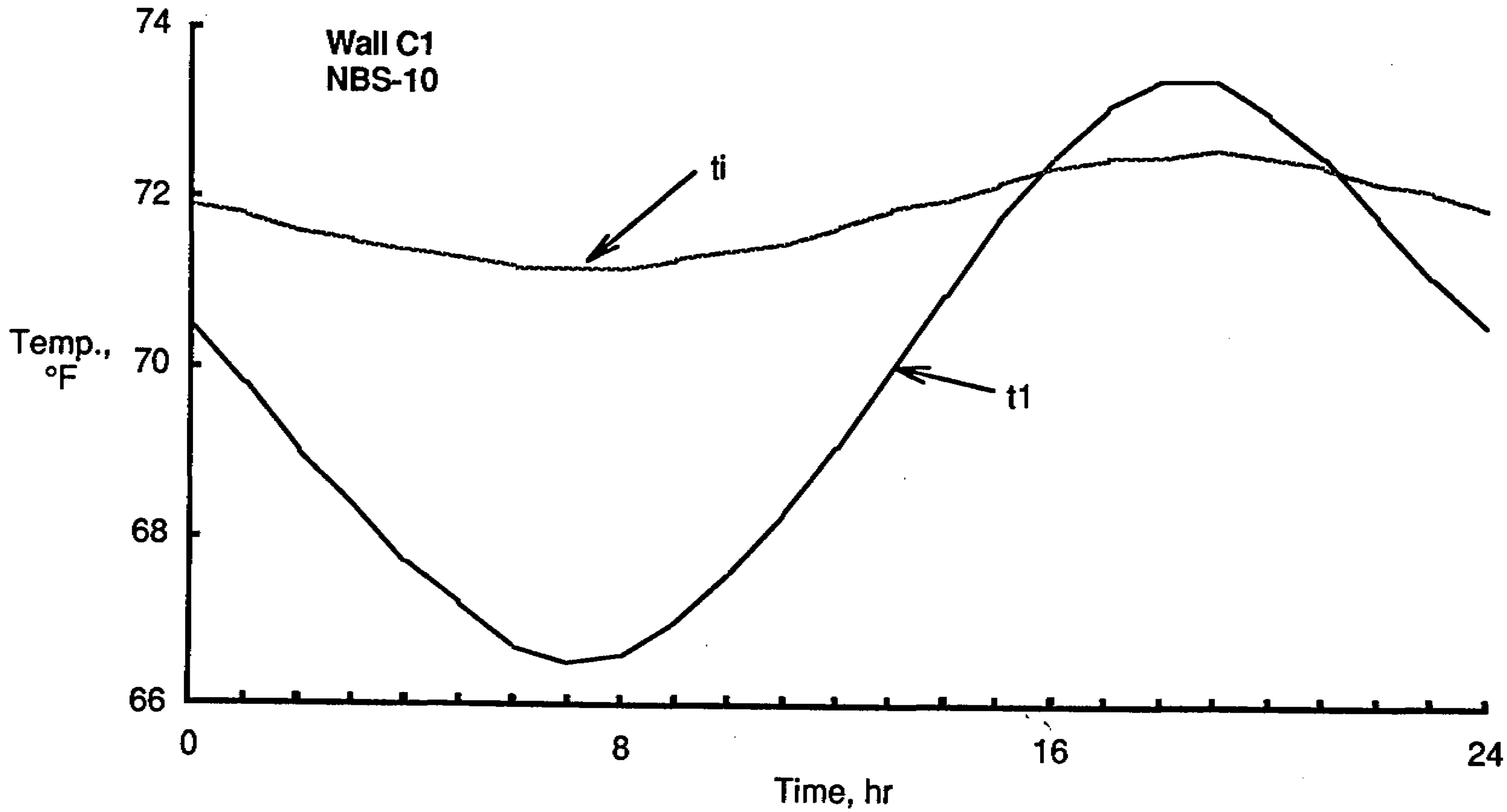


Fig. 22 Measured Indoor Air and Surface Temperatures for NBS-10 Test Cycle Applied to Wall C1

