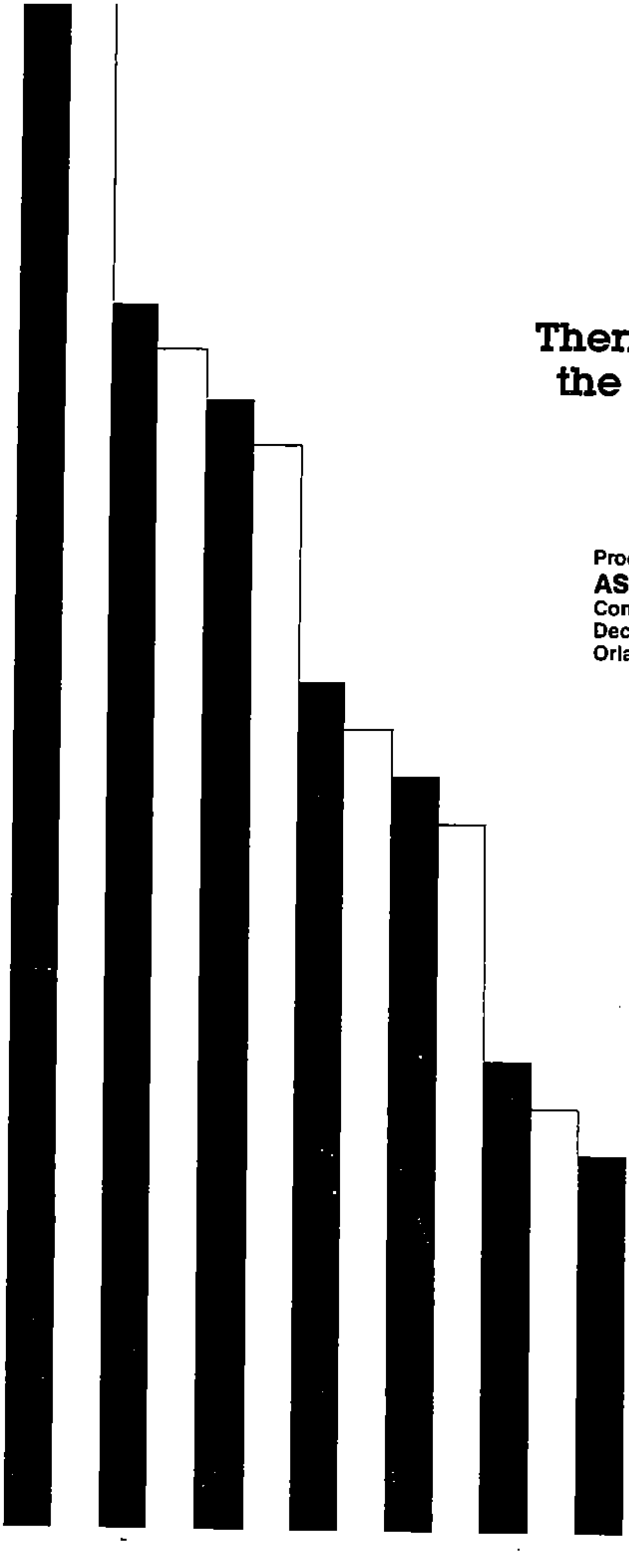

Thermal Performance of the Exterior Envelopes of Buildings IV

Proceedings of the
ASHRAE/DOE/BTECC/CIBSE
Conference
December 4-7, 1989
Orlando, Florida

**American Society of Heating,
Refrigerating, and
Air-Conditioning Engineers, Inc.**

Effects of Ties on Heat Transfer through Insulated Concrete Sandwich Panel Walls

M.G. Van Geem, P.E.
Member **ASHRAE**

ABSTRACT

Tests were conducted to evaluate thermal performance of three insulated concrete sandwich panel walls. Heat transfer through the walls was measured for steady-state and dynamic temperature conditions. The objective of the test program was to investigate effects of ties connecting wall layers on thermal properties of insulated sandwich panel walls.

The three walls tested were similar except for the type of connectors joining the insulation and concrete layers. Each wall consisted of 2 in. (50 mm) of extruded polystyrene insulation board sandwiched between two 3 in. (75 mm) normal weight concrete layers. The first wall, a control wall, contained no ties. Layers of the second wall were connected using stainless steel ties and anchors. Layers of the third wall were connected using high-tensile fiberglass-composite ties.

Walls were tested in the calibrated hot box facility (ASTM designation: C976) at a national laboratory. Steady-state tests were used to measure thermal resistance (R_T) and thermal transmittance (U). A comparison of results from steady-state tests on the control wall and the wall with stainless steel connectors showed that stainless steel connectors reduced wall thermal resistance by 7%. A comparison of results from steady-state tests on the control wall and the wall with high-tensile fiberglass-composite ties showed that the ties did not measurably reduce wall thermal resistance.

Dynamic calibrated hot box tests provided a measure of thermal response under selected temperature ranges. Heat storage capacities of the walls delayed heat flows through specimens. Average thermal lag values ranged from five to six hours for the three walls. The tie systems present in walls P2 and P3 did not significantly affect thermal lag of the wall systems.

Thermal resistances of insulations used in the walls were measured using a guarded hot plate (ASTM designation: C177). Wall resistances measured in a calibrated hot box were compared to resistances calculated from wall material properties.

INTRODUCTION

A significant amount of energy is lost from conditioned environments of buildings through thermal bridges. Heat transfer measurements of building components with thermal bridges are needed to assess the severity of heat loss through particular bridges so that remedial measures may be used, if necessary. Heat transfer measurements are also used to verify analytical methods of predicting heat losses through thermal bridges.

Martha G. Van Geem, Senior Research Engineer, Fire/Thermal Technology Section, Construction Technology Laboratories, Inc., 5420 Old Orchard Road, Skokie, IL 60077, 312-965-7500.

Tests were conducted to evaluate thermal performance of three insulated concrete sandwich panel walls. Heat transfer through the walls was measured for steady-state and dynamic temperature conditions in a calibrated hot box. The three walls tested were similar except for the type of connectors joining the insulation and concrete layers. Each wall consisted of 2 in. (50 mm) of extruded polystyrene insulation board sandwiched between two 3 in. (75 mm) normal weight concrete layers. The first wall, designated wall P1, was a control wall and contained no ties. Layers of the second wall, designated wall P2, were connected using stainless steel ties and anchors. Layers of the third wall, designated wall P3, were connected using high-tensile fiberglass-composite ties.

The objective of the test program was to investigate thermal effects of metal and non-metal ties connecting wall layers on thermal properties of insulated sandwich panel walls. Van Geem and Shirley (1987) gives more detailed information on test specimens, instrumentation, equipment, procedures, and test results.

BACKGROUND

One method of insulating structural concrete walls is to provide a layer of insulation between two layers of concrete. Ties or other fasteners are used to connect the three layers. Ties are often necessary for stability and load transfer, as either or both concrete layers may be designed to be load bearing.

Ties or other elements that penetrate an insulation layer act as thermal bridges when their conductivity is large compared to insulation. Heat losses are concentrated at the location of conductive elements because heat will flow through the path of least resistance, as illustrated in Figure 1. Metal ties connecting layers of insulated concrete sandwich panel walls reduce the thermal resistance of a wall assembly.

Materials other than metal may be used for connectors if they provide enough strength to resist the conductor design loads. High-tensile fiberglass-composite ties have been developed to reduce thermal bridging through insulation. The conductivity of the fiberglass-composite material is approximately 1/100 that of stainless steel. Tie thermal conductivities are documented in the "Design Heat Transmission Coefficients" portion of this paper.

The guarded hot plate test method [ASTM designation: C177 (ASTM 1985)] is the most widely accepted method of measuring thermal resistance of building materials. Generally, tests are performed using relatively small samples of homogeneous materials. Sample sizes generally range from 0.2 to 4 ft^2 (0.02 to 0.4 m^2), depending on the hot plate used. Average thermal resistance of a system containing a thermal bridge such as a stainless steel tie cannot be measured using a guarded hot plate.

