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Development of a "Guarded Hot Box" Type Thermal Conductivity Tester

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Abstract

The purpose of this project is to research and develop a "Guarded Hot Box" type thermal conductivity tester used to determine the insulating properties (R-value) of construction materials and wall systems according to ASTM C 236-89 (1998). (See Appendix A) In this type of system, a construction material or wall unit is placed between a cold box and a hot box which consists of a guard area and a metering box. Mathematical equations for heat transfer and energy are used to solve for R-value. The design of the box is in accordance with ASTM C 236-89 which allows for the fixing of constants within these equations. The degree to which these constants are held are by the use of an advanced electronics console which controls temperature in the guard and metering box.

University of Northern Iowa

Department of Industrial Technology

RESEARCH PAPER

DEVELOPMENT OF A "GUARDED HOT BOX" TYPE THERMAL CONDUCTIVITY TESTER

Submitted By

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December, 2003

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By:

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Department of Industrial Technology

University of Northern Iowa

Acknowledgments

At this point it is appropriate to acknowledge those who played an instrumental role in the completion of this research. First, a very special thanks to Dr. Catherine Zeman, Director of the Recycling & Reuse Technology Transfer Center (RRTTC) at the University of Northern Iowa for the personal and financial support for this project. Also, I would like to thank Dr. Mohammed Fahmy, Department Head of the Department of Industrial Technology at the University of Northern Iowa for the ability to use the facilities in the department production lab and for his continued support for the RRTTC and the Materials Testing Service. Dr. Recayi Pecen, Electronics Professor in the Department of Industrial Technology also played an important role advising on electronics related problems and taking the time to check wiring diagrams to ensure that the very expensive electronics equipment used was wired correctly. Also, a special thanks to my advisor on the project, Dr. Teresa Hall for her work with me concerning the completion of this project.

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Development of a "Guarded Hot Box" Type Thermal Conductivity Tester

Introduction

Thermal conductivity, heat capacity and R-value are key properties to consider in designing structures (Wang & Chen, 2001). These factors affect the design of Heating Ventilation and Cooling (HVAC) systems and the overall environmental performance of buildings which commercially are rated by their energy requirements and efficiency. Proper thermodynamic analysis of structures is a very complex and detailed methodology employed by HVAC engineers to examine such things as building materials, heat transfer and air flow patterns which all have an affect on indoor air quality (Flaga, 2000). Understanding thermal conductivity, or the reciprocal relationship of thermal resistivity (R-value) of building materials is one of the more important factors to consider.

Many of the traditional building materials have well documented and defined properties like R-value. However, with the ever increasing use of alternative building materials, many of which utilize recycled content, properties such as R-value, are not known and must be investigated. It is to this end that the Recycling & Reuse Technology Transfer Center (RRTTC) and the Materials Testing Service (MTS) were created. Working in conjunction with the Department of Industrial Technology, the

RRTTC and MTS have become a very active center of research for the use of alternative materials. Therefore, it was the purpose of this project to develop and build a guarded hot box type thermal conductivity tester to measure the R-value of wall panels, wall units and masonry walls. This tester will expand the test capabilities of the Materials Testing Service and support continued research in the Department of Industrial Technology and RRTTC at the University of Northern Iowa.

Construction

The purpose of this project is to research and develop a "Guarded Hot Box" type thermal conductivity tester used to determine the insulating properties (R-value) of construction materials and wall systems according to ASTM C 236-89 (1998). (See Appendix A) In this type of system, a construction material or wall unit is placed between a cold box and a hot box which consists of a guard area and a metering box. Mathematical equations for heat transfer and energy are used to solve for R-value. The design of the box is in accordance with ASTM C 236-89 which allows for the fixing of constants within these equations. The degree to which these constants are held are by the use of an advanced electronics console which controls temperature in the guard and metering box.

To determine the thermal conductivity of a material it is necessary to know the area (A), heat flux (q), and the temperature differences on both sides of the specimen, all of which must be measured under steady state conditions. The technology behind the hot box's design is such to allow for the measuring of heat flux (q). Heat flux is a measure of the total heat input to the metering box through a known area (Douzane, Rõucoult & Langlet, 1999). Temperature and area can be measured directly, but heat flux can not. The design calls for a five sided box metering box to be placed within a larger five sided guard box (hot box) with the open ends facing the open end of the cold box. Separating the hot and cold boxes is the material or wall unit to be tested (ASTM, 1998). The problem is that if heat travels laterally instead of through the test panel, the data received would be corrupted. The guard box gets its name because it guards against the problem of lateral heat transfer. The basic premise is that if the guard box and metering box temperatures (average) are kept at a given value, then the net interchange across the walls of the metering box will be zero. At this point the total heat energy input into the metering box and the temperature differential across the test panel can be measured accurately. To accomplish this, the tester must contain adequate controls and temperature monitoring equipment for the accurate collection of data to determine the thermal conductivity of a given material.

The hot and cold boxes are 30" x 30" x 30" inches square, constructed of 3/4" plywood without internal bracing. The boxes are insulated with Owens Corning 1 inch rigid foam insulation (r-value = 7.5) attached to the inside of the boxes with construction adhesive. The boxes are further jacketed with ½ inch drywall on the inside (attached to the plywood outer housing with drywall screws) and taped and textured to ensure that the boxes are sealed to guard against thermal leakage. ASTM C-236-89 (1998) does not contain requirements for the size of the boxes or their insulation. The design of the boxes and the steps taken to insulate them were a function of space requirements, cost, and the anticipated size of wall panels to be tested. The size of the guard area (space between the hot box walls and the metering box walls) determines the thickness of wall panels that can be tested. The boxes designed here have a guard area of approximately 7-8 inches, which would allow for the testing of walls up to 8 inches thick (expected thickness of a masonry wall made of individual blocks). The cold box has an internal baffle to direct the cold air flow (from an air conditioner) through the box and evenly across the test panel or wall unit to be tested. The hot box has a baffle which sits directly behind the metering box that contains the circulating fans and heaters. Additional heat shielding and baffles are used to direct the air flow smoothly across the test panel. The metering box is constructed in a similar manner with its dimensions being 12 inches square. The metering box is centered in the hot box and has a separate track system so it can be removed for maintenance or for the maintenance of the hot box components (i.e., heaters, fans and baffles). Figure 1 shows a cutaway drawing of the boxes:

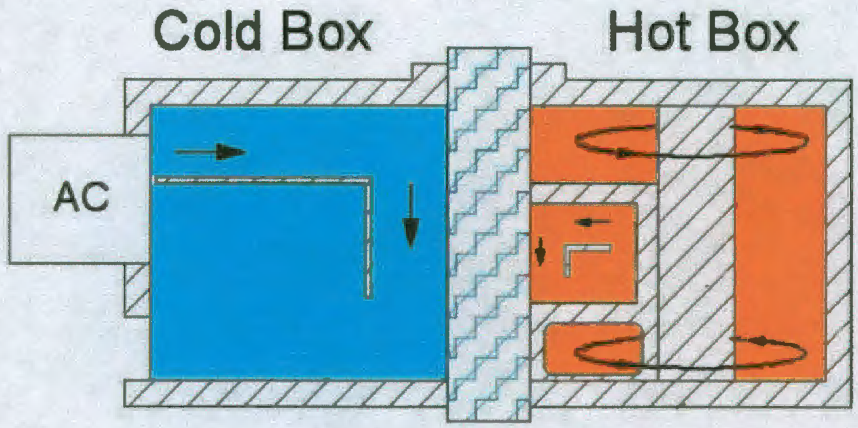
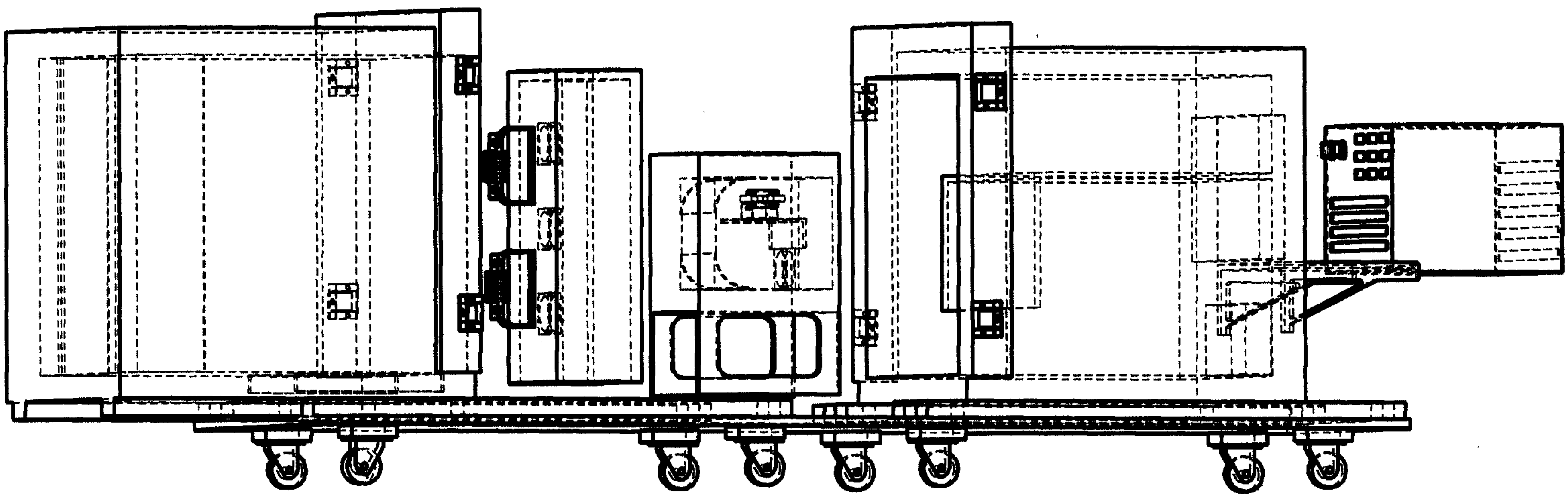


Figure 1. Cutaway drawing of hot and cold boxes with airflow patterns.

The entire unit is attached to a cart with casters so the unit can be easily moved to a storage area when not in use. The cart has tracks to ensure the two boxes will be aligned for testing. The cold box is permanently attached to the cart while the hot box is free to move along the tracks. The opening faces of the hot, cold and metering boxes are sealed against the test specimen using a flat 2 inch wide neoprene gasket. The boxes are held tightly against each other using mounting brackets fabricated of 1/8 inch steel plate and threaded rod attached to the boxes in four places to ensure a positive seal.

Drawings. The following pages contain the technical and three-dimensional assembly drawings for the guarded hot box.



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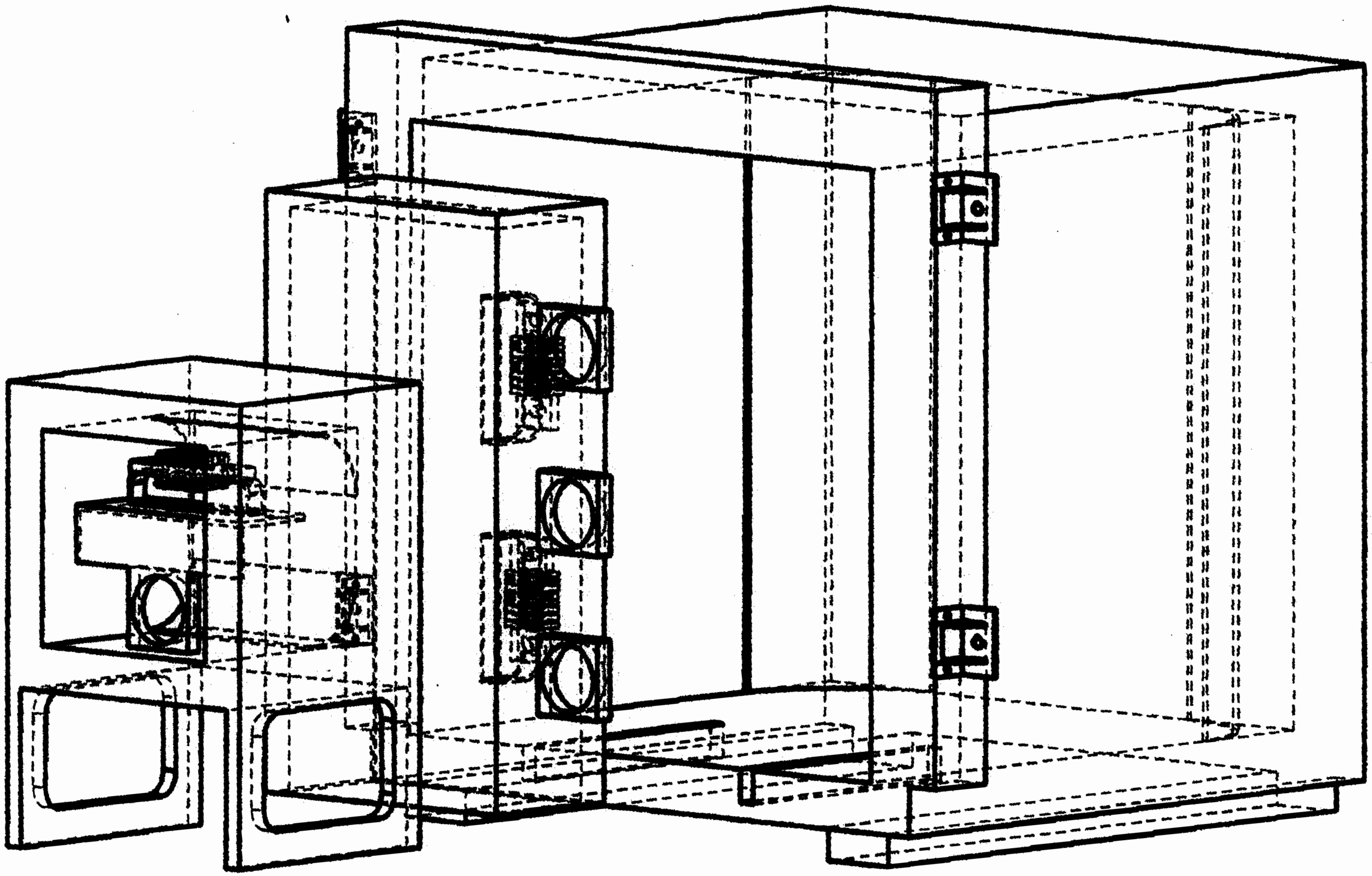