TABLE 8 - RELATIVE HUMIDITIES AT WHICH CONDENSATION WOULD BE EXPECTED TO OCCUR FOR DYNAMIC TESTS

Surface Temperature Measurement	Wall	Dynamic Test Cycle*	t_i Indoor Air Temp., °F	t_{surf} Indoor Surface Temp., °F	Maximum Air-to-Surface Temp. Differential, °F	Calc. RH, %
Average of 16 Thermocouples	P1	NBS-10	72.0	71.6	0.4	98
	P2	NBS-10	72.0	71.6	0.4	98
	P2	Jan. Den.	71.6	70.4	1.2	94
	C1	NBS-10	71.2	66.5	4.7	85
Average of 4 T.C.'s in Bottom Row	P1	NBS-10	72.0	71.0	1.0	96
	P2	NBS-10	72.0	71.0	1.0	96
	P2	Jan. Den.	71.6	69.6	2.0	92
	C1	NBS-10	71.2	62.7	8.5	75
Minimum Temperature Near Tie	P1	NBS-10	72.0	71.9	0.1	99
	P2	NBS-10	72.0	71.9	0.1	99
	P2	Jan. Den.	71.7	71.2	0.5	97

*Mean wall temperatures for the NBS-10 Test Cycle applied to Wall P1, the NBS-10 Test Cycle applied to Wall P2, and the January Denver Test Cycle applied to Wall P2 were 65.9, 67.1 and 54.2°F, respectively. Mean wall temperature for the NBS-10 Test Cycle applied to Wall C1 was 67.0°F.

previously using air and wall surface temperatures measured during dynamic calibrated hot box tests.

Relative humidities were determined for temperatures measured at the time when the difference between average indoor air temperature and indoor surface temperature was greatest. Results from three measures of indoor wall surface temperature are shown in Table 8. The first measure is the average reading of 16 thermocouples uniformly distributed in a 4x4 grid over the wall area. The second measure is the average reading of four thermocouples located in the bottom row of the grid. This measure shows the effect of cooler temperatures near the bottom of the wall. The third measure, applied only to Walls P1 and P2, is the minimum indoor surface temperature measured by thermocouples in the vicinity of monitored ties. Indoor air temperature for all cases was the average of 16 thermocouples uniformly distributed over the wall area.

Table 8 shows that relative humidities determined for the NBS-10 Dynamic Test Cycle are identical for Walls P1 and P2. This suggests that the metal ties in Wall P2 have a negligible effect on the potential for condensation at the inside surface of the wall. Relative humidities determined from surface temperatures measured at the bottom row of the thermocouple grid are lowest, as is expected, but even these are 96% for the NBS-10 Test Cycle.

Relative humidities for the January Denver Test Cycle applied to Wall P2 are lower than those for the NBS-10 Test Cycle. This is due to the lower temperature for the January Denver Test Cycle compared to the NBS-10 Test Cycle. The mean temperature of Wall P2 during the January Denver Test Cycle was 54°F, which is similar to the mean wall temperature during the second steady-state test, 56°F. Relative humidities at which condensation would be likely to occur range from 2 to 4% lower for the January Denver Test Cycle than for the second steady-state test. This is because the outdoor air temperature fluctuates from 24 to 56°F for the dynamic test and remains constant at 38°F for the steady-state test. Since there is no heat flow reversal during the January Denver Test Cycle, the maximum indoor air-to-surface temperature differential for the dynamic test is greater than that for the steady-state test.

Relative humidities at which condensation is likely to occur during the NBS-10 Test Cycle are significantly lower for the solid concrete wall than for the insulated concrete sandwich panel walls. For average readings of 16 indoor surface thermocouples, calculated relative humidity is 13% lower for Wall C1 compared to Walls P1 and P2. For the average of four bottom row thermocouples, calculated relative humidity is 21% lower for Wall C1 compared to Walls P1 and P2. Lower condensation-causing relative humidities occur because of the low thermal resistance of uninsulated concrete which causes low indoor surface temperatures. Critical relative humidities calculated from the dynamic tests are higher than those determined from steady-state test results. Because of heat flow reversals through the wall and the higher mean wall temperatures during the NBS-10 Test Cycle, indoor air-to-surface temperature differentials are lower than during the steady-state tests.

For the dynamic test cycles considered, the greatest indoor air-to-surface temperature differential for the insulated sandwich panel walls, 2°F, would cause condensation at 92% relative humidity. Humidity of this magnitude is significantly higher than that typically encountered inside residential and commercial buildings in winter months.