The calibrated hot box [ASTM designation: C976 (ASTM 1985)] and the guarded hot box [ASTM designation: C236 (ASTM 1985)] are used to measure thermal performance of full-scale wall assemblies. Specimens may be constructed of homogeneous materials, such as concrete, or composite systems, such as insulated frame walls, masonry walls, or panels with metal connectors. Some calibrated hot boxes are used to measure performance for steady-state or dynamic temperature conditions. Dynamic testing is particularly important for massive envelope components that store as well as transmit heat. Test results are used to evaluate performance of comparative wall systems and to verify analytical models. Heat transfer characteristics of building elements must be known to evaluate energy losses through a building envelope.

TEST SPECIMENS

Three insulated concrete sandwich panel walls were constructed and subsequently tested in a calibrated hot box. Walls consisted of insulation board sandwiched between normal weight concrete layers, as shown in Figure 1. Overall nominal dimensions of each wall were 103 by 103 in. (2.62 by 2.62 m). Nominal dimensions of concrete and insulation layers were 3 in. (75 mm) and 2 in. (50 mm), respectively.

Wall Construction

Concrete and Insulation. Walls were reinforced with a single layer of 6 in. by 6 in. (150 by 150 mm) W1.4 x W1.4 welded wire fabric located at the center of each 3 in. (750 mm) concrete layer, as detailed in Figure 2. Walls were oriented horizontally for casting. The wire mesh was supported at a distance of 1.5 in. (38 mm) from the face of the layer by concrete chairs. These chair supports raised the wire mesh off the formwork base before and during concrete placement. Chair supports were also used to raise wire mesh above the insulation prior to casting the second concrete layer. Chair supports were made of the same concrete used for wall construction. Concrete rather than steel or plastic chairs were used to eliminate potential thermal bridging caused by supports.

Threaded inserts were cast into one side of walls P1, P2, and P3 at mid-thickness of the concrete layer. The steel loop-type inserts were used to transport each wall after the concrete had attained the necessary strength.

The same concrete mix design was used to construct walls P1, P2, and P3. Type I cement and Elgin coarse and fine aggregate were used in the concrete for all walls. The nominal maximum size of the coarse gravel was 3/4 in. (20 mm). These aggregates are considered dolomitic (Abrams 1973). Laboratory test results for average measured slump, air content, and unit weight of the fresh concrete are summarized in Table 1. The average water-cement ratio of concrete used for each of the three walls was 0.57.

The 2 in. (50 mm) thick insulation board used for the walls was obtained in nominal 4 ft by 8 ft (1.22 by 2.44 m) sheets and was identified as extruded polystyrene. Insulation was pieced together to form 8 ft, 7 in. (2.62 m) square panels. Measured thicknesses and densities of the insulations are presented in Table 1. Insulation for walls P1 and P2 were obtained from one manufacturer, while insulation for wall P3 was obtained from a different manufacturer. Insulation pieces for walls P1 and P2 were secured at joints using continuous strips of duct tape on each surface. Insulation pieces of wall P3 were joined using a transparent cellophane tape provided by the insulation manufacturer. Taping of the seams prevented infiltration of concrete paste during placement.

Placement of concrete to form the first 3 in. (75 mm) thick concrete layer was performed initially. Concrete was consolidated using a vibrating pad and then screeded to obtain a uniform 3 in. (75 mm) thickness. Insulation board with thermocouple wires attached was then placed on top of the concrete. After the insulation board and thermocouples were positioned, construction procedures described above were repeated for the second concrete layer. The top layer of concrete was troweled to obtain a uniform surface.

Walls were allowed to cure in formwork for 14 to 15 days. After removing formwork, walls were allowed to air dry in the laboratory at a temperature of 73±5°F (23±3°C) and 45%±15% RH for approximately three months. Prior to testing, wall faces were coated with a cementitious waterproofing material to seal minor surface imperfections. A textured, non-cementitious paint was subsequently used as a finish coat. These coatings provided a white, uniform surface for both wall faces. Wall edges were not coated.

Tie Systems. Torsion anchors and ties, identified as stainless steel, were used to connect concrete layers of wall P2. Locations of the 4 torsion anchors and 16 metal ties are shown in Figure 3. A Type A-3 tie consists of two 0.118 in. (3 mm) diameter bars with a nominal height of 5 in. (125 mm) penetrating the insulation. Dimensions of Type A and Type B torsion anchors are shown in Figure 4. Connectors were installed per manufacturer's instructions. Ties and torsion anchors were attached directly to the wire mesh of the lower layer before concrete was placed. Two 28 in. (700 mm) long No. 2 (6 mm) diameter) bars were installed in the same planes as the wire mesh at the location of each torsion anchor.

Sections of insulation were cut out at locations of ties and torsion anchors. Cut-out sections were saved and replaced after insulation board was placed on the first concrete layer. Seams of cut-out sections were taped on the top surface using duct tape.

Ties, described as high-tensile fiberglass-composite, were used to connect concrete layers of wall P3. Thirty-six ties were placed in six rows of six, with a uniform spacing of 16.97 in. (0.42 m) between ties. Connectors were installed per manufacturer's instructions. Dimensions of the 6 in. (150 mm) long connectors are shown in Figure 5. Prior to placing the insulation on the concrete, 15/32 in. (12 mm) holes were drilled through the insulation at the location of ties. High-tensile fiberglass-composite ties were pushed through the pre-drilled holes in the insulation into the lower concrete layer.

Wall Properties. Measured unit weights, thicknesses, and surface areas of walls P1, P2, and P3 are summarized in Table 1. Selected insulation and concrete properties for the walls are also listed. Average moisture content and unit weight of concrete in each wall at the time of calibrated hot box tests were estimated using air dry and ovendry unit weights of 6 in. by 12 in. (150 by 300 mm) cylinders cast at the same times as individual walls.

Instrumentation

Ninety-six 20-gauge thermocouples corresponding to ASTM designation: E230, "Standard Temperature-Electromotive Force (EMF) Tables for Thermocouples," (ASTM 1985) Type T, were used to measure temperatures during thermal testing. For each test wall, 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 3/4 in. (525 mm) apart in four rows of four over the wall area. Thermocouples measuring temperatures in the air space of each chamber of the calibrated hot box were located approximately 3 in. (75 mm) 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. (100 mm). The tape covering the sensors was painted the same color as the test wall surface.

Internal thermocouples placed at the concrete/insulation interfaces were taped directly to the insulation board prior to placement in the wall. This technique ensured desirable thermocouple location during concrete placement. Thermocouples were wired to form a thermopile, such that an electrical average of four thermocouple junctions, located along a horizontal row across the wall, was obtained. Wires for thermocouples mounted on insulation were routed through side formwork prior to casting the second concrete layer of each wall.

Additional thermocouples were also used to monitor temperatures on and near ties bridging concrete layers for walls P2 and P3. Locations and readings of these additional thermocouples are presented in Van Geem and Shirley (1987).

THERMAL RESISTANCE OF INSULATION

Thermal resistance of insulation used to construct walls was determined in accordance with ASTM designation: C177, "Steady-State Thermal Transmission Properties by Means of the Guarded Hot Plate" (ASTM 1985). Guarded hot plate specimens were cut from the same lot of insulation board as that used in the concrete-insulation sandwich walls. Two specimens were cut from each brand of insulation. Nominal specimen dimensions were 2 by 12 by 12 in. (50 by 300 by 300 mm). The measured thickness and density of insulation used for walls P1 and P2 were 1.99 in. (49.8 mm) and 1.8 lb/ft^3 (35.2 kg/m^3), respectively. The measured thickness and density of wall P3 insulation were 1.94 in. (48.5 mm) and 2.2 lb/ft^3 (35.2 kg/m^3), respectively.

Measured thermal resistances are presented in Figure 6 as a function of specimen mean temperature, the average temperature of specimen cold and hot surfaces. The average temperature difference across specimens ranged from 24° to 45°F (13° to 25°C) for the nine tests. Thermal resistance decreases with increasing mean temperature for both brands of insulation.