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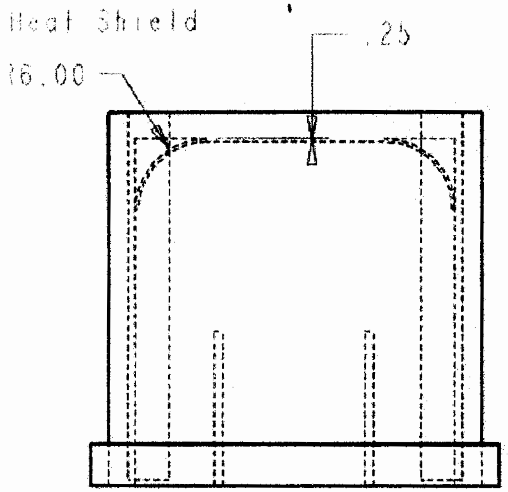
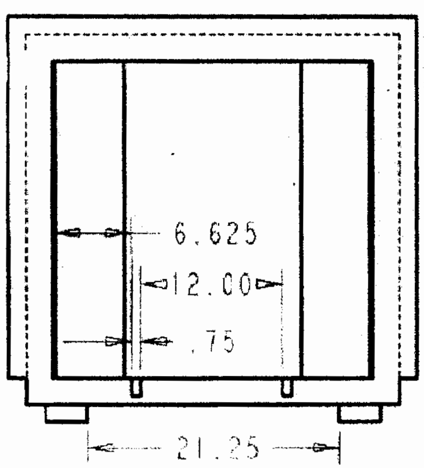
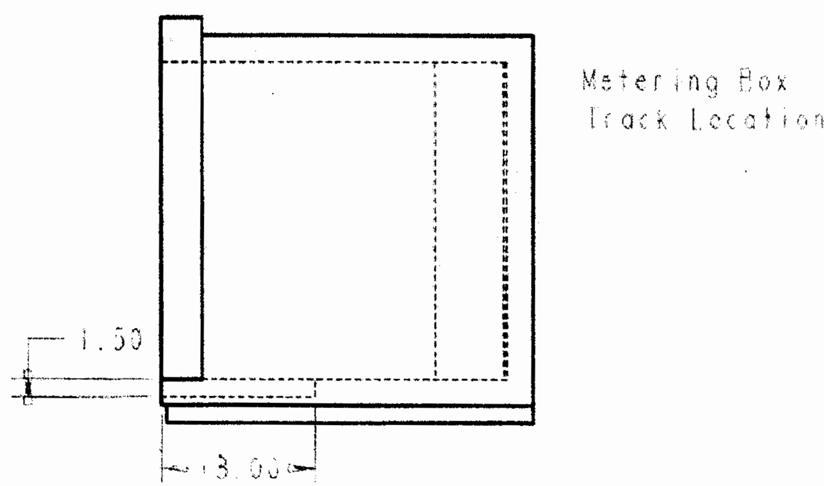


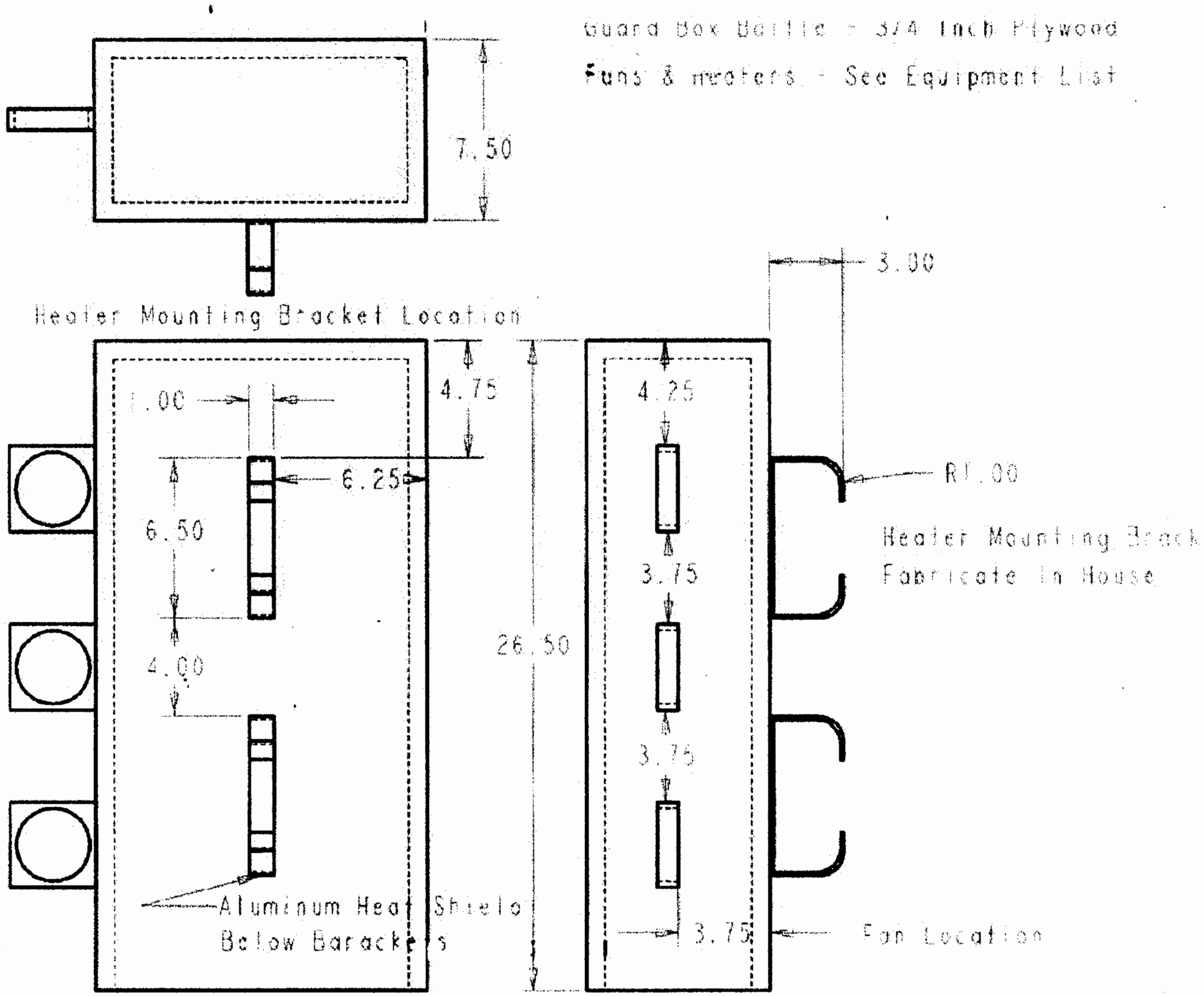
Hot Box - 3/4 Inch Plywood, 5 sided 30 x 30 x 3

Box Interior 1 Inch Rigid Foam Insulation
1/2 Inch Drywall Textured Finish

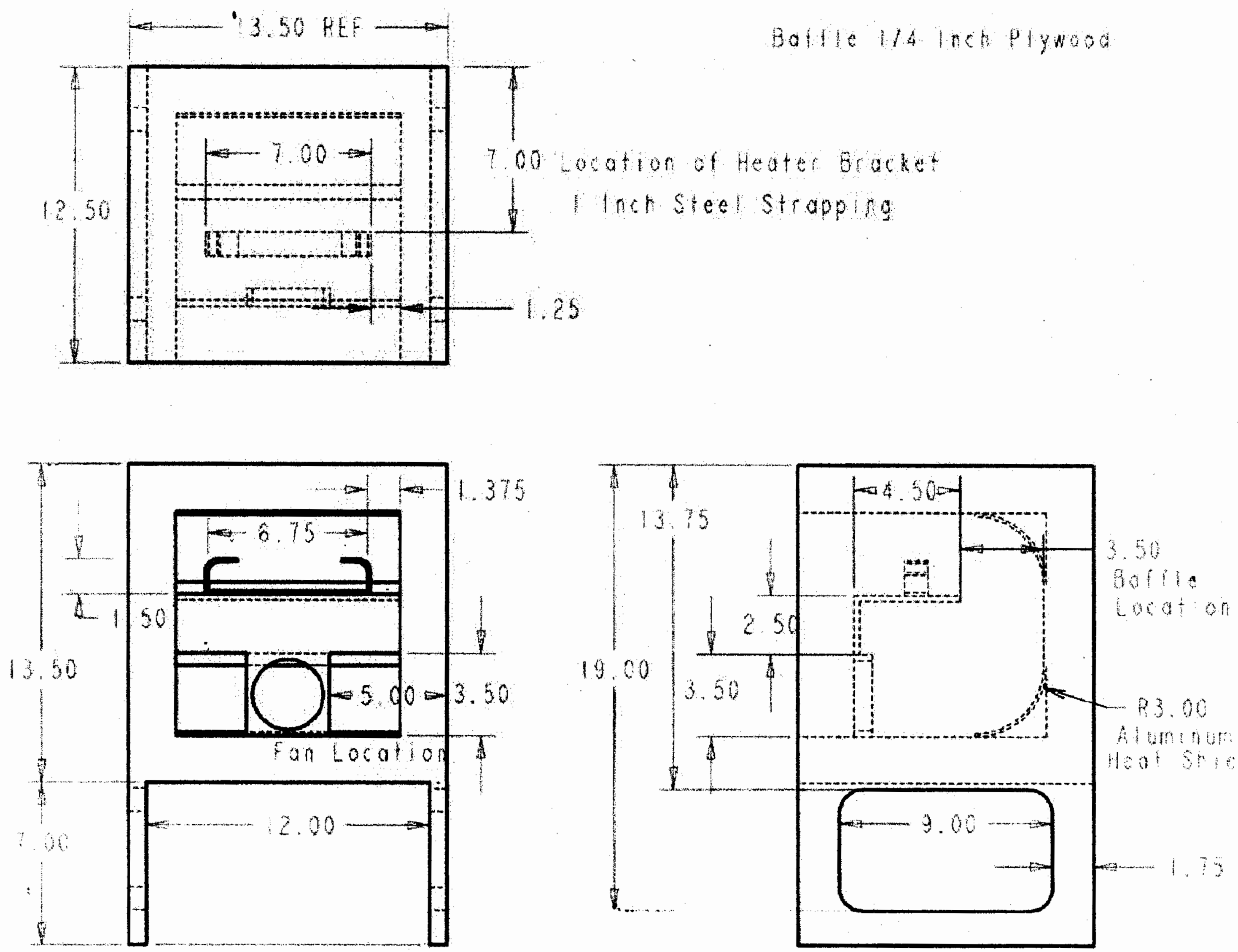
Clamp Bracket Mounting Face & Tracks
2 x 4 Inch Construction