However, on uninsulated portions of concrete sandwich panel walls condensation has the potential to occur at lower relative humidities. Near the bottom of the solid concrete wall during the NBS-10 Test Cycle, condensation would be likely to occur at 75% RH. For a colder outdoor temperature cycle, this threshold relative humidity would decrease. Therefore, in relatively humid indoor environments, condensation may be a problem on solid portions of concrete sandwich panel walls.

Dynamic versus Steady-State Results

Dynamic tests on massive walls can give more accurate results than steady-state tests for determining relative humidities at which condensation would be expected to occur. Temperature profiles from dynamic tests take into account effects of thermal storage in building components.

The benefit of dynamic testing can be seen by comparing steady-state and dynamic test results for Wall C1, constructed of uninsulated normal weight concrete. The outdoor air temperature was 34.4°F for the steady-state test with a mean wall temperature of 55°F. The minimum outdoor air temperature was 34.5°F for the NBS-10 Test Cycle. The relative humidities expected to cause condensation were 80% for the steady-state test and 85% for the dynamic test, based on the average of 16 thermocouples. If the steady-state temperature profile was used to predict the expected relative humidity to cause condensation, the concrete would be penalized 5% relative humidity, the difference between 80 and 85%.

Comparisons between steady-state and dynamic test results are summarized in Table 9 for the three walls considered in this investigation. The difference between steady-state and dynamic results is small for the insulated walls because, in these cases, the effects of insulation rather than mass dominate the temperature profile across the wall.

OTHER CONSIDERATIONS

This test program presented results for one metal tie system for insulated concrete sandwich panel walls. The influence of metal ties on indoor condensation was negligible.

TABLE 9 - COMPARISON OF STEADY-STATE AND DYNAMIC TEST RESULTS

Wall	Steady-State Test			Dynamic Test			Difference in RH Between Steady-State and Dynamic Test Results, %
	Wall Mean Temp., °F	Outdoor Air Temp., °F	Calc. RH to Cause Condensation,* %	Test	Minimum Outdoor Air Temp., °F	Calc. RH to Cause Condensation,* %	
P1	56	38.6	97	NBS-10	34.7	98	1
P2	56	37.8	98	NBS-10	36.9	98	0
C1	55	34.5	80	NBS-10	34.4	85	5

*Based on average temperatures from 16 thermocouples.

Potential for indoor wall surface condensation is greater for walls with less insulation, for tie systems with greater cross-sectional area, or when insulation is not tightly packed around ties as it was in this test program. Any of these situations will produce cooler indoor surface temperatures, and a greater potential for condensation, at tie locations.

As shown from results for the solid concrete wall, condensation potential is greater for concrete or masonry walls with little or no insulation. In this case, larger steady-state air-to-surface temperature differentials occur on the indoor surface of the wall because of the wall's lower thermal resistance. The effect of thermal mass under dynamic conditions is to reduce this temperature differential and decrease the likelihood of indoor surface condensation compared to steady-state conditions.

SUMMARY AND CONCLUSIONS

Relative humidities of indoor air at which condensation would be expected to occur on indoor wall surfaces were evaluated from temperatures measured during steady-state and dynamic calibrated hot box tests on three walls. Two of the walls were multi-layered insulated concrete walls, one with metal ties joining concrete layers and one without ties. The third wall was an uninsulated concrete wall. Relative humidities required to potentially cause condensation were determined for measured indoor air and indoor surface temperatures.

Relative humidities required to potentially cause condensation on the insulated concrete sandwich panel walls for selected winter temperature conditions ranged from 88% to 99%. Humidities of this magnitude are significantly higher than those typically encountered inside residential and commercial buildings in winter months. It can be concluded that condensation would not be a problem on insulated portions of indoor surfaces of this type of wall, with or without the type of metal ties considered in this investigation. The fact that these walls are well insulated allows the indoor surface temperature to remain close to indoor air temperatures. The influence of the metal ties appeared to be negligible, both in overall wall performance and in conditions at the location of a tie.

Relative humidities estimated from dynamic tests of the sandwich panel walls were not significantly different from those determined from steady-state tests. This results because half of the mass of the wall is isolated from fluctuating outdoor temperatures, thus maintaining a relatively constant indoor surface temperature close to the indoor air temperature. Steady-state relative humidities ranged from 88 to 99% while results from dynamic tests ranged from 92 to 99%.