Thermal resistances at specimen mean temperatures of 75°F (24°C) were linearly interpolated from measured values. Insulation in walls P1 and P2 had a thermal resistance of 8.92 h ft^2 °F/Btu (1.57 m^2 K/W) and apparent thermal conductivity of 0.223 Btu in./h ft^2 °F (0.032 W/m K) at a specimen mean temperature of 75°F (24°C). Wall P3 insulation had a thermal resistance of 9.02 h ft^2 °F/Btu (1.59 m^2 K/W) and an apparent thermal conductivity of 0.215 Btu in./h ft^2 °F (0.030 W/m K) at a specimen mean temperature of 75°F (24°C).

THERMAL RESISTANCE OF WALLS

Two steady-state calibrated hot box tests were performed on walls P1, P2, and P3. Heat flow and temperature measurements were used to determine average thermal properties of total thermal resistance (R_T) and transmittance (U). Design heat transmission coefficients are calculated for the walls and compared to measured values.

Design Heat Transmission Coefficients

Design values are calculated in accordance with procedures established by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) (ASHRAE 1985). Wall configurations and thermal conductivities of wall materials are used to calculate design values. Thermal conductivities used to calculate design heat transmission coefficients are listed in Table 2. Values of all materials are for a 75°F (24°C) temperature. Detailed calculations are presented in Van Geem and Shirley (1987).

Calculated total thermal resistance of wall P1 is 10.15 h ft^2 °F/Btu (1.79 m^2 K/W) and was determined by summing resistances of wall layers. Total resistance values, R_T,* include surface resistances equal to 0.68 h ft^2 °F/Btu (0.12 m^2 K/W) for indoor surfaces and 0.17 h ft^2 °F/Btu (0.03 m^2 K/W) for outdoor surfaces (ASHRAE 1985). These values are commonly used in design and are considered to represent still air on the indoor wall surface and an airflow of 15 mph (24 km/h) on the outdoor wall surface. Actual surface resistances may be calculated using measured temperatures and heat flux presented in the "Calibrated Hot Box Test Results" section of this paper. Thermal transmittance, U, is equal to the reciprocal of total thermal resistance, R_T.

Calculations of design heat transmission coefficients for wall P2 were made using the isothermal planes method, also designated the series parallel method (ASHRAE 1981; Valore 1980). This method of calculation is applicable for wall assemblies in which heat can flow laterally in any continuous layer. Lateral heat flow in continuous layers is assumed to result in isothermal planes. These planes provide a means for heat flow toward areas with higher thermal conductivities. In this case, the ties used to bridge concrete layers in wall P2 act as heat sinks or thermal bridges.

The 16 stainless steel ties penetrating the insulation of wall P2 had an aggregate cross-sectional area of 0.351 in.^{2} (226 mm^2). The four torsion anchors had an aggregate cross-sectional area of 0.430 in.^{2} (277 mm^2). Total cross-sectional area of stainless steel in wall P2 was 0.781 in.^{2} (504 mm^2).

Total thermal resistance of wall P2 calculated using the isothermal planes method is 9.64 h ft^2 °F/Btu (1.70 m^2 K/W). This value is 5% less than the calculated thermal resistance of the wall with no ties, wall P1.

Design heat transmission coefficients for wall P3 were calculated using the parallel path method. This method is preferred when the material penetrating the insulation has a lower conductivity than the highly conductive surrounding layer (ASHRAE 1981). In this case, the high-tensile fiberglass-composite ties have a lower thermal conductivity than the concrete.

Total thermal resistance of wall P3 calculated using the parallel path method is 10.25 h ft^2 °F/Btu (1.81 m^2 K/W). This value is 1% greater than the calculated thermal resistance of the wall with no ties, wall P1. The higher resistance of wall P3 compared to wall P1 is attributed to the different insulation board used for wall P3. The high-tensile fiberglass-composite ties cannot increase a wall's R-value when the thermal conductivity of the ties is greater than that of the insulation, as is the case for wall P3.

Calibrated Hot Box Test Results

The most exact method of determining heat transmission coefficients of complex wall assemblies such as walls P2 and P3 is to test them in a guarded or calibrated hot box (ASTM designations: C236 and C976, respectively) (ASTM 1985). ASHRAE calculation methods are considered approximations, although calculated values frequently agree with hot box test results (ASHRAE 1985).

---

*This paper uses the term total thermal resistance as defined by ASHRAE (1985). This same term is identified as overall thermal resistance, R_u, by ASTM (1985).

Test Procedures. Steady-state heat flow measurements were performed in accordance with ASTM designation: C976, "Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box" (ASTM 1985). Instrumentation and calibration details are described in Van Geem and Shirley (1987) and Fiorato (1981).

Steady-state calibrated hot box tests were conducted by maintaining constant indoor and outdoor chamber temperatures. Results are calculated from data collected when specimen temperatures reach equilibrium and the rate of heat flow through the test wall is constant. Steady-state tests were run at two temperature differentials. For the first case, indoor air temperature was maintained at approximately 73°F (23°C), while outdoor air temperature was maintained at approximately 134°F (56°C). This provided a nominal temperature differential of approximately 61°F (34°C) and mean wall temperature of approximately 104°F (40°C). In the second case, indoor air temperature was maintained at approximately 71°F (22°C), while outdoor air temperature was maintained at approximately -4°F (-20°C). This provided a nominal temperature differential of 75°F (42°C) and a mean wall temperature of approximately 34°F (1°C).

Test Results. Steady-state results from calibrated hot box tests on walls P1, P2, and P3 are summarized in Table 3. Data are averages for 16 consecutive hours of testing. The second column of Table 3 lists the mean wall temperature, t_m, during each steady-state test. Wall mean temperature is determined from the average of the indoor and outdoor wall surface temperatures. Measured temperatures are presented in Table 3 using the following notation:

t_{oa} = outdoor air temperature

t_{os} = wall surface temperature, outdoor side

t_{oc} = internal wall temperature at the interface of concrete and insulation on the outdoor side

t_{ic} = internal wall temperature at the interface of concrete and insulation on the indoor side

t_{is} = wall surface temperature, indoor side

t_{ia} = indoor air temperature

All temperatures are averages of the 16 thermocouples located in each plane, as previously described in the "Instrumentation" section of this paper.

Total thermal resistance and transmittance coefficients were determined using measured values of heat flow and surface resistance coefficients of 0.68 h ft^2 °F/Btu (0.12 m^2 K/W) for indoors and 0.17 h ft^2 °F/Btu (0.03 m^2 K/W) for outdoors. Design heat transmission coefficients are shown in the last row of each section in Table 3 for comparison. The design values for each wall were calculated at a mean wall temperature of 75°F (24°C).

Measured relative humidity within the indoor and outdoor chambers of the calibrated hot box is listed in Table 3.

Thermal Resistance Comparisons. Wall P1 is a control wall for this test program. Since walls P1 and P2 were constructed using the same concrete mix and insulation, differences in thermal performances of the walls can be attributed to stainless steel torsion anchors and ties in wall P2. Walls P1 and P3 were constructed with the same concrete mix but different brands of extruded polystyrene insulations. Differences in thermal performance of walls P1 and P3 can be attributed to the insulations or the high-tensile fiberglass-composite ties in wall P3.

Figure 7 shows measured and design thermal resistances for walls P1, P2, and P3 as a function of mean temperature. At a mean wall temperature of approximately 104°F (40°C) the measured total thermal resistance of wall P1 was 8.89 h ft^2 °F/Btu (1.57 m^2 K/W). At this same mean temperature walls P2 and P3 had measured total thermal resistances of 8.27 and 10.55 h ft^2 °F/Btu (1.46 and 1.85 m^2 K/W), respectively.

At a mean wall temperature of approximately 34°F (1°C) the measured total thermal resistance of wall P1 was 10.95 h ft^2 °F/Btu (1.94 m^2 K/W). At this same mean temperature walls P2 and P3 had measured total thermal resistances of 10.31 and 11.30 h ft^2 °F/Btu (1.82 and 1.99 m^2 K/W), respectively.

For steady-state tests at mean wall temperatures of 104°F (40°C) and 34°F (1°C), respectively, total thermal resistances of wall P2 were 7% and 6% less than for wall P1. This reduction in thermal resistance is due to greater heat flow through stainless steel ties and torsion anchors in wall P2. The design thermal resistance of wall P2 calculated at a mean wall temperature of 75°F (24°C) using the isothermal planes method is 5% less than that for wall P1. The calculation is consistent with the measured decrease in thermal resistance of wall P2.