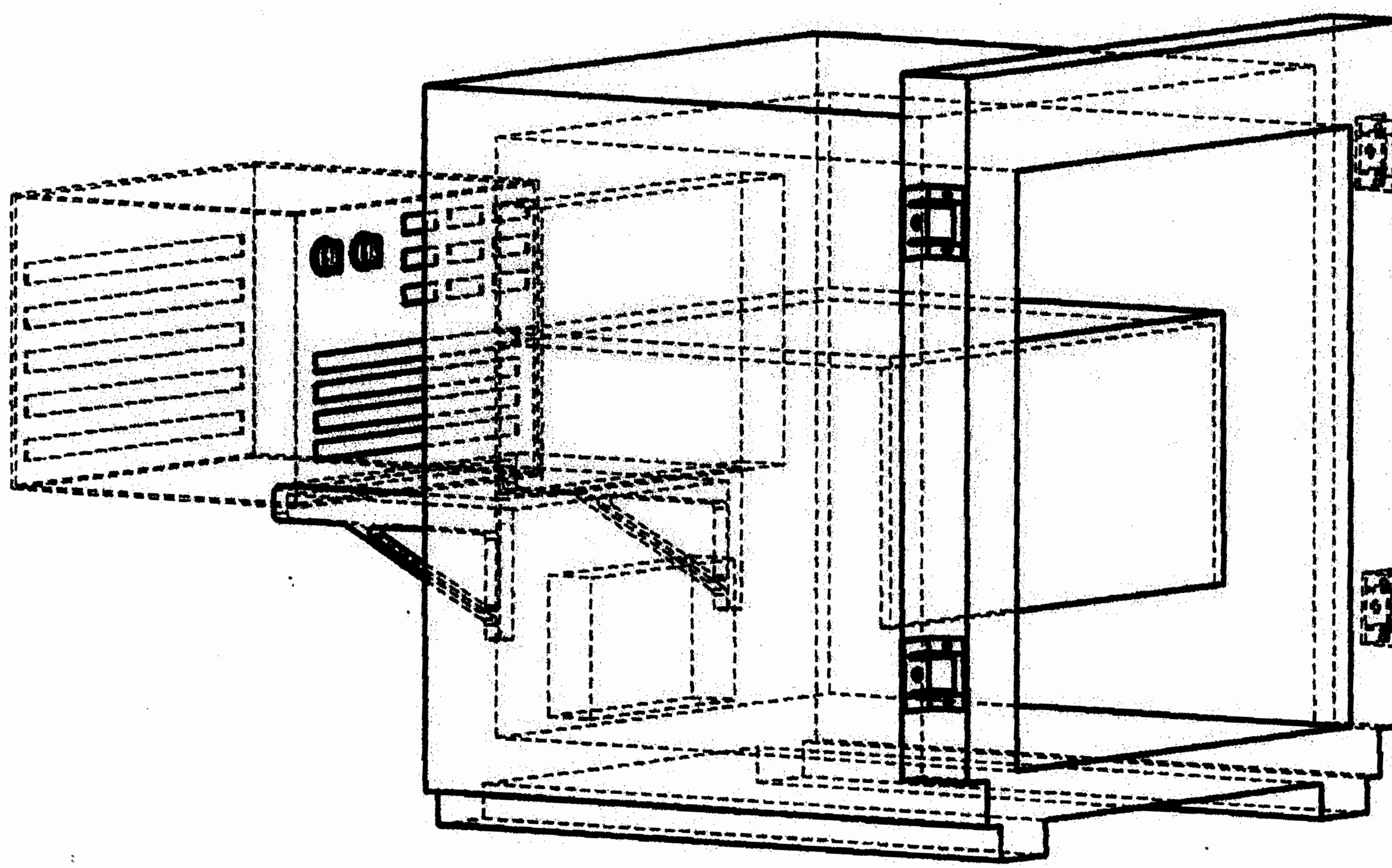


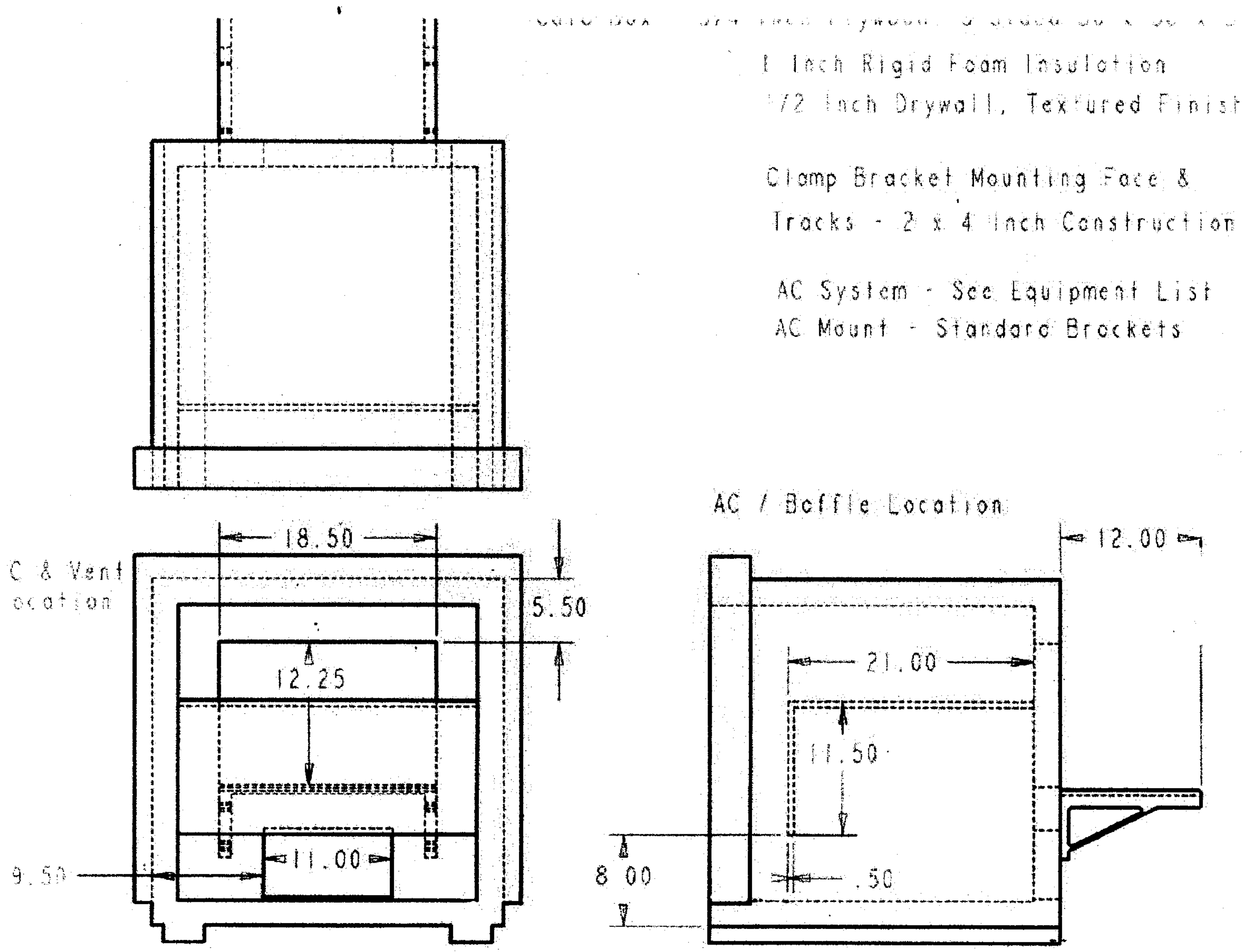


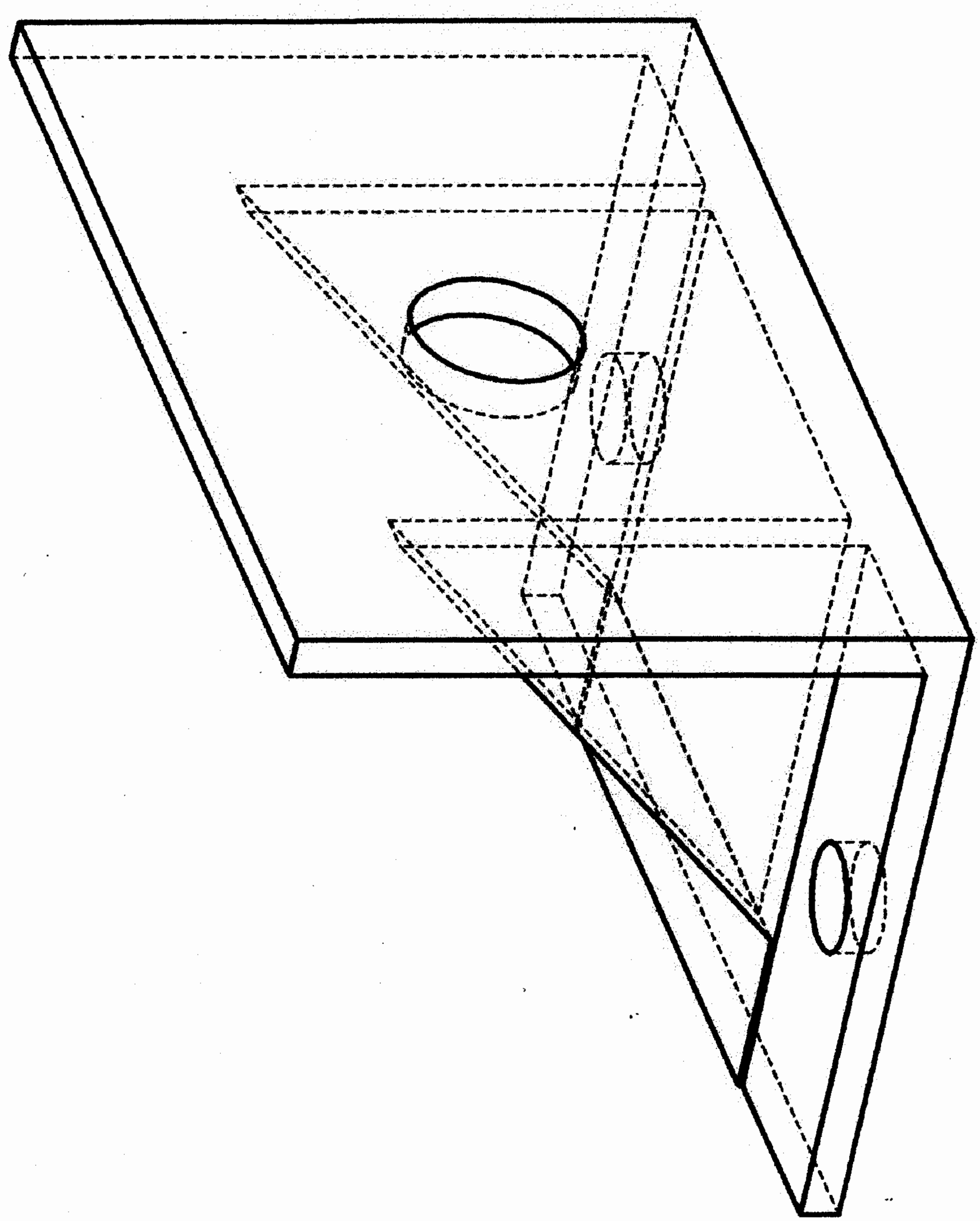


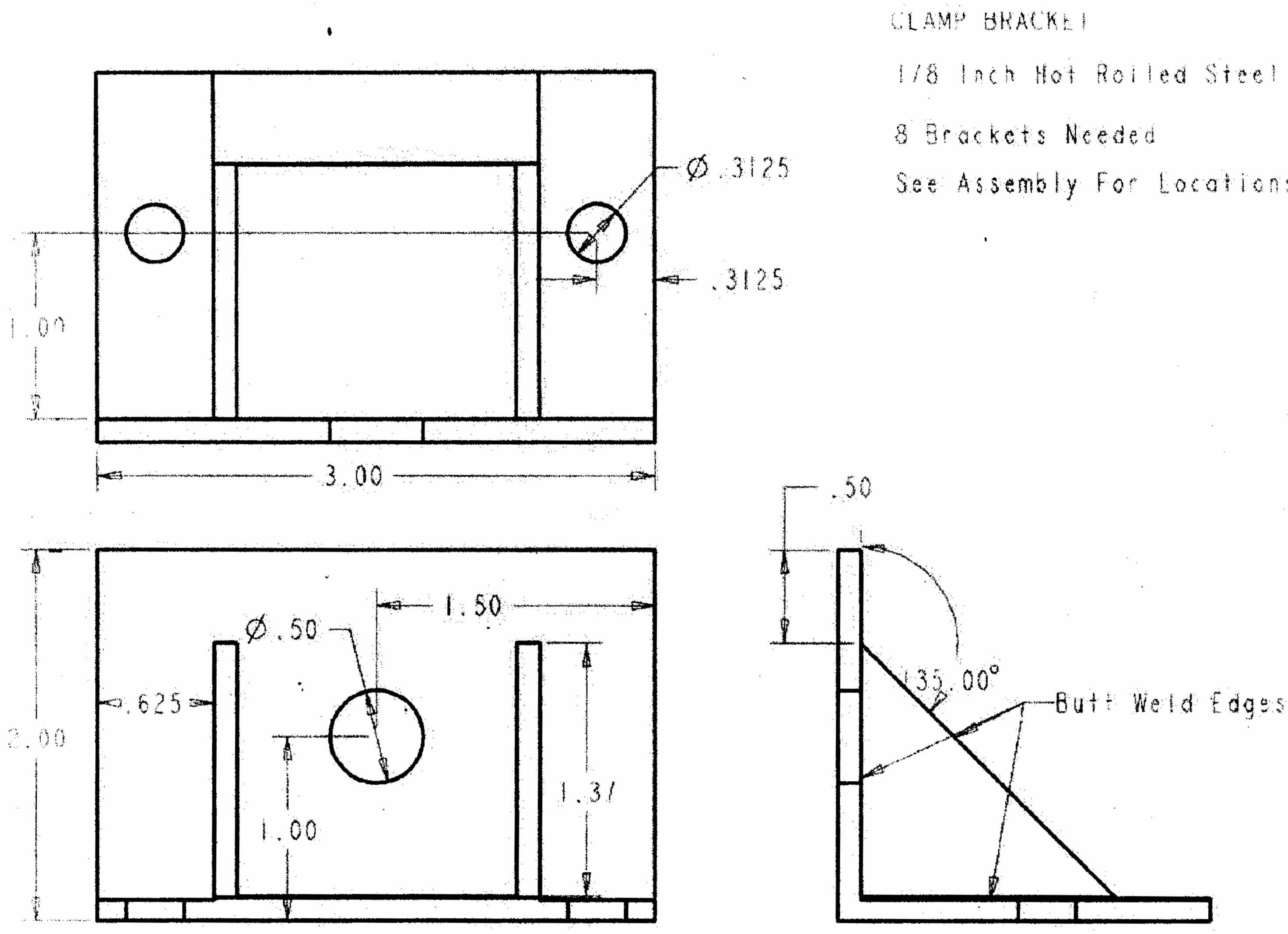
Guard Box Baffle - 3/4 Inch Plywood
Fans & heaters - See Equipment List
7.50
Heater Mounting Bracket Location
1.00
4.75
6.25
6.50
4.00
26.50
4.25
3.75
3.75
3.00
R1.00
Heater Mounting Bracke
Fabricate In House
Aluminum Heat Shield
Below Barackets
3.75
Fan Location