Solid portions of concrete sandwich panel walls will be more likely to experience condensation. Steady-state test results on the solid concrete wall indicate that condensation is likely to occur for relative humidities of 42 to 80%, depending on temperature conditions and location on the wall. For the one dynamic test considered, condensation would potentially occur at relative humidities of 75 to 85%. These higher relative humidities reflect the benefits of thermal mass. Because of heat flow reversals through the wall, steady-state conditions are never attained within the wall. As a result, indoor surface temperatures remain closer to indoor air temperatures, reducing the likelihood of condensation.

REFERENCES

1. Van Geem, M. G., and Shirley, S. T., "Heat Transfer Characteristics of Insulated Concrete Sandwich Panel Walls," Construction Technology Laboratories, Portland Cement Association, Skokie, 1986, 198 pages.

2. Van Geem, M. G., Fiorato, A. E., and Julien, J. T., "Heat Transfer Characteristics of a Normal Weight Concrete Wall," Construction Technology Laboratories, Portland Cement Association, Skokie, 1983, 89 pages.

3. 1985 Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, 1985.

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

5. "ASHRAE Psychrometric Chart No. 1 (Normal Temperature, Sea Level)," American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, 1963.

6. Peavy, B. A., Powell, F. J., and Burch, D. M., "Dynamic Thermal Performance of an Experimental Masonry Building," Building Science Series 45, U.S. Department of Commerce, National Bureau of Standards, Washington, D.C., 1973, 98 pages.

7. ASHRAE Handbook - 1985 Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1985.

APPENDIX A. MEASURED TEMPERATURES FOR JANUARY DENVER TEST CYCLE APPLIED TO WALL P2

APPENDIX A. MEASURED TEMPERATURES FOR JANUARY DENVER TEST CYCLE APPLIED TO WALL P2

Measured temperatures are listed in Table A1 for the January Denver Temperature Cycle applied to Wall P2. Values are illustrated in Fig. A1.

For Wall P2, outdoor air (t_0), indoor air (t_1), outdoor surface (t_2), indoor surface (t_1), and internal wall (t_3,t_4) temperatures are average readings of the 16 thermocouples placed as described in the "Instrumentation" section of this report. Internal concrete/insulation interface temperatures on the indoor and outdoor sides, (t_3) and (t_4), respectively, are average readings of thermocouples placed on each side of the insulation board.

Air-to-air (t_0-t_1), surface-to-surface (t_2-t_1), and surface-to-air (t_0-t_2, t_1-t_1) temperature differentials are illustrated in Fig. A2 for the January Denver Temperature Cycle applied to Wall P2.

TABLE A1 - MEASURED TEMPERATURES FOR JANUARY DENVER TEST CYCLE APPLIED TO WALL P2

Time, hr	Measured Temperatures, °F					
	to Outdoor Air	t2 Outdoor Surface	t4 Internal Outdoor	t3 Internal Indoor	t1 Indoor Surface	ti Indoor Air
1	24.1	30.3	33.2	70.0	70.8	71.7
2	24.3	29.7	32.0	69.9	70.7	71.7
3	24.4	29.2	31.1	69.8	70.7	71.7
4	23.7	28.5	30.4	69.8	70.6	71.7
5	23.9	28.2	29.7	69.7	70.6	71.7
6	23.9	27.9	29.3	69.6	70.5	71.6
7	24.1	27.7	28.9	69.6	70.5	71.6
8	33.0	31.4	29.0	69.5	70.4	71.6
9	41.6	36.3	31.2	69.5	70.4	71.6
10	47.1	40.2	34.0	69.6	70.5	71.6
11	51.4	44.1	37.5	69.6	70.5	71.6
12	53.9	47.2	40.9	69.7	70.5	71.6
13	55.7	49.8	44.1	69.8	70.5	71.6
14	56.4	51.6	46.8	70.0	70.6	71.6
15	54.4	52.1	49.0	70.1	70.7	71.6
16	48.2	50.0	50.0	70.3	70.7	71.6
17	38.0	45.2	49.2	70.4	70.8	71.6
18	33.1	41.7	46.8	70.4	70.9	71.7
19	30.9	39.3	44.1	70.5	70.9	71.7
20	29.2	37.3	41.7	70.4	70.9	71.7
21	27.6	35.4	39.5	70.4	70.9	71.7
22	26.8	33.9	37.6	70.3	70.9	71.7
23	26.4	32.8	35.9	70.2	70.8	71.7
24	25.2	31.5	34.5	70.1	70.8	71.7
Mean	35.3	37.6	37.8	70.0	70.7	71.7