For steady-state tests at mean wall temperatures of 104°F (40°C) and 34°F (1°C), respectively, total thermal resistances of wall P3 were 19% and 3% greater than for wall P1. The design thermal resistance for wall P3 was 1% greater than that for wall P1. The magnitude of the higher resistance of wall P3 at a mean temperature of 104°F (40°C) was not predicted. The increase in resistance cannot be attributed to the high-tensile fiberglass-composite ties penetrating the concrete because of the small percentage of gross wall area represented by the ties. Ties represent less than 0.06% of the wall area perpendicular to heat flow. The use of ties cannot increase a wall's R-value when the thermal conductivity of the ties is greater than that of the insulation, as is the case for wall P3. The increase in resistance cannot be attributed to the concrete because the concrete contributes less than 4% to the wall's thermal resistance. More research is needed to determine the reason for the increase in resistance of wall P3 at a mean temperature of 104°F (40°C).

Total thermal resistances of walls P1, P2, and P3 at 75°F (24°C) mean temperatures were estimated to be 9.74, 9.10, and 10.87 h ft^2 °F/Btu (1.72, 1.60, and 1.91 m^2 K/W), respectively. Values were linearly interpolated from measured resistances at 104°F (40°C) and 34°F (1°C).

Interpolated thermal resistances for walls P1 and P2, respectively, at a 75°F (24°C) mean temperature were 4% and 6% less than design resistances. Interpolated resistance for wall P3 at a 75°F (24°C) mean temperature was 6% greater than the design resistance.

Temperature data presented in Table 3 show that temperature profiles are similar for each of the three walls. The presence of stainless steel connectors, used in wall P2, and high-tensile fiberglass-composite ties, used in wall P3, does not significantly affect average temperatures at the wall surfaces and concrete/insulation interfaces.

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. The heat flow through walls as a response to temperature changes is a function of both thermal resistance and thermal storage capacity.

Test Procedures

Dynamic tests were conducted on walls P1, P2, and P3 using a calibrated hot box. For these tests, the calibrated hot box indoor air temperature was held constant while the outdoor air temperature was cycled over a pre-determined time vs. temperature relationship. The rate of heat flow through a test specimen was determined from hourly averages of data.

A 24-hour (diurnal) temperature cycle, denoted the NBS test cycle, was applied to each wall in this investigation and has been used in previous studies using the CTL calibrated hot box (Van Geem 1986; 1987). This periodic cycle is based on a simulated sol-air* cycle used by

---

*Sol-air temperature is that temperature of outdoor air which, in the absence of all radiation exchanges, would give the same rate of heat entry into the surface as would exist with the actual combination of incident solar radiation, radiant energy exchange, and convective heat exchange with outdoor air (ASHRAE 1985).

the National Bureau of Standards in its evaluation of dynamic thermal performance of an experimental masonry building (Peavy, et al. 1973). It represents a large variation in outdoor temperature over a 24-hour period. The mean outdoor temperature of the cycle is approximately equal to the mean indoor temperature.

Outdoor chamber air temperatures for the NBS test cycle applied to walls P1, P2, and P3 are illustrated in Figure 8. Outdoor air temperatures represent the average of the 16 thermocouples located 3 in. (75 mm) from the test specimen surface in the outdoor chamber. Average indoor air temperature over the 24-hour period for each cycle was approximately 72°F (22°C).

For all walls, the dynamic cycle was repeated until conditions of 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.

Test Results

Measured temperatures for the NBS test cycle applied to wall P1 are presented in Figure 9. Outdoor air (t_{oa}), indoor air (t_{ia}), outdoor surface (t_{os}), indoor surface (t_{is}), and internal wall (t_{oc}, t_{ic}) temperatures are average readings of 16 thermocouples placed as described in the "Instrumentation" section of this report. Internal concrete/insulation interface temperatures on the indoor and outdoor sides, (t_{ic}) and (t_{oc}), respectively, are average readings of thermocouples placed on each side of the insulation board.

Measured Heat Flow. Figure 10 shows measured and calculated heat flows through walls P1, P2, and P3 for the NBS temperature cycle. Heat flow is designated positive when heat flows from the calibrated hot box outdoor chamber to the indoor chamber. Heat flow determined from calibrated hot box tests is denoted q_w. Heat flow predicted by steady-state data analysis is denoted q_{ss}. Values were calculated on an hourly basis from wall surface temperatures using the following equation:

$$q_{ss} = (t_{os} - t_{is})/R \qquad (1)$$

where

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

R = average thermal resistance, h ft^2 °F/Btu (m^2 K/W)

t_{os} = average temperature of outdoor wall surface, °F (°C)

t_{is} = average temperature of indoor wall surface, °F (°C)

Thermal resistances for each wall are dependent on wall mean temperature and were derived from steady-state calibrated hot box test results.

Measured heat flow curves, q_w, for walls P1, P2, and P3 show significantly reduced and delayed peaks compared to calculated heat flows, q_{ss}. The amplitudes of calculated heat flows, q_{ss}, for wall P2 are greater than those for wall P1 due to the decreased resistance of wall P2. Measured heat flows, q_w, for the NBS test cycle applied to walls P1, P2, and P3 are not significantly different.

Actual maximum heat flow through a wall is important in determining the peak energy load for a building envelope. Test results show anticipated peak energy demands based on actual heat flow are less than those based on steady-state predictions for walls with thermal storage capacity. Calculations based on steady-state analysis overestimate peak heat flow for the three dynamic temperature cycles applied to walls P1, P2, and P3.

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

Average thermal lag values range from five to six hours for the NBS temperature cycle applied to walls P1, P2, and P3. Calibrated hot box thermal lag is quantified by two methods. In one measure, lag is calculated as the time required for the maximum or minimum indoor surface temperature to be reached after the maximum or minimum outdoor air temperature is attained. In the second measure, lag is calculated as the time required for the maximum or minimum heat flow rate, q_w, to be reached after the maximum or minimum heat flow rate based on steady-state predictions, q_{ss}, is attained. Both measures give similar results. Thermal lags for walls P2 and P3 are not significantly different from those for wall P1, the control wall. Thermal lags exhibited by the three walls are predominantly due to the thermal storage capacity of the concrete and the thermal resistance of the insulation board. The tie systems present in walls P2 and P3 did not significantly affect thermal lag of the wall systems.

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.

It should be noted that comparison of total measured heat flow values for the test walls is limited to specimens and dynamic cycles evaluated in this program. Results are for a particular diurnal test cycle 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.

SUMMARY AND CONCLUSIONS

This paper presents results of an experimental investigation of heat transmission characteristics of three concrete-insulation sandwich panel walls. Wall P1 contained no ties connecting layers. Layers of wall P2 were connected using stainless steel ties and torsion anchors. Layers of wall P3 were connected using high-tensile fiberglass-composite ties. Walls were tested for steady-state and dynamic temperature conditions using a calibrated hot box.

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

1. Measured thermal conductivity of extruded polystyrene used in construction of walls P1 and P2 was 0.22 Btu in/h ft^2 °F (0.032 W/m K) for a specimen mean temperature of 75°F (24°C). Measured thermal conductivity of extruded polystyrene used in construction of wall P3 was 0.21 Btu in/h ft^2 °F (0.030 W/m K) for a specimen mean temperature of 75°F (24°C). Values were linearly interpolated from steady-state guarded hot plate (ASTM designation: C177) test results.
2. Total thermal resistances, R , for walls P1, P2, and P3 were 9.7, 9.1, and 10.9 h ft^2 °F/Btu (1.72, 1.60, and 1.91 m^2 K/W). Resistances are for a wall mean temperature of 75°F (24°C) and were linearly interpolated from steady-state calibrated hot box test results. Values include standard surface film resistances. The higher R-value for wall P3 compared to wall P1, the control, should not be interpreted to mean the high-tensile fiberglass-composite ties increase a wall's R-value. The use of ties cannot increase a wall's R-value when the thermal conductivity of the ties is greater than that of the insulation, as is the case for wall P3.
3. A comparison of steady-state calibrated hot box test results from walls P1 and P2 shows that stainless steel connectors reduced total wall resistance by 7%.
4. A comparison of steady-state calibrated hot box test results from walls P1 and P3 shows that use of high-tensile fiberglass-composite ties did not measurably reduce total wall thermal resistance.
5. The isothermal planes method of calculating total wall thermal resistance predicted performance of wall P2. A 5% decrease in total resistance for wall P2 compared to wall P1 was predicted. A 7% decrease was measured.
6. Design total thermal resistances for walls P1, P2, and P3 were within 6% of calibrated hot box test results.