13.50 REF
Baffle 1/4 Inch Plywood
12.50
7.00
7.00 Location of Heater Bracket
1 Inch Steel Strapping
1.25
1.375
6.75
1.50
13.50
5.00
3.50
Fan Location
7.00
12.00
4.50
13.75
3.50
Baffle
Location
2.50
19.00
3.50
R3.00
Aluminum
Heat Shie
9.00
1.75



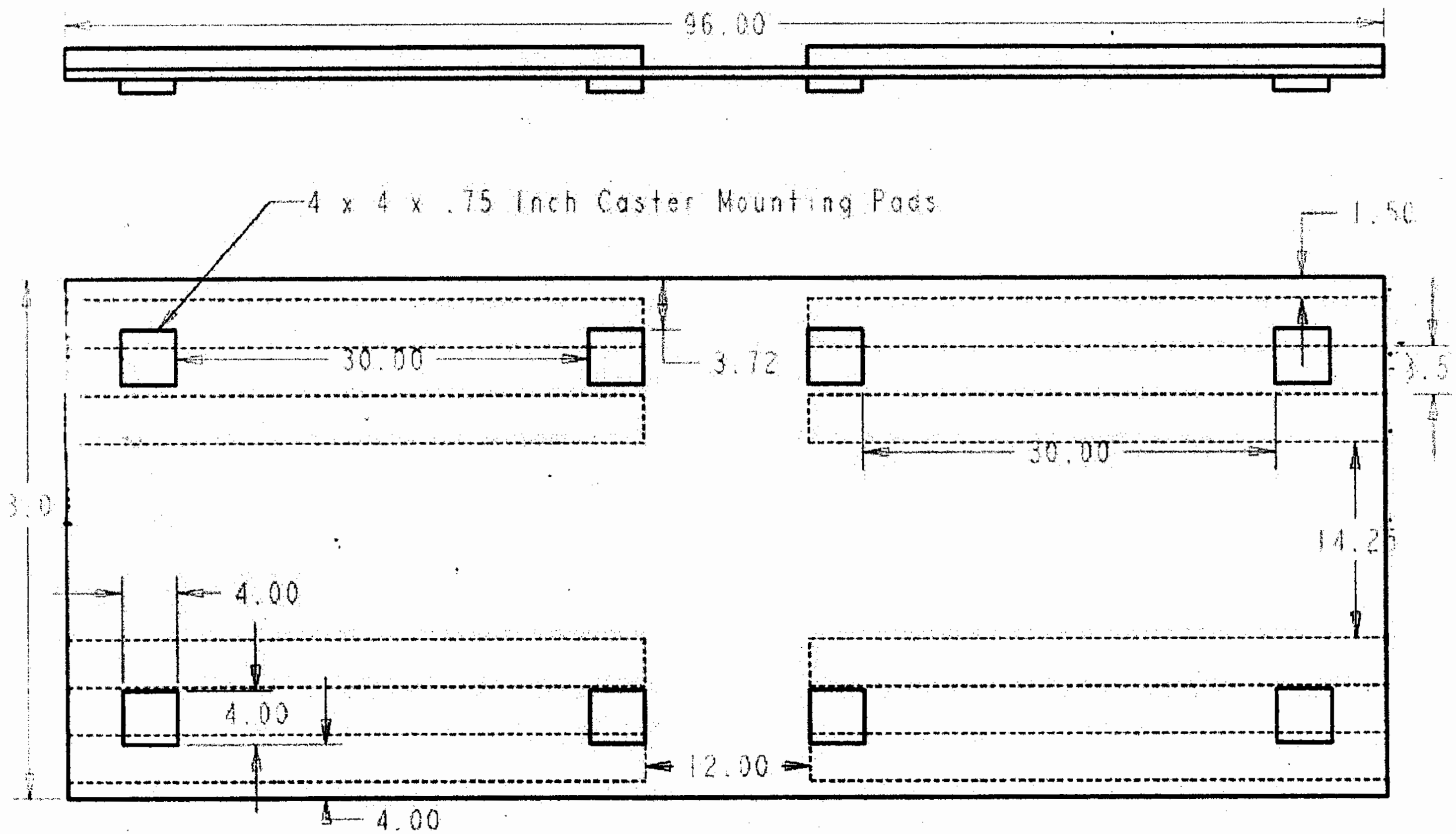

1 Inch Rigid Foam Insulation
1/2 Inch Drywall, Textured Finish
Clamp Bracket Mounting Face &
Tracks - 2 x 4 Inch Construction
AC System - See Equipment List
AC Mount - Standard Brackets
AC / Baffle Location
C & Vent
ocation
18.50
5.50
12.25
11.00
9.50
12.00
21.00
11.50
8.00
.50




CLAMP BRACKET
1/8 Inch Hot Rolled Steel
8 Brackets Needed
See Assembly For Locations
Ø .3125
.3125
1.00
3.00
.50
2.00
Ø .50
1.50
.625
1.37
1.00
135.00°
Butt Weld Edges

Cart Drawing - 3/4 Inch Plywood Construction

Track System - 2 x 4 Construction



Instrumentation & Control

As mentioned previously, to accurately collect the necessary data and maintain control over system functions, a sophisticated electronics control console was designed and developed for the guarded hot box. The control console is a self contained unit connected to the guarded hot box tester by quick connect plugs and cables to allow the control console to be placed in a safe place when the unit is not in operation. The following are the controls that make up the various circuits to control: 1) Guard box heaters / temperature controls and sensing; 2) Metering box heater / temperature controls and sensing; 3) Cold box temperature control and sensing instrumentation; and 4) Guard and metering box circulation fan circuits.

Guard Box Circuit. To generate the heat in the guard box, two 300 watt AC Watlow Controls Inc. resistance heaters were employed. These heaters were wired through a Watlow Controls Inc. Series 982 Controller, Variac (voltage regulation control) and solid state relay. Temperature sensing and feedback to the controller is accomplished through the use of two 3-wire RTD air temperature sensors. To maintain steady state operations the variac is used as a fine tuning adjustment to the voltage input to the heaters. The theory is to input a setpoint temperature setting on the controller and adjust the voltage input to the heaters to maintain the temperature in the guard box without the controller opening the circuit. If the controller is allowed to cycle the heaters off and on, the temperature in the guard box would fluctuate and steady state conditions could not be achieved. Figure 2 shows the wiring diagram of the guard box circuit:

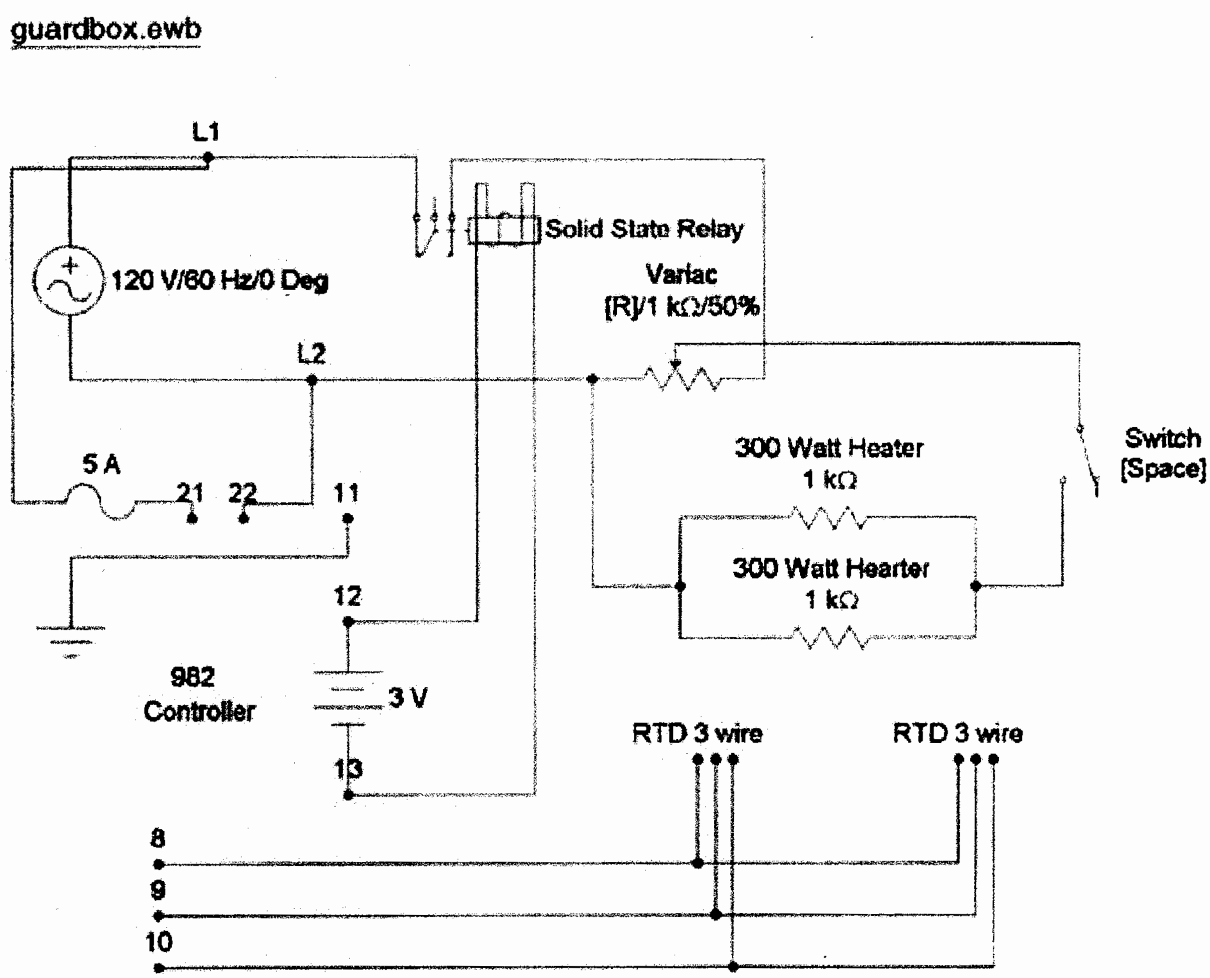


Figure 2. Guard Box Wiring Diagram

Metering Box Circuit. To generate the heat in the metering box, one 150 watt AC Watlow Controls Inc. resistance heater was employed. The heater was wired through a Watlow Controls Inc. Series 982 Controller, Variac (voltage regulation control) and solid state relay. Temperature sensing and feedback to the controller was accomplished through the use of one 3-wire RTD air temperature sensor. To maintain steady state operations in the metering box a second variac is used as a fine tuning adjustment to the voltage input to the heater to match that of the guard box circuit. Figure 3 is the wiring diagram of the metering box circuit:

meterbox.ewb

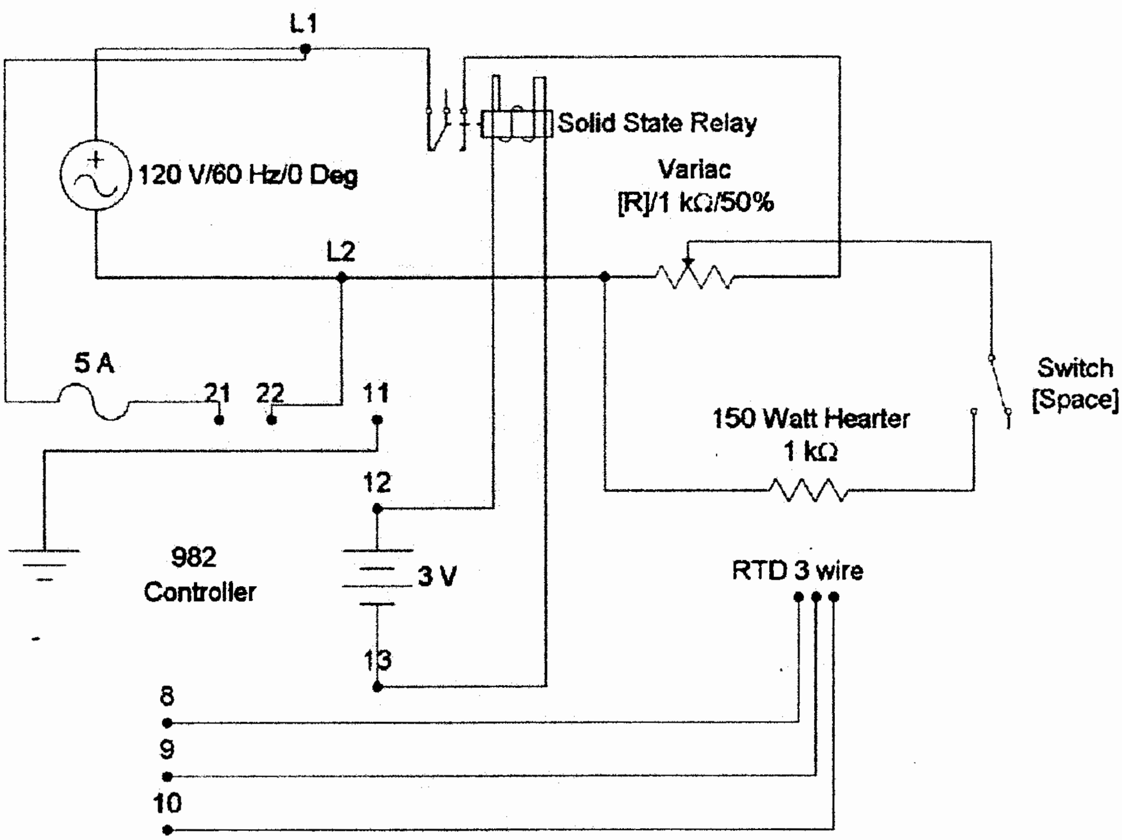


Figure 3. Metering Box Wiring Diagram

Cold Box Circuit. To generate the cooling in the cold box an off the shelf 8,000 BTU air conditioner was employed and modified to accept control from a Watlow Controls Inc. Series 93 Controller and solid state relay. As in the guard box circuit, temperature sensing and feedback to the controller of the cold box was accomplished through the use of two 3-wire RTD air temperature sensors. Figure 4 is the wiring diagram of the cold box circuit:

coldbox.ewb

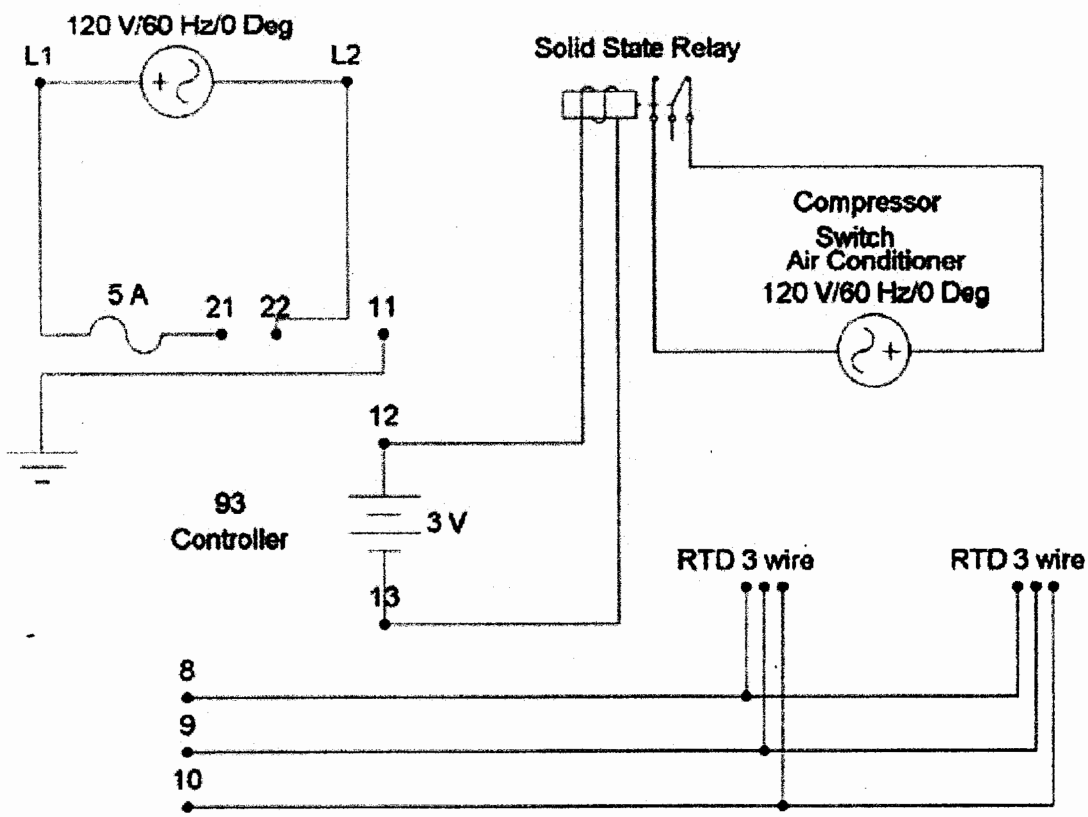


Figure 4. Cold Box Wiring Diagram

Circulating Fan Circuits. Both the guard and metering boxes incorporate fans to circulate the air through their respective boxes. The guard box uses three 24 volt fans wired in parallel while the metering box uses one 6 volt fan. The fans are powered by a Hewlett Packard Triple Output Power Supply, also part of the electronics console. Figure 5 shows the wiring diagrams of the guard and metering box fans:

cooling fans.ewb

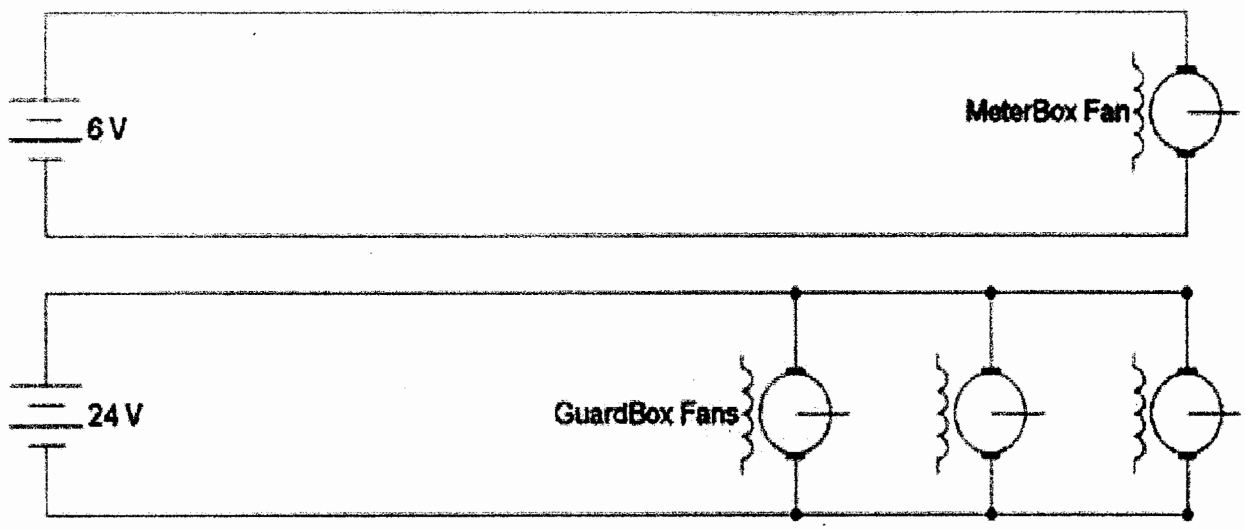


Figure 5. Guard and Metering Box Fan Wiring Diagrams

Thermocouples. The guarded hot box also uses twelve 2-wire K type thermocouples attached to both sides of the test panel to measure temperatures on the surface of the test specimen. These thermocouples are read through the use of a Watlow Controls Inc. Series 93 Controller. The controller in this area is only used as a digital readout of the temperature. Each thermocouple has a number corresponding to either the cold or hot side and its specific position on the test panel. A 20 channel selector switch is used to switch the display to the reading of the corresponding thermocouple for data collection. The placement of the thermocouples are such that two are placed on the test specimen in the guard area and four in the metering box evenly spaced. The remainder are placed opposite the other thermocouples on the cold side of the test specimen.

Operational Test Results

To test the accuracy of the guarded hot box test system, an operational testing regimen was developed. This was accomplished by using a test panel of a known r-value as a standard to compare to the test results received from the tester. The test panel was fabricated using two 1 inch sheets of Owens Corning rigid foam insulation (r-value = 7.5 each) measuring 40" x 40" square. On both sides of the insulation sheets, a ½ inch sheet of plywood was used to jacket the test panel. The two sheets of insulation and 2 sheets of ½ inch plywood are sandwiched together using construction adhesive. Screws and other mechanical fasteners are not used on the test panel to prevent areas of erroneous results through heat transfer by either direct leakage or conduction through the fastener. The test panel has an approximate r-value of 16.2 (2 sheets insulation = 15.0; and 2 sheets of ½ inch plywood is approximately 1.2 r-value).

R-value of a test panel is calculated according to the following formula:

$$R = \frac{(t_1 - t_2) * A}{Q}$$

Where R = r -value of the specimen in °F. Hr ft^2 / btu units; t_1 and t_2 are the temperature / area weighted averages of the thermocouples on the hot side metering area and the cold side respectively; A = the area of the metering box in m^2; and Q = the total energy through the metering box in watts. The number arrived at by the equation must then be multiplied by 5.678, the conversion factor for °K m^2 / W into r-value units °F. Hr ft^2 / btu.

For the operational test the guard and metering box setpoints were set at 120°F and the cold box was set to 55°F for a temperature difference across the test panel of 65°F. To achieve steady state conditions, the variacs are used to adjust the power to the heaters to maintain the desired temperature within the boxes using the least amount of electrical energy. The reason for this action is that one of the key elements in the equation for determining r-value is the total heat energy input into the metering box as noted in the equation. This is the sum of the all of the energy inputs (heaters and fans).

To achieve steady state conditions requires anywhere from 8 to 24 hours to dial in the proper settings on the electronics console. Only when all of the temperature thermocouples on both sides of the metering area, and the temperature sensors on the guard, metering area and the cold side no longer fluctuate in temperature, is the unit ready to sample the data. According to ASTM C-236-89 (1998) the data sampling must be taken over an 8 hour period with at least one data set taken at each hour. Another 4 hours of data must be sampled to ensure no significant change in steady state conditions has occurred. The operational test was performed at the University of Northern Iowa's Department of Industrial Technology Production Lab in June of 2001. The test unit was set up on a Thursday and Friday. The actual test process began by dialing in the proper settings on the control console to achieve steady state conditions. This process took the entire day and actual data gathering began on Saturday morning. The following is the information gathered from the operational test and the results:

Metering Area "A" = $.0582m^2$

$t_{1avg} = 315.344$

$t_{2avg} = 292.334$

$Q_{total} = .4585$ Watts

$$R = \frac{(t_1 - t_2) * A}{Q}$$

$$R = \frac{(315.344 - 292.334) * .0582}{.4585W} = \frac{1.339}{.4585}$$

R = 2.92 °K m² / W
R- value Conversion = 2.92 * 5.678

Tested R-Value = 16.5
Approximate R-Value of Test Panel = 16.2
Error = +1.85%

The data shows that the test unit accurately measured the r-value of the test panel with an error of +1.85%, well within the allowable 3% margin of error as prescribed by ASTM C-236-89 (1998).

References

American Society of Testing & Materials (ASTM). (1998). C-236-89 "Standard Test Method for Steady State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box". Pennsylvania: ASTM International.

Douzane, O., Roucoult, J., & Langlet, T. (February, 1999). "Thermophysical Property Requirements of Building Materials in a Periodic State". International Journal of Heat & Mass Transfer (42). Elsevier Science Ltd.

Flaga, K. (2000). "Advances in Materials Applied in Civil Engineering". Journal of Materials Processing Technology. (106). Elsevier Science B.V.

Appendix A

ASTM Standard C-236-89

Designation: C 236 – 89 (Reapproved 1993)$^{\epsilon 1}$

Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box[1]

This standard is issued under the fixed designation C 236; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense. Consult the DoD Index of Specifications and Standards for the specific year of issue which has been adopted by the Department of Defense.

$^{\epsilon 1}$ Note—Section 12 was added editorially in September 1993.