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

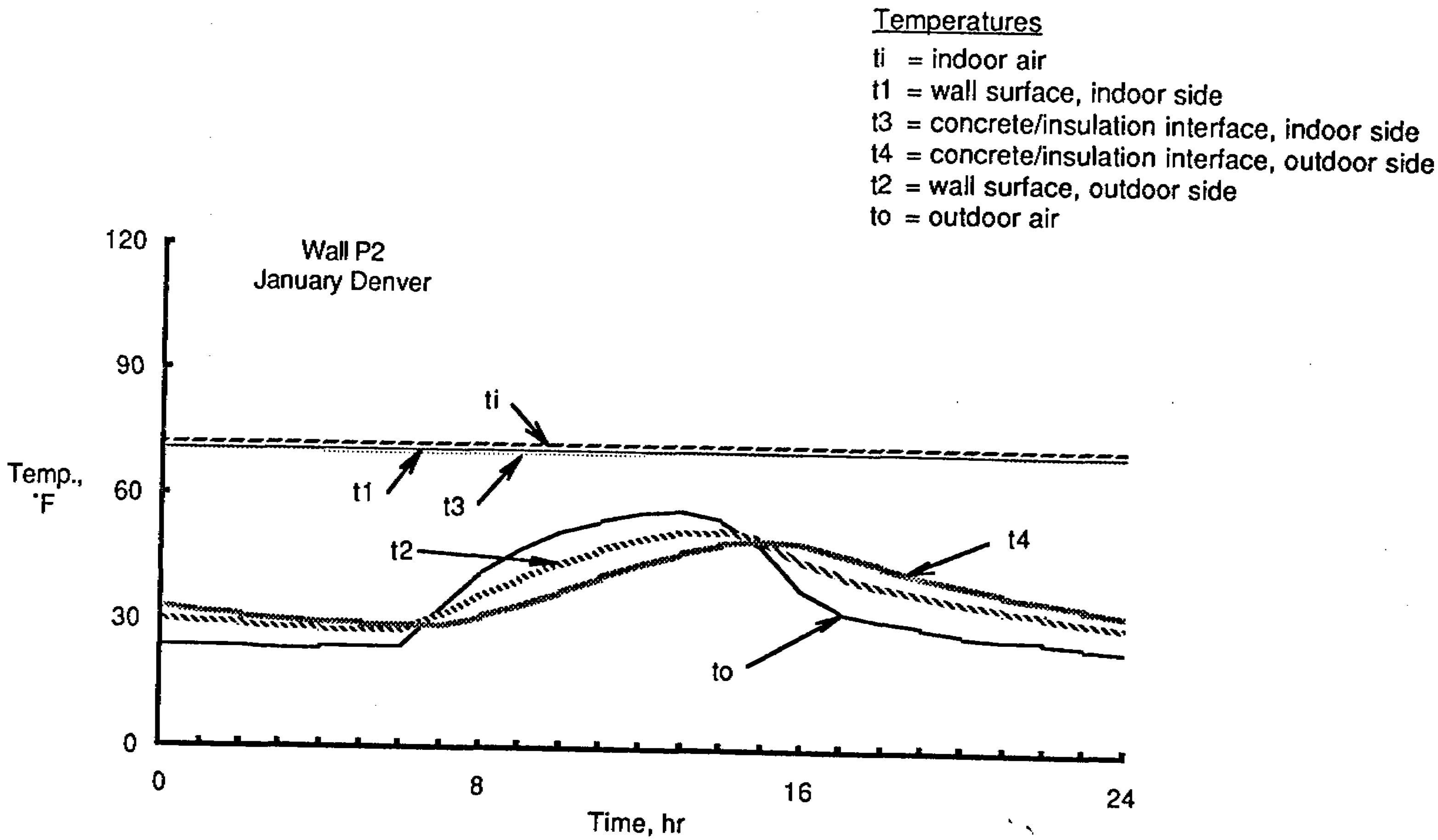


Fig. A1 Measured Temperatures for January Denver Test