7. As indicated by thermal lag, heat storage capacities of insulated concrete sandwich panel walls delayed heat flow through specimens. Average thermal lag values ranged from five to six hours for walls P1, P2, and P3. The tie systems present in walls P2 and P3 did not significantly affect thermal lag of the wall systems.

8. As indicated by the damping effect, heat storage capacities of the walls reduced peak heat flows through specimens for the dynamic temperature condition considered when compared to steady-state predictions. The tie systems present in walls P2 and P3 did not significantly affect the reduction in peak heat flows for the wall systems.

Limitations

Calibrated hot box test results presented in this paper are limited to the test specimens and temperature cycle used in this investigation. It is anticipated that results would differ for walls with different insulation thicknesses, for tie systems with different cross-sectional areas, or when insulation is not packed tightly around ties, as it was in this test program.

Results described in this paper provide data on thermal response of concrete-insulation sandwich panel walls subjected to steady-state and diurnal sol-air temperature cycles. A complete analysis of building energy requirements must include consideration of the entire building envelope, building orientation, building operations, 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.

ACKNOWLEDGMENTS

The test program was performed at Construction Technology Laboratories, Inc. and was part of a project sponsored jointly by the U.S. Department of Energy (Office of Buildings and Community Systems), Amoco Foam Products Co., and the Portland Cement Association. It was part of the Building Thermal Envelope Systems and Materials Program (BTESM) at Oak Ridge National Laboratory (ORNL).

Extruded polystyrene insulation for walls P1 and P2 was provided by Dow Chemical U.S.A. Extruded polystyrene insulation for wall P3 was provided by Amoco Foam Products Co. Stainless steel ties and torsion anchors used for wall P2 were provided by the Burke Co. Fiberglass ties used for wall P3 were provided by Thermomass Technology Inc.

The preparation of this paper was jointly sponsored by Dow Chemical U.S.A. and Construction Technology Laboratories, Inc.

REFERENCES

Abrams, M.S. 1973. "Compressive strength of concrete at temperatures to 1600°F." Research and Development Bulletin RD016, Portland Cement Association, Skokie, IL, 11 pages.

Architectural graphic standards, 7th edition. 1981. New York: John Wiley and Sons.

ASHRAE. 1981. ASHRAE handbook-1981 fundamentals, chapter 23. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

ASHRAE. 1985. ASHRAE handbook-1985 fundamentals, chapter 23. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

ASTM. 1985. 1985 annual book of ASTM standards. Philadelphia: American Society for Testing and Materials.

Fiorato, A.E. 1981. "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, FL, December 1979; ASHRAE SP28, pp. 221-236.

Peavy, B.A.; Powell, F.J.; and Burch, D.M. 1973. "Dynamic thermal performance of an experimental masonry building." Building Science Series 45, U.S. Department of Commerce. Washington, D.C.: National Bureau of Standards.

Thermomass Technology, Inc. 1984. "The Thermomass building system." Cedar Rapids, IA.

Valore, R.C., Jr. 1980. "Calculation of U-values of hollow concrete masonry." Concrete International: Design and Construction, February, Vol. 2, No. 2. Detroit: American Concrete Institute.

Van Geem, M.G. 1986. "Summary of calibrated hot box test results for 21 wall assemblies." ASHRAE Transactions 1986, Vol. 92, Part 2. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Also, ASHRAE Technical Data Bulletin TDB-84, "Thermal Performance of Building Components," ASHRAE, Atlanta, 1986.

Van Geem, M.G. 1987. "Measuring thermal performance of wall assemblies under dynamic temperature conditions." Presented at the Workshop for Hot Box Operators, Colorado Springs, CO, March 1985. Journal of Testing and Evaluation, JTEVA, Vol. 15, No. 3, May 1987, American Society for Testing and Materials, Philadelphia, pp. 178-187.

Van Geem, M.G.; and Larson, S.C. 1985. "Heat transfer characteristics of walls with similar thermal resistance values." Construction Technology Laboratories, Portland Cement Association, Skokie, IL, 94 pages.

Van Geem, M.G.; and Shirley, S.T. 1987. "Heat transfer characteristics of insulated concrete sandwich panel walls." Oak Ridge National Laboratory Report No. ORNL/Sub/79-42539/8, Construction Technology Laboratories, Inc., 217 pages.

TABLE 1 - SUMMARY OF PHYSICAL PROPERTIES FOR WALLS P1, P2, and P3

Property	Measured Value		
	Wall P1	Wall P2	Wall P3
Unit Weight of Fresh Concrete, lb/ft^3 (kg/m^3)	144.1 (2308)	144.9 (2321)	143.3 (2296)
Slump of Fresh Concrete, in. (mm)	3.7 (94)	3.2 (81)	2.9 (74)
Air Content of Fresh Concrete, %	7.3	6.1	7.8
Estimated Moisture Content of Concrete at Start of Calibrated Hot Box Tests, % Ovendry Weight	1.8	2.3	2.2
Estimated Unit Weight of Concrete at Start of Calibrated Hot Box Tests, lb/ft^3 (kg/m^3)	143 (2280)	144 (2300)	144 (2300)
Insulation Thickness, in. (mm)	2 (50)	2 (50)	2 (50)
Insulation Density, lb/ft^3 (kg/m^3)	1.87 (29.9)	1.86 (29.8)	2.08 (33.3)
Unit Weight of Wall, lb/ft^2 (kg/m^2)	77.1** (376)	74.5* (364)	75.1* (366)
Average Wall Thickness, in. (mm)	8.20 (208)	8.20 (208)	8.19 (208)
Wall Area, ft^2 (m^2)	73.90 (6.86)	73.94 (6.87)	74.09 (6.88)

*Measured before calibrated hot box testing.
**Measured after calibrated hot box tests were completed.

TABLE 2 - THERMAL CONDUCTIVITIES USED TO CALCULATE DESIGN HEAT TRANSMISSION COEFFICIENTS

Material	Thermal Conductivity*		Source
	$\frac{\text{Btu}\cdot\text{in}}{\text{hr}\cdot\text{ft}^2\cdot{}^\circ\text{F}}$	W/m•K	
Normal Weight Concrete	16.0	2.31	Ref. 5
Wall P1 and P2 Insulation	0.223	0.0322	Interpolated for a mean temperature of 75°F (24°C) from guarded hot plate test results.
Wall P3 Insulation	0.215	0.0310	Interpolated for a mean temperature of 75°F (24°C) from guarded hot plate test results.
Stainless Steel	182	26.2	Ref. 6
High-Tensile Fiberglass-Composite Tie	2.1	0.303	Manufacturer's literature, Ref. 7

*Values are for material temperatures of 75°F (24°C).