1. Scope

1.1 This test method, known as the guarded hot box method, covers the measurement of the steady-state thermal transfer properties of panels. In distinction to Test Method C 177, which is primarily applicable to homogeneous samples, the guarded hot box method provides for the evaluation of thermal performance of building assemblies. This test method is suitable for building construction assemblies, building panels, and other applications of nonohomogeneous specimens at similar temperature ranges. It may also be used for homogeneous specimens.

1.2 This test method may be applied to any building construction for which it is possible to build a reasonably representative specimen of size appropriate for the apparatus.

Note 1—A calibrated hot box, Test Method C 976, may also be used for the described measurements and may prove more satisfactory for testing assemblies under dynamic conditions (nonsteady-state) and to evaluate the effects of water migration and air infiltration. The choice between the calibrated or the guarded hot box should be made only after careful consideration of the contemplated use.

1.3 In applying this test method, the general principles outlined must be followed; however, the details of the apparatus and procedures may be varied as needed.

1.3.1 The intent of this test method is to give the essential principles and the general arrangement of the apparatus. Any test using this apparatus must follow those principles. The details of the apparatus and the suggested procedures that follow are given not as mandatory requirements but as examples of this test method and precautions that have been found useful to satisfy the essential principles.

1.3.2 Persons applying this test method shall be trained in the methods of temperature measurement, shall possess a knowledge of the theory of heat flow, and shall understand the general requirements of testing practice.

1.3.3 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

Note 2—While various units may be found for thermal properties, the International System of units is used exclusively in this test method. For conversion factors to inch-pound and kilogram-calorie systems, see Table 1.

2. Referenced Documents

2.1 *ASTM Standards:*

- C 168 Terminology Relating to Thermal Insulating Materials[2]
- C 177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus[2]
- C 518 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus[2]
- C 578 Specification for Preformed Cellular Polystyrene Thermal Insulation[2]
- C 976 Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box[2]
- C 1045 Practice for Calculating Thermal Transmission Properties from Steady-State Heat Flux Measurements[2]
- E 178 Practice for Dealing With Outlying Observations[3]
- E 230 Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples[4]
- E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method[3]

3. Terminology

3.1 *Definitions*— For definitions of terms used in this test method, refer to Terminology C 168.

3.2 *Symbols:*

3.2.1 The symbols used in this test method have the following significance:

λ = thermal conductivity, $W/(m \cdot K)$,
C = thermal conductance, $W/(m^2 \cdot K)$,
h = surface conductance, $W/(m^2 \cdot K)$,
U = thermal transmittance, $W/(m^2 \cdot K)$,
q = heat flux (time rate of heat flow through Area A), W/m^2.

[1] This test method is under the jurisdiction of ASTM Committee C-16 on Thermal Insulation and is the direct responsibility of Subcommittee C16.30 on Thermal Measurement.

Current edition approved Sept. 29, 1989. Published June 1990. Originally published as C 236 – 60. Last previous edition C 236 – 87.

[2] *Annual Book of ASTM Standards*, Vol 04.06.

[3] *Annual Book of ASTM Standards*, Vol 14.02.

[4] *Annual Book of ASTM Standards*, Vol 14.03.

TABLE 1 Conversion Factors for Thermal

	W/(m·K)[B]	W/(cm·K)	cal/(s·cm·K)	kg-cal/(h·m·K)	Btu/(h·ft·°F)	Btu·in./(h·ft²·°F)
1 W·m⁻¹·K⁻¹ =	1.000	1.000×10^{-2}	2.388×10^{-3}	0.8598	0.5778	6.933
1 W·cm⁻¹·K⁻¹ =	100.0	1.000	0.2388	85.98	57.78	693.3
1 cal·s⁻¹·cm⁻¹·K⁻¹ =	418.7	4.187	1.000	360.0	241.9	2903.00
1 kg-cal·h⁻¹·m⁻¹·K⁻¹ =	1.163	1.163×10^{-2}	2.778×10^{-3}	1.000	0.6720	8.064
1 Btu·h⁻¹·ft⁻¹·°F⁻¹ =	1.731	1.731×10^{-2}	4.134×10^{-3}	1.488	1.000	12.00
1 Btu·in.·h⁻¹·ft⁻²·°F⁻¹ =	0.1442	1.442×10^{-3}	3.445×10^{-4}	0.1240	8.333×10^{-2}	1.000

Thermal Conductance[A]

	W/(m²·K)[B]	W/(cm²·K)	cal/(s·cm²·K)	kg-cal/(h·m²·K)	Btu/(h·ft²·°F)
1 W·m⁻²·K⁻¹ =	1.000	1.000×10^{-4}	2.388×10^{-5}	0.8598	0.1761
1 W·cm⁻²·K⁻¹ =	1.000 × 104	1.000	0.2388	8598	1761
1 cal·s⁻¹·cm⁻²·K⁻¹ =	4.187×10^{4}	4.187	1.000	3.600×10^{4}	7373
1 kg-cal·h⁻¹·m⁻²·K⁻¹ =	1.163	1.163×10^{-4}	2.778×10^{-5}	1.000	0.2048
1 Btu·h⁻¹·ft⁻²·°F⁻¹ =	5.678	5.678×10^{-4}	1.356×10^{-4}	4.882	1.000

[A] Units are given in terms of (1) the absolute joule per second or watt, (2) the calorie (International Table) = 4.1868 J, or the British thermal unit (International Table) = 1055.06 J.

[B] This is the SI unit.

Q = time rate of heat flow, total input to the metering box, W,
A = metering area normal to heat flow, m²,
L = length of path of heat flow (thickness of specimen), m,
N = minimum number of thermocouples (see Eq 1, 6.5.1.1),
r = surface resistance, K·m²/W,
R = thermal resistance, K·m²/W,
R_u = overall thermal resistance, K·m²/W,
t_h = average temperature of air 75 mm or more from the hot surface, K,
t_1 = area weighted average temperature of hot surface, K,
t_2 = area weighted average temperature of cold surface, K, and
t_c = average temperature of air 75 mm or more from cold surface, K.

4. Summary of Test Method

4.1 To determine the conductance, C, the thermal transmittance, U, and the thermal resistance, R, of any specimen, it is necessary to know the area, A, the heat flux, q, and the temperature differences, all of which must be determined under such conditions that the flow of heat is steady. The hot box is an apparatus designed to determine thermal performance for representative test panels and is an arrangement for establishing and maintaining a desired steady temperature difference across a test panel for the period of time necessary to ensure constant heat flux and steady temperature, and for an additional period adequate to measure these quantities to the desired accuracy. The area and the temperatures can be measured directly. The heat flux, q, however, cannot be directly measured, and it is to obtain a measure of q that the hot box has been given its characteristic design. In order to determine q, a five-sided metering box is placed with its open side against the warm face of the test panel. If the average temperature across the walls of the metering box is maintained the same, then the net interchange between the metering box and the surrounding space is zero, and the heat input to the metering box is a measure of the heat flux through a known area of the panel. The portion of the panel outside the meter area, laved by the air of the surrounding guard space, constitutes a guard area to minimize lateral heat flow in the test panel near the metering area. Moisture migration, condensation, and freezing within the specimen can cause variations in heat flow; to avoid this, the dew point temperature on the warm side must be kept below the temperature of the cold side when the warm surface is susceptible to ingress of moisture vapor. It is expected that, in general, tests in the guarded hot box apparatus will be conducted on substantially dry test panels, with no effort made to impose or account for the effect of the vapor flow through or into the panel during the test.

4.2 Since the basic principle of the test method is to maintain a zero temperature difference across the metering box walls, adequate controls and temperature-monitoring capabilities are essential. It is recognized that small temperature gradients could occur due to the limitations of controllers. Since the total wall area of the metering box is often more than twice the metering area of the panel, small temperature gradients through the walls may cause heat flows totaling a significant fraction of the heat input to the metering box. For this reason, the metering box walls may also be equipped to serve as a heat flow meter so that heat flow through them can be estimated and minimized by adjusting conditions during tests, and so that a heat flow correction can be applied in calculating test results.

5. Significance and Us

5.1 When the guarded hot box is constructed to test assemblies in the vertical orientation, it is suited for evaluating walls and other vertical structures. When constructed to test assemblies in the horizontal orientation, it is suited for evaluating roof, ceiling, floor, and other horizontal structures. Other orientations are allowable. The same apparatus may be used for both vertical and horizontal testing if it can be rotated or reassembled in either orientation.

NOTE 3—Horizontal structures that incorporate attic spaces between a ceiling and a sloping roof are highly complex constructions, and testing in the guarded hot box would be extremely difficult. Proper consideration must be given to specimen size, natural air movement, ventilation effects, radiative effect, baffles at the guard-meter demarcation, etc. All of these special conditions must be included in the report (10.1.1). Consideration should be given to the use of the calibrated hot box for such large, complex constructions.

5.2 For vertical specimens with air spaces that significantly affect thermal performance, the metering box height should ideally match the construction height. If this is not possible, horizontal convection barriers must be installed to prevent air exchange between meter and guard areas, unless it can be shown that the omission of such barriers does not significantly affect results.

5.3 For all specimens it is necessary to maintain a near zero lateral heat flow between the guard area and the meter area of the specimen. This can be achieved by maintaining a near zero temperature difference on the specimen surface between the metered and guard areas. In specimens incorporating an element of high lateral conductance (such as a metal sheet), it may be necessary to separate the metered and the guard areas of the highly conductive element by a narrow gap such as a saw cut.

5.4 Since this test method determines the total flow of heat through the test area demarcated by the metering box, it is possible to determine the heat flow through a building element smaller than the test area, such as a window or representative area of a panel unit, if the parallel heat flow through the remaining surrounding area or mask is determined (see Annex A1).

6. Apparatus

6.1 *Arrangement*—Fig. 1 (*a*) shows a schematic arrangement of the test panel and of various major elements of the apparatus; Fig. 1(*b*) and (*c*) show alternative arrangements. Still other arrangements, accomplishing the same purpose, may be preferred for reasons of convenience or ease of installing panels. In general, the size of the metering box determines the minimum size of the other elements.

6.2 *Metering Box:*

6.2.1 *Size*—The size of the metering box is largely governed by the metering area required to obtain a representative test area of panel. For example, for panels incorporating air spaces or stud spaces, the metering area, preferably, should exactly span an integral number of spaces. The height of the metering box should be not less than the width and is subject to the limitations as described in 5.2. The depth of the metering box should be not greater than that required to accommodate its necessary equipment.

6.2.2 *Thermal Resistance*—The metering box walls shall have a thermal resistance of not less than 0.83 m^2 K/W. In order that the resistance of the box wall shall be uniform over the entire box area, a construction without internal ribs shall be used, for example, a glued balsa wood or a sandwich construction with aged urethane foam core. The edge in contact with the panel shall, if necessary, be narrowed on the outside only, to hold a gasket not more than 13 mm wide. If necessary, a wood nosepiece can be used to carry the gasket. The metering area of the panel shall be taken as the area included between the center lines of the gaskets. All surfaces that can exchange radiation with the specimen must have a total hemispherical emittance greater than 0.8.

6.2.3 *Heat Supply and Air Circulation*—Fig. 2 shows a possible arrangement of equipment in the metering box to assure an even, gentle movement of air over the metering

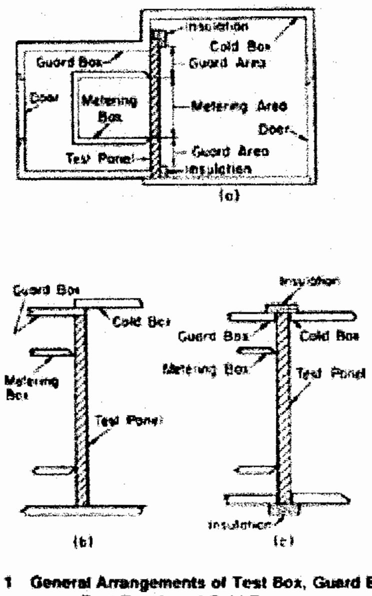


FIG. 1 General Arrangements of Test Box, Guard Box, Test Panel, and Cold Box

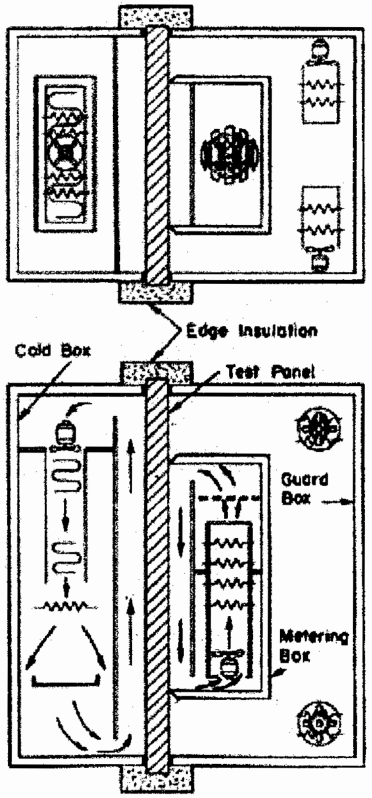


FIG. 2 Arrangement of Equipment During the Test

area of the panel. The electric heaters are mounted in a housing with walls of resistance not less than 0.83 m² K/W, and with a low emittance outside surfacing to minimize radiation heat transfer to the metering box walls. In this arrangement air is continuously circulated by a small fan upward through the cylindrical housing and downward between the baffle and the panel in accordance with the motion that would result from natural convection forces. A slat-type baffle is placed some distance above the outlet of the cylindrical housing to prevent impingement of a jet of heated air against the top inner surface of the metering box. For large meter boxes the cylindrical housing may cause concentrations of air flow. To direct the air properly across the specimen, other fan arrangements may be preferable. A curved vane is mounted at the top of the baffle to smooth the entrance of air into the baffle space. In a hot box apparatus used for testing panels in a vertical position only, the moderate circulation of air resulting from natural convection may be sufficient without the use of a fan. The change in temperature of the air as it moves along the surface of the panel will, in general, be greater with natural circulation than with a fan. If a fan is used, its motor should be within the metering box, its electrical input should be as small as feasible, and the input should be carefully measured. If it is necessary to locate the motor outside the metering box, the heat equivalent of the shaft power must be accurately measured, and air leakage into or out of the metering box around the shaft must be zero.