Cycle Applied to Wall P2

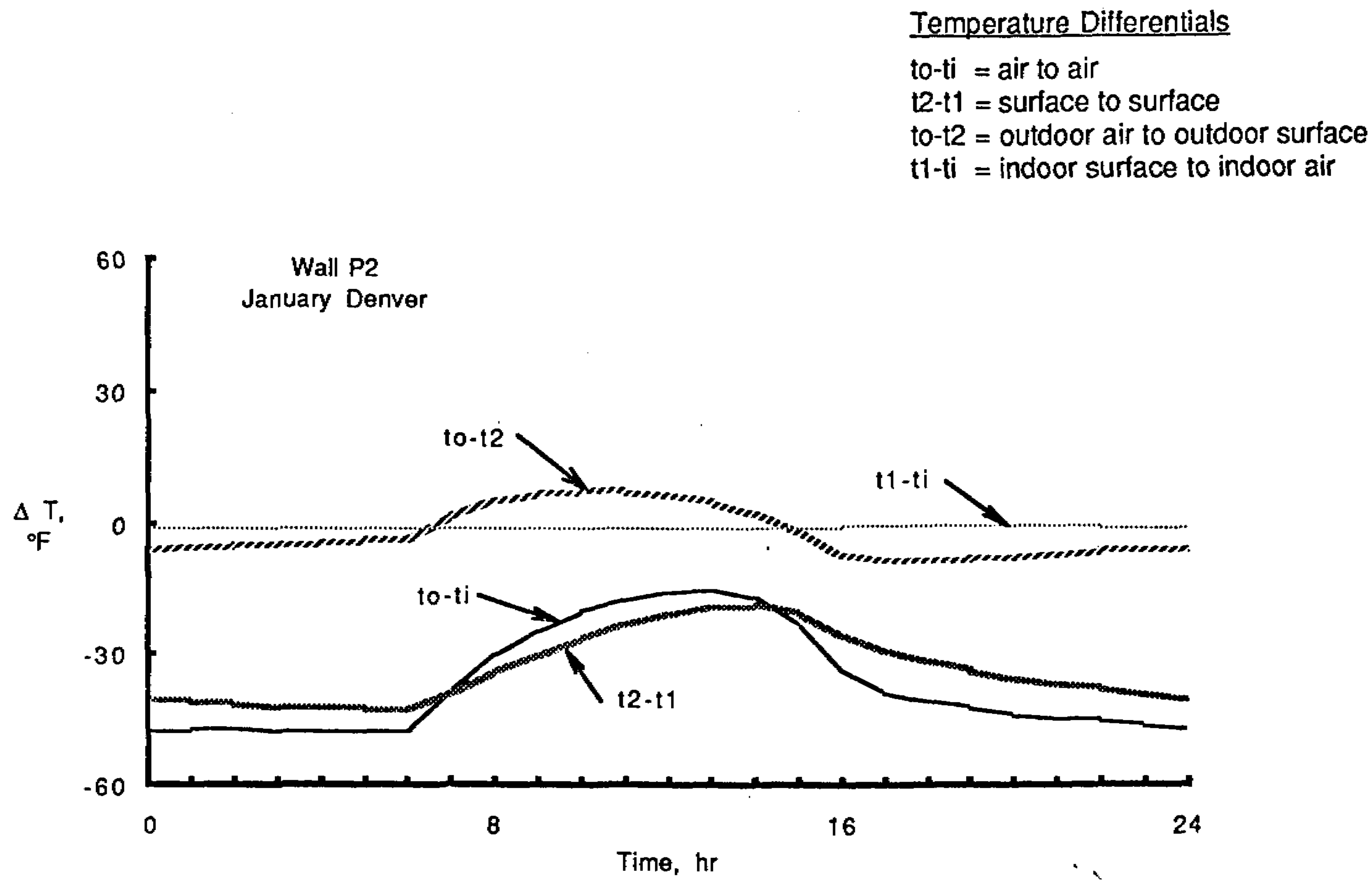


Fig. A2 Temperature Differentials for January Denver Test Cycle Applied to Wall P2