TABLE 3 - STEADY-STATE RESULTS FROM CALIBRATED HOT BOX TESTS

		Measured Temperatures, °F (°C)						q* Heat Flow, Btu	R_T**, hr•ft^2•°F	U**, Btu	Relative Humidity	
Wall Desig-nation	Nominal Test Condition	t_{oa} Outdoor Air	t_{os} Outdoor Surface	t_{oc} Internal Outdoor	t_{ic} Internal Indoor	t_{is} Indoor Surface	t_{ia} Indoor Air	hr•ft^2 (W/m^2)	Btu (m^2•K/W)	hr•ft^2•°F (W/m^2•K)	Indoor Chamber, %	Outdoor Chamber, %
P1	t_m=104°F (40°C)	133 (56)	132 (55)	128 (53)	78 (26)	75 (24)	73 (23)	6.97 (22.0)	8.89 (1.57)	0.112 (0.636)	22	21
P1	t_m=34°F (1°C)	-5 (-21)	-1 (-18)	1 (-17)	67 (19)	69 (21)	71 (22)	-6.99 (-22.0)	10.95 (1.94)	0.091 (0.517)	23	22
P1	Design Values†	--	--	--	--	--	--	--	10.15 (1.79)	0.098 (0.559)	--	--
P2	t_m=103°F (39°C)	132 (55)	131 (55)	128 (53)	78 (26)	76 (24)	73 (23)	7.46 (23.5)	8.27 (1.46)	0.121 (0.686)	33	15
P2	t_m=34°F (1°C)	-5 (-21)	-1 (-18)	0 (-18)	67 (19)	69 (21)	71 (22)	-7.44 (-23.5)	10.31 (1.82)	0.097 (0.551)	37	23
P2	Design Values†	--	--	--	--	--	--	--	9.64 (1.70)	0.1066 (0.6053)	--	--
P3	t_m=105°F (41°C)	136 (58)	135 (57)	132 (55)	77 (25)	75 (24)	72 (23)	6.17 (19.5)	10.55 (1.85)	0.095 (0.538)	***	9
P3	t_m=35°F (2°C)	-2 (-19)	2 (-17)	3 (-16)	67 (20)	69 (21)	71 (22)	-6.39 (-20.2)	11.30 (1.99)	0.088 (0.502)	***	20
P3	Design Values†	--	--	--	--	--	--	--	10.25 (1.81)	0.0976 (0.554)	--	--

*Measured by the calibrated hot box.

**Total thermal resistance, R_T, and transmittance, U, for steady-state tests were calculated using the design surface resistance coefficients and measured values of heat flow.

***Not available.

†Values computed for t_m = 75°F (24°C).