6.2.4 *Temperature Control*—To obtain reliable test results, accurate temperature control equipment must be utilized. Temperature controllers must be capable of controlling temperature within 0.25 K during the test period. The heaters should be the open-wire type of minimal heat capacity and lag.

6.2.5 *Gaskets*—The contact edges of the metering box should ensure, by a gasket or other means, a tight air seal against the surface of the test panel. For some panels special provisions may be necessary. The metering box should be pressed tightly against the panel by suitable means. Some gasket materials age with time and service. Periodic inspection of gaskets is recommended in order to confirm their ability to provide a tight seal under test conditions.

6.2.6 *Heat Flux Transducer*—To equip the metering box walls to serve as a heat flux transducer, a means of detecting the temperature difference across the metering box walls or the heat flux through the metering box walls shall be provided. One method found satisfactory for this purpose is to apply a number of differential thermocouples connected in a series to the inside and outside surfaces of the metering box walls to form a thermopile. Precautions must be taken when determining the number of differential thermocouples. Based on a survey of guarded hot box operators, the number of differential thermocouple pairs located on metering box walls shall be five pairs per square metre of specimen metered area located on the metering box sides. At no time shall there be less than 1 pair of differential thermocouples on each of the five sides of the metering box (1).[5] Precautions must also be [illegible] when determining locations of the differential thermocouples, as temperature gradients on the inside and outside of the metering box walls are likely to exist and have been found to be a function of metering and guard box air velocities and temperature. The junctions and the thermocouple wires for at least a 100-mm distance from the junctions shall be flush with, and in thermal contact with, the surface of the wall. The output of the thermocouple pairs shall be averaged.

6.2.7 *Thermopile emf and Heat Flow Relationship*—The relationship between thermopile emf and heat flow through the metering box walls shall be determined. This relationship shall be determined for each set of metering box conditions (temperature and air velocity). A suggested method of accomplishing this objective is outlined in Appendix X1.

6.3 *Guard Box:*

6.3.1 *Size*—It is recommended that the guard box be large enough so that there is a clear distance between its inner wall and the nearest surface of the metering box of not less than the thickness of the thickest panel to be tested, but in no case less than 150 mm.

6.3.2 *Thermal Conductance*—To assure that there shall be a temperature difference of no more than a few degrees between the guard box air and its inner surfaces, the walls shall have a thermal conductance not greater than 0.6 W/(m²·K). A low conductance is also desirable for operating reasons, to assure that the heat flow into or out of the guard box from outside will be only a small fraction of the heat flow through the guard area of the test panel.

6.3.3 *Heat Supply and Air Circulation*—One or more reflective-surfaced cylindrical heater units with a fan may be used to supply heat to the guard box air and also to circulate the air to avoid stratification. The fan air intake of at least one such heater unit should be located at the lowest point in the guard box, to prevent pooling of cool air at the bottom. The air discharged from the heater cylinder shall not impinge directly against either the metering box or the test panel.

6.3.4 *Temperature Control*—The guard box air temperature and heat input can be controlled by a differential thermopile such as that used on the metering box for a heat flow meter, or by a sensitive bridge circuit with opposed temperature-sensitive arms located in the guard and metering boxes. To avoid hunting due to the small periodic temperature variations of the metering box air, as its thermostat functions, it is desirable to put the temperature-sensitive element of the differential control in the metering box in good thermal contact with the inside surfaces of the metering box. The temperature-sensitive element in the guard box should be placed to avoid being directly in the air stream of the heater units and should be of minimum thermal lag. The control equipment used to maintain guard box temperatures must be capable of controlling to within 0.25 K.

6.4 *Cold Box:*

6.4.1 *Size*—The size of the cold box is governed by the size of the test panel or by the arrangement of boxes used, as illustrated in Fig. 1.

6.4.2 *Insulation*—The cold box should be heavily insulated to reduce the required capacity of the refrigerating equipment, and the exterior of the cold box should be provided with a good vapor barrier to prevent ingress of

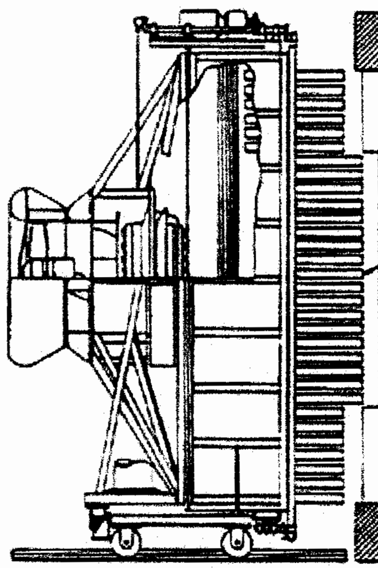
[5] The boldface numbers in parentheses refer to the list of references at the end of this test method.

vapor and heavy frost accumulations on the cooling coils.

6.4.3 *Temperature Control*—The cold box may be cooled in any manner that is capable of the close control of air temperature necessary during a test. An arrangement of equipment similar to that in the metering box may be used with a fan to force air downward through the enclosed refrigerating coils and upward through the space between a baffle and the test panel as indicated in Fig. 2. It has been found satisfactory with an arrangement of this sort to operate a unit refrigeration system continuously, with the evaporation temperature of the coil held constant by an automatic back-pressure regulating valve, and refrigerant supplied to the coil through an automatic expansion valve. An alternative method is to use an exterior located refrigeration system and insulated ducts to supply chilled air to the cold box. Liquid nitrogen in connection with a solenoid valve regulating its flow may also be used. For fine control of the cold box, installation of open wire electrical heaters in the blower duct or other fast moving part of the air circulation system and controlling these heaters by a sensor located in the discharge of the air circulation system is recommended. The use of desiccants to remove excessive moisture in the recirculating cold air may be useful. Temperature controllers for steady-state tests must be capable of controlling temperatures within ±0.25 K.

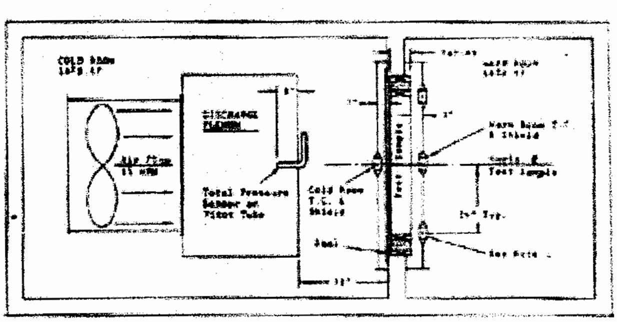
6.4.4 *Air Circulation*—High air velocities are permissible when their effect upon heat flow is to be determined. This may be accomplished by directing the airflow either parallel or perpendicular to the specimen cold surface. One method of obtaining parallel uniform velocity is to force air through a space between the specimen and a parallel baffle whose spacing may be adjustable to aid in changing the air curtain velocity. Parallel velocities, as provided in this test method, aid in obtaining uniform specimen surface temperatures and simulate the effect of cross winds. Velocities commonly used to simulate cross wind conditions are 3.35 m/s for summer conditions and 6.70 m/s for winter conditions. Perpendicular velocities, simulating direct wind impingment require moving larger amounts of air than most parallel situations, with corresponding larger power requirements. Also, the baffle should be placed further from the specimen surface and should have a porous section (a screen or honeycomb flow straightener) that directs the wind at the specimen surface (see Fig. 3 and 4). Velocities commonly used to simulate wind conditions are 3.35 m/s for summer conditions and 6.70 m/s for winter conditions. Air leakage through the specimen should be eliminated by sealing all cracks and joints with tape, caulk, or foam strips.

6.4.4.1 After construction of the air circulation system a velocity scan across the air curtain is required to verify that a uniform air curtain is formed. The apparatus should provide a means for determining air velocity past the specimen surface. One method is to locate velocity sensors directly in the air curtain.



NOTE—One inch is equal to 25.4 mm.

FIG. 3 DBR Wind Machine



NOTE 1—Thermocouples and shields on the warm side are movable to maintain 3 in. spacing to test sample.
NOTE 2—Overall chamber length may vary.
NOTE 3—One inch is equal to 25.4 mm.
NOTE 4—Thirty-two degrees farenheit is equal to 0°C.

FIG. 4 Thermal Chamber Diagram

6.5 *Temperature-Measuring Equipment:*

6.5.1 *Surface Temperatures*—Thermocouples of wire not larger in size than 0.25 mm (No. 30 AWG gage), and which meet or are calibrated to the special limits of error specified in Tables E 230, are recommended for measuring surface temperatures in the apparatus (larger thermocouples can be used if it can be shown that there is no difference in bias); for this purpose the thermocouple junction and the adjoining lead wires for a distance of at least 100 mm should be taped, or preferably cemented, tightly to the surface. The emittance of the surfacing material tape or cement should be close to the emittance of the surface.

6.5.1.1 If the specimen (and therefore its thermal resistance) is uniform, or nearly so, over the area and thus the surface temperatures vary only slightly at lower air velocities, a minimum number of thermocouples spaced uniformly and symmetrically over the surface is sufficient. This minimum number depends on the specimen size. Experience has shown that the required minimum number of thermocouples, N, can be determined from the relation that:

$$N = A/(0.07 + 0.08\sqrt{A}) \qquad (1)$$

where A is the metering area in m². If the number of thermocouples used is within 10 % of the number determined by this relation, then the requirements of this section are judged to be met.

6.5.1.2 If the specimen is of nonuniform construction, the number of thermocouples specified in 6.5.1.1 may still be sufficient. In this case the thermocouples shall be judiciously located to represent each of the construction elements. Such representation shall be distributed approximately uniformly and symmetrically over the specimen surface.

6.5.1.3 If the surface temperatures are expected to be greatly nonuniform, additional thermocouples must be used to sample adequately the different temperature areas so that reliable weighted mean temperatures may be obtained.

6.5.1.4 With some nonhomogeneous walls, such as concrete, it may be advisable to use copper shim stock under the thermocouples to average the temperature. Large aggregates in the concrete can create biased temperature readings.

6.5.1.5 At least two surface thermocouples shall be placed on the guard area of the specimen at suitable locations to indicate the effectiveness of the guard area.

6.5.1.6 Surface temperatures on the cold side of the test panel shall be measured by surface thermocouples placed directly opposite those on the warm side.

6.5.2 Air temperatures may be measured by thermocouples, temperature sensitive resistance wires, or other sensors. Air thermocouples shall be made of wire not larger than 0.51 mm (No. 24 AWG).

6.5.2.1 If thermocouples or other point sensors are used, they shall be located in the metering box area in the same quantity and spacing as that specified for surface thermocouples in 6.5.1.1. The thermocouple shall be located midway between the face of the panel and the baffle, if one is used, but in no case less than 75 mm from the face of the panel. The junctions of the thermocouples shall have bright metallic surfaces and shall be as small as possible to minimize radiation effects. Another method is to shield the thermocouple junction. The thermocouples may be placed directly opposite the surface thermocouples; in any case they should be located as [illegible] ...ay as possible over the metering area.

6.5.2.2 Thermocouples shall also be placed in the guard space at suitable locations, to indicate the degree of uniformity of guard space air temperatures; preferably, one shou' be placed opposite each guard area surface thermocouple, but not less than 75 mm from the panel.

6.5.2.3 Air temperatures on the cold side of the panel shall be measured by one thermocouple placed directly opposite each of the warm side air temperature thermocouples and located in a plane parallel to the specimens surface and spaced far enough away that they are unaffected by temperature gradients in the boundary layer. The thermocouples shall be located midway between the face of the panel and the baffle, if one is used. For low velocities, a minimum spacing of 75 mm from the specimen surface is required. At higher velocities the required minimum spacing is less but in no case less than 20 mm. No thermocouples need be placed in the cold space opposite guard space thermocouples remote from the panel surface.