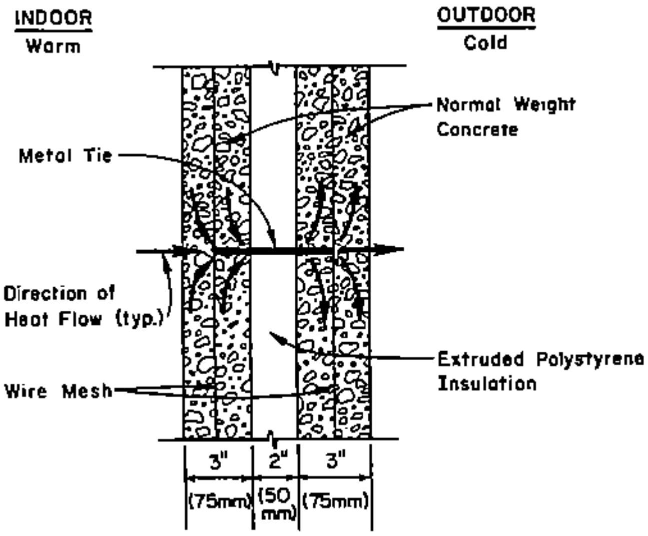

Figure 1. Thermal bridge due to metal tie penetrating insulation

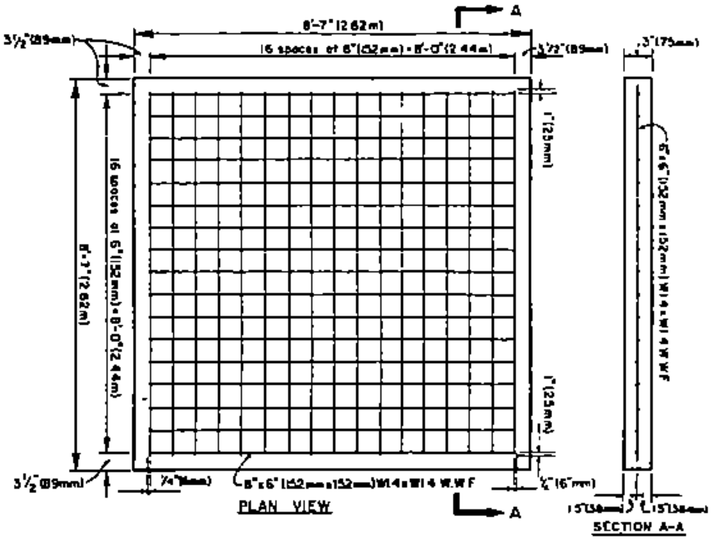

Figure 2. Reinforcement detail for concrete layers

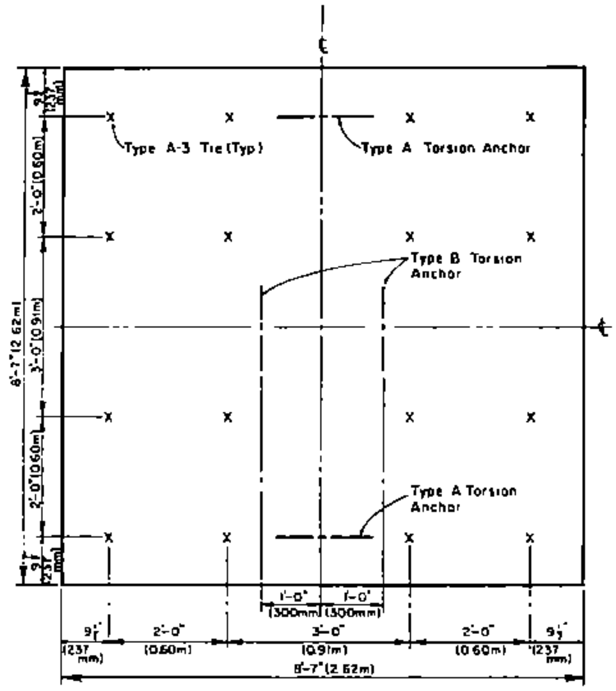

Figure 3. Location of stainless steel torsion anchors and ties in wall P2

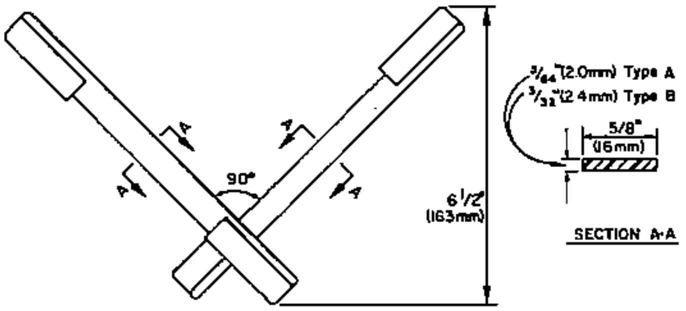

Figure 4. Dimensions of type A and B torsion anchors

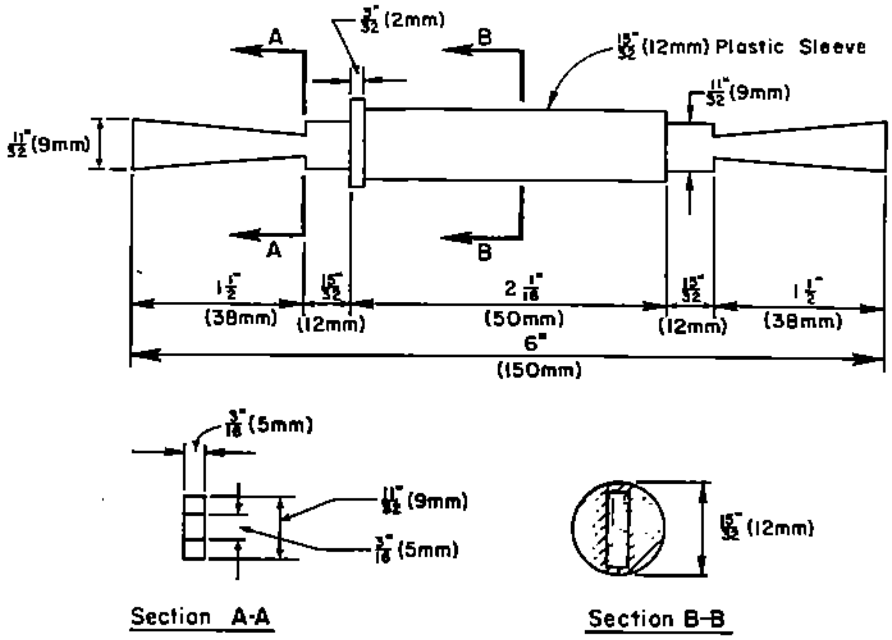

Figure 5. Dimensions of high- tensile fiberglass-composite tie

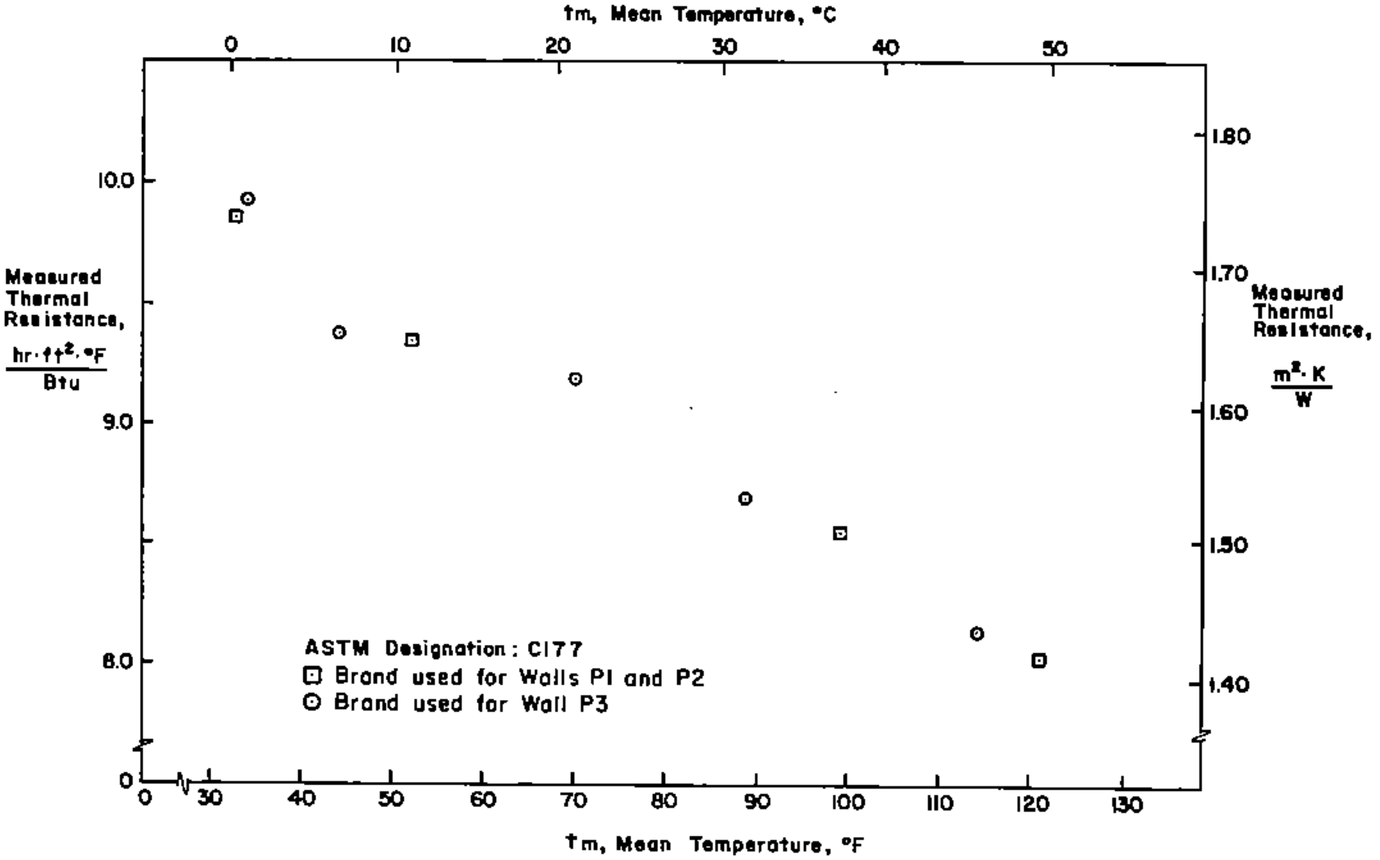

Figure 6. Measured thermal resistances of insulations

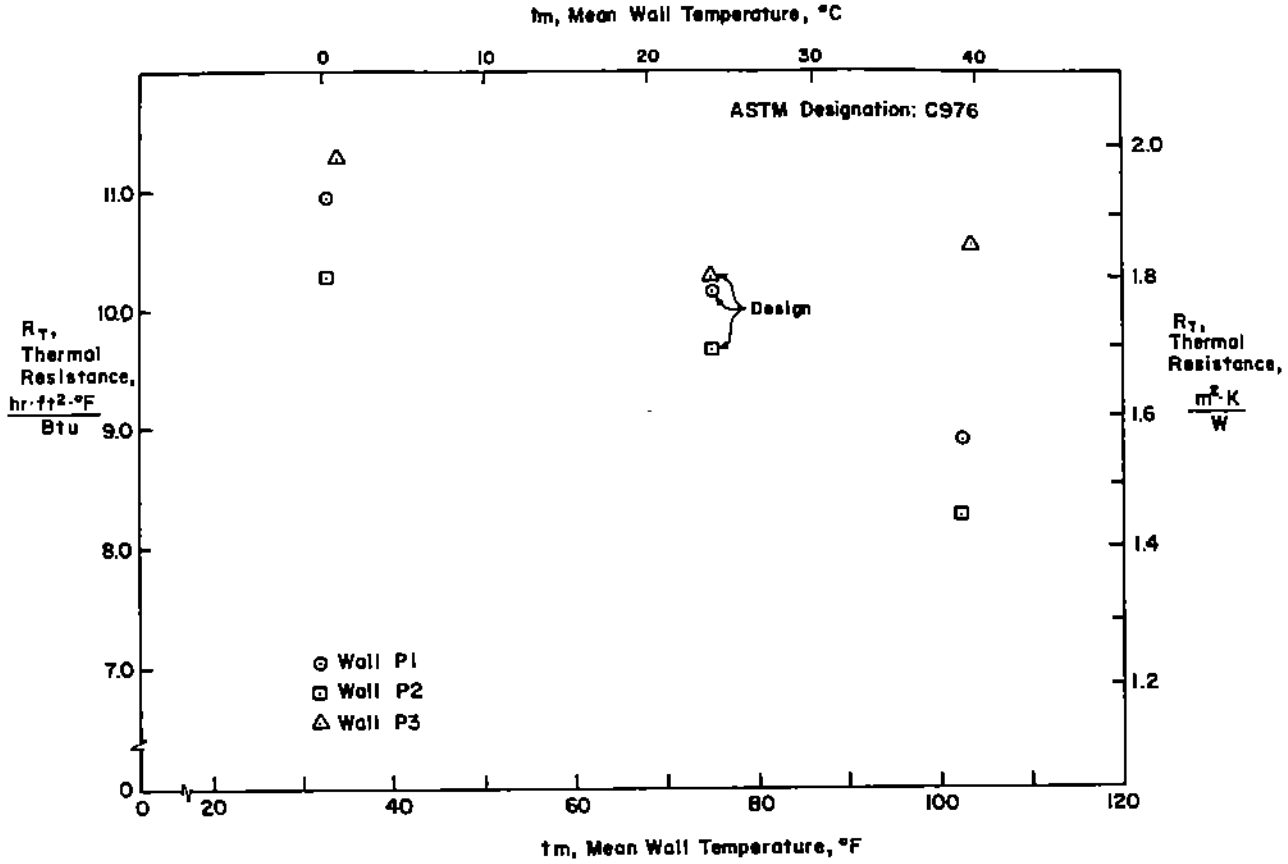

Figure 7. Total thermal resistance as a function of wall mean temperature

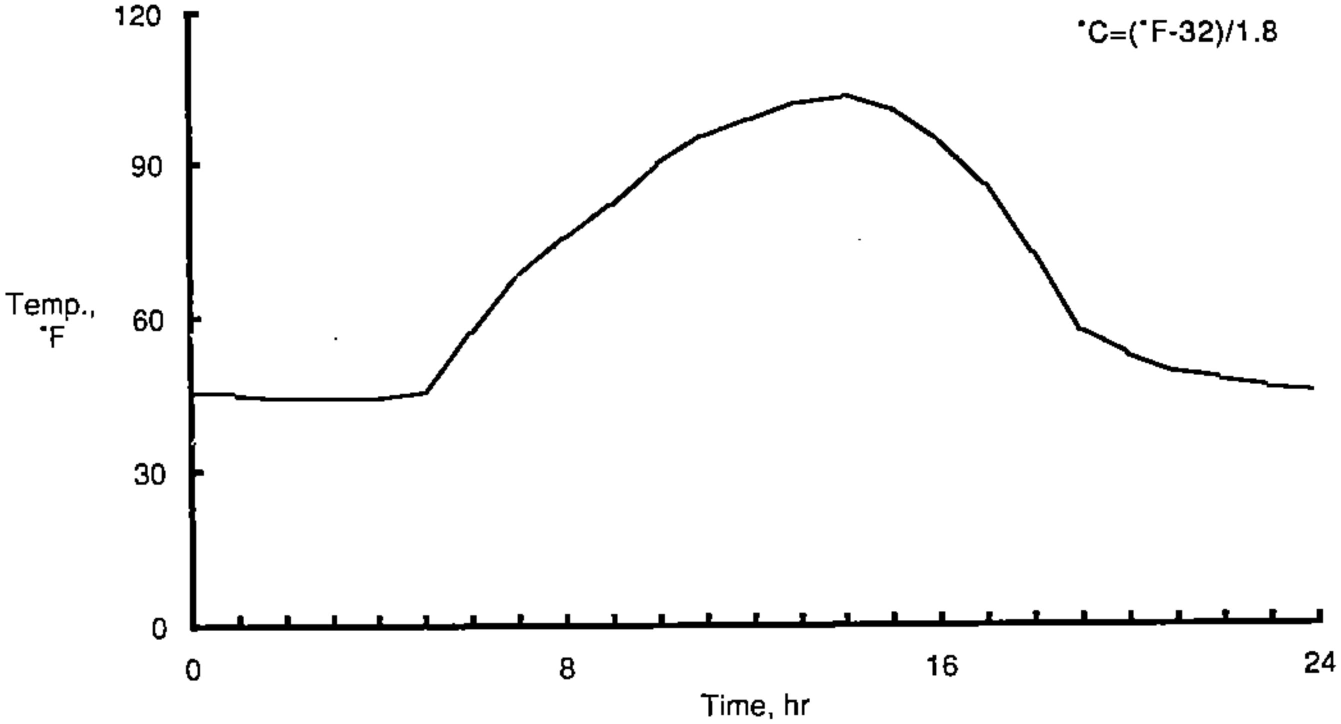

Figure 8. Outdoor chamber air temperature for the dynamic temperature cycle

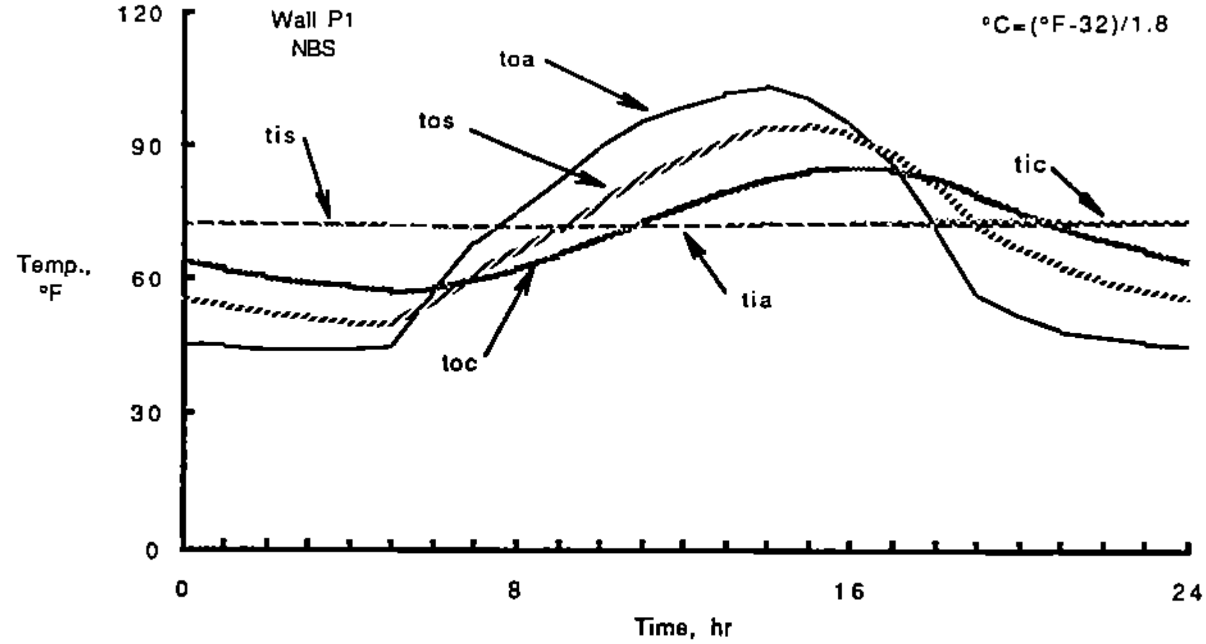

Figure 9. Measured temperatures for NBS test cycle applied to wall P1

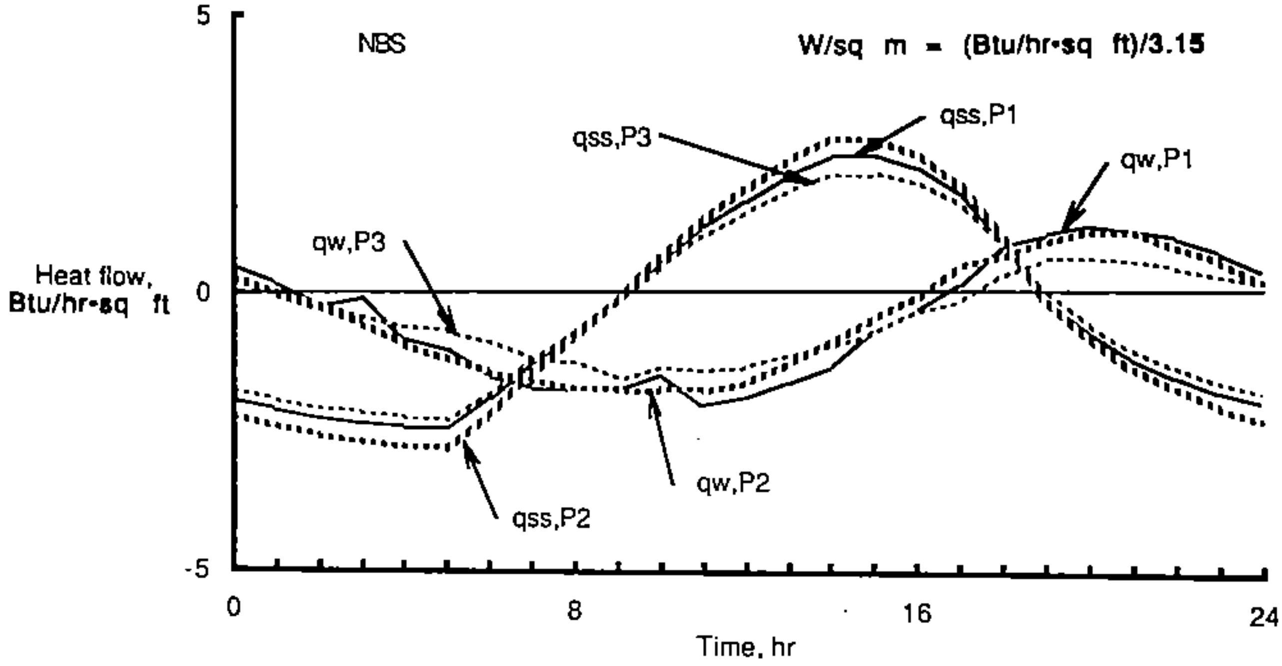

Figure 10. Heat flow for NBS test cycle applied to walls P1, P2, and P3