6.5.2.4 If air temperatures are to be measured by means of resistance wire grids, the wire shall be distributed uniformly to indicate approximately the average temperature of the air on both sides of the panel at a plane midway between the baffle and the panel but in no case less than 75 mm from the panel.

6.5.2.5 It is recommended that the surface temperature of the baffles on the hot and cold sides be measured by placing thermocouples on all surfaces the specimen can see.

NOTE 4—This is not a requirement of this test method but is highly recommended. There are several reasons for the recommendation: (*1*) this indicates any difference between the baffle surface and air temperatures; (*2*) it will allow corrections to be made to the radiati component of the surface conductances due to differences in these temperatures; and (*3*) it is necessary to do this for specimens such as glass which have a high-thermal conductance.

6.6 *Instruments*:

6.6.1 All thermocouples or other temperature sensors for observing surface and air temperatures shall have their leads brought out individually to suitable measuring instruments capable of indicating temperatures to within ±0.05 K.

6.6.2 Total average power (or integrated energy over a specified time period) for all energy to the meter box shall be accurate to within ±0.5 % of reading under conditions of use. Power measuring instruments must be compatible with the power supplied whether ac, dc, on-off proportioning, etc. Voltage stabilized power supplies are strongly recommended.

6.6.3 Velocities of air over both surfaces of the panel should be measured with suitable instruments or be calculated from a heat balance between the rate of loss or gain of heat as it moves through the baffle space, as indicated by its temperature change, and the rate of heat flow through the test panel, average values of which can be determined from the test data. It should be recognized that radiant transfer between the baffle and the specimen can affect the calculation if the radiation is significant. For this reason direct velocity measurement is desirable.

NOTE 5—It is recommended that a central control location be established, that automatic scanning and recording equipment for unattended operation be used, and that data be computer processed.

6.7 *Verification*—When a new or modified apparatus is constructed, verification tests shall be conducted on panels made from materials of known conductance that does not exceed 1.5 W/(m²·K) as determined in Test Methods C 177 or Test Method C 518[6]. Any differences in results should be carefully analyzed and corrective measures taken. Further periodic checks are recommended.

7. Sampling and Test Specimens

7.1 Specimens shall be representative of the construction to be investigated but may be modified if necessary for test purposes as mentioned in 5.2 and 5.3. It must be recognized that modifications to the construction may result in conditions that do not represent true field conditions. In many cases conduction and convection paths have considerable effect on the performance of the specimen and must be left intact. Other considerations are:

7.1.1 *Sensors*—Install temperature sensors as directed in 6.5. When desired, temperature and other sensors may be installed throughout the interior of the specimen for special investigations.

7.1.2 *Conditioning*—The usual pre-test conditioning is in ambient air long enough to come to practical equilibrium. Assemblies that may have significant moisture content, which can influence test results, must be allowed to reach steady-state moisture conditions. Since the specimen size will probably preclude oven drying, concrete wall specimens may require 6 to 8 weeks of room temperature aging.

7.1.3 *Edge Insulation*—When a test panel is installed, its edges shall, if necessary, be insulated to prevent edge effect from overtaxing the guarding effect of the guard area of the panel. For this purpose, the edges of the panel may be protected against heat loss or gain by a thickness of insulation with an R of 1 or 1.25 K·m²/W. It may be necessary to vapor-proof the insulation to prevent condensation of moisture in the edges of the panel, if a test arrangement similar to that shown in Fig. 1(*c*) is used. The edge of the specimen should be well sealed to prevent air infiltration between the guard and the cold box.

8. Procedures

8.1 Test conditions of temperature and orientation should be chosen to correspond as closely as possible to the circumstances of use of the construction to be tested. This test method is primarily designed for the temperatures encountered in normal building use, however, it is recognized that the method may find application in testing conditions that are outside this normal range. It is recommended that a minimum temperature differential of approximately 25 K be maintained for accurate measurement.

8.2 The required stabilization and test periods are as follows:

8.2.1 Impose steady-state conditions for at least 4 h prior to final data collection. This condition is satisfied when, over this 4-h period, the average surface temperature did not vary by more than ±0.06°C (±0.1°F) and the average power in the meter area did not vary by more than ±1 % and the data did not change unidirectionally. During this period, data shall be collected at intervals of 1 h or less.

8.2.2 After the conditions in 8.2.1 have been satisfied, continue the test period at least 8 h, but do not terminate the test until two or more successive 4-h periods produce results that do not differ by more than 1 %. During this period take data at intervals of 1 h or less. The average of the data for the two or more successive 4-h periods that agree within 1 % are used in calculating the final results. In testing panels that are heavily insulated, very massive, or both, it may be necessary to extend the duration of the test beyond the minimum period of two consecutive 4-h periods in order to be assured that conditions are steady, as it has been observed that continuing but small incremental changes can give a premature appearance of stability.

8.2.3 The calculation of a time constant, generated from apparatus measurements (Note 6) combined with an estimate of the thermal properties of the specimen, will help in estimating the time required for the test set-up to reach equilibrium. (2) It is also suggested that C and U values be calculated for the test specimen, utilizing known properties of the components. This will serve as general check of the measured results and avoid serious errors in measurement.

NOTE 6—The thermal mass of the apparatus may be the major factor contributing to the time constant of the system.

8.3 Data to be determined include:

8.3.1 The total net energy or average power through the specimen during a measurement interval. This includes all meter box heating and power to fans or blowers, and any corrections for meter box wall heat flow.

8.3.2 All air and surface temperatures specified in 6.5.1 and 6.5.2 (Note 7).

8.3.3 The effective dimensions of the metered area.

NOTE 7—In 6.5 the locations of thermocouples or temperature-measuring elements at various points are stipulated, for example, in the guard space and on the guard area of the test panel. The temperatures indicated by such thermocouples are of great value in evaluating the uniformity of temperatures prevailing in the guard space and on the test panel surfaces, but it is not feasible to stipulate generally the limits within which certain of these measured temperatures must agree. It must, therefore, be the responsibility of the test engineer to observe and weigh the significance of these temperatures to ascertain their effect upon the validity of a particular test measurement.

9. Calculation

9.1 Calculate the final test results by means of the following equations using the average data obtained in 8.2.2 for the two 4-h periods that agree within 1 %:

$$U = Q/A(t_h - t_c)$$
$$C = Q/A(t_1 - t_2)$$
$$R = (t_1 - t_2)A/Q$$
$$R_u = (t_h - t_c)A/Q \doteq r_c + R + r_h$$
$$r_h = (t_h - t_1)A/Q$$
$$r_c = (t_2 - t_c)A/Q$$
$$h_h = Q/A\,(t_h - t_1)$$
$$h_c = Q/A\,(t_2 - t_c)$$
$$\lambda = QL/A\,(t_1 - t_2)$$

9.1.1 For a relatively uniform but nonhomogeneous specimen such as normal walls, floors, ceilings, etc., the properties that may be calculated are transmittance U, conductance C, resistance R, overall resistance R_u, surface resistances and surface conductances, h.

9.1.2 For uniform and homogeneous specimens all of the

[6] Practice C 1045 must be used in conjunction with Test Methods C 177 and Test Method C 518.

properties listed in 9.1.1 may be calculated plus thermal conductivity λ.

9.1.3 For elements smaller than the metering area, the properties that apply to the element, according to the distinctions of 9.1.1 and 9.1.2 may be calculated if tests have been run that allow the element heat flow to be determined. Annex A1 presents considerations for these calculations.

10. Report

10.1 Report the following information:

10.1.1 Name, and any other identification or description of the test construction, including if necessary a blueprint showing important details, dimensions, and all modifications made to the construction, if any, and specimen orientation. Description of the test construction and a complete and detailed description of all materials. This includes the generic name of the material and its density. (For hygroscopic materials, such as some concrete materials and wood, the moisture content should also be given). If the thermal conductivities of these materials, at the test conditions, have been measured in a hot box facility (Test Method C 236 or Test Method C 976), a guarded hot plate (Test Method C 177) or a heat flow meter (Test Method C 518), these values should also be included.

NOTE 8—By generic description, the name of the material in addition to the brand name should be given (for example, preformed, cellular polystyrene Type VIII with a density of 22 kg/m³; spruce-pine-fir with a moisture content of 12 % and a dry density of 486 kg/m³).

10.1.2 Pertinent information in regard to preconditioning of the test panel.

10.1.3 Size and dimensions of the metering and guard areas of the test panel.

10.1.4 Average values during the test period of the temperatures and velocities of the air on both sides of the metering area of the panel, and of the temperature of the surfaces on both sides. (If significant, give the average values of the temperature of specific areas of the surface of the panel.)

10.1.5 Average rate of net heat input to the metering box.

10.1.6 Any thermal transmission properties calculated in 9.1 and the known precision of the equipment. Precision of the equipment should be checked using the propagation of errors theory.

NOTE 9—Discussions of this method can be found in many textbooks on engineering experimentation and statistical analysis (3).

10.1.7 Test duration and date.

10.2 All values shall be reported in both SI and inch-pound units unless specified otherwise by the client.

10.3 Where this test method is specifically referenced in published test reports and published data claims, and where deviations from the specifics of the test method existed in the tests used to obtain said data, the following statement shall be required to accompany such published information: "This test did not fully comply with the following provisions of Test Method C 236" (followed by a listing of specific deviations from this test method and any special test conditions that were applied).

11. Precision and Bias

11.1 *Background*—A round robin for guarded and calibrated hot boxes was conducted in accordance with Practice E 691. This round robin involved 21 different laboratories which 16 had guarded hot boxes (4). Data were reported for 100-mm (4-in.) thick homogeneous specimens of expanded polystyrene board (Specification C 578). Each laboratory received material from a special manufacturer's lot that was controlled to maintain a uniform density. Data reduction and analysis using Practice E 178 identified one of the 16 laboratories as a statistical outlier. Results from the other 15 laboratories showed that at a mean temperature (t) of 24°C (75°F), the average R value was determined to be 2.78 K m²/W (15.77 F ft² h/Btu). The regression equation for the data set was:

$$R = 3.146 - 0.016\,t \ (R \text{ in K·m}^2\text{/W and } t \text{ in °C}) \quad (2a)$$

$$R = 17.867 - 0.028\,t \ (R \text{ in F ft}^2\text{h/Btu and } t \text{ in °F}) \quad (2b)$$

over the mean temperature range from 4°C to 43°C (40°F to 110°F). The mean specimen density ranged from 20.2 to 23.9 kg/m³ (1.26 to 1.49 lbs/ft³).

11.2 *Precision*—At a specimen thermal resistance of R = 2.78 K·m²/W (15.76 F ft²h/Btu) and on the basis of test error alone, the difference in absolute value of two test results obtained in different laboratories on the same specimen materials will be expected to exceed the reproducibility interval only 5 % of the time according to Table 2. For example, measurements from two different laboratories on the same specimen could differ by up to ±7.8 % at a mean temperature of 24°C (75°F) 95 % of the time.

11.3 *Bias*—Based on guarded hot plate data (Test Method C 177) from the National Institute of Standards and Technology—Center for Building Technology and supported by measurements from other laboratories, the true value for the round-robin specimen is a thermal resistance of 2.81 K·m²/W (15.94 F ft²h/Btu). The mean value measured by the guarded hot box differed by −1.07 %.

NOTE 10—Another test series was conducted on homogeneous common lot specimens in three guarded hot boxes at different laboratories. (5, 6) R-values of the specimens ranged from approximately 0.5 to 2.1 K·m²/W (3 to 11.8 F ft²h/Btu) at mean temperatures of 4, 24, and 43°C (40, 75, and 110°F). This series indicated that results with precision of ±5 % may be achieved.

NOTE 11—Both round robins used a homogeneous specimen, an ideal wall section. Actual wall sections will be nonhomogeneous. The precision and bias has not yet been determined for nonhomogeneous specimens. The above statements provide a bound.

12. Keywords

12.1 building assemblies; guarded hot box; test method; thermal performance; thermal resistance

TABLE 2 Precision for Test Method C 236

Mean Temperature, °C (°F)	Thermal Resistance, K·m²/W (F ft²h/Btu)	Reproducibility Interval, %	Change in R, K·m²/W (F ft²h/Btu)
4 (40)	2.95 (16.75)	±7.3	±0.22 (±1.23)
24 (75)	2.78 (15.77)	±7.8	±0.22 (±1.23)
43 (110)	2.60 (14.79)	±6.6	±0.22 (±1.27)

Appendix B

Test Procedure Sheet

Thermal Conductivity Test Procedure

Basic Machine Setup

1. Plug in extension cord and power strip of electronics console to uninterrupted power.
2. Plug in all power cords to their appropriate outlet on back of console & tester.
3. Turn on main power to electronics console (located on back). ***Note:** Make sure guard box and metering box main switches are in the off position and that the guard and metering box variacs are set to zero.
4. Set all controllers to desired temperature settings. ***Note:** Controller memory will save the setup parameters of the previous test. Therefore, if the same parameters will be used as in the previous test, this step can be skipped.
5. Turn both guard and metering box main switches to the on position.
6. Turn guard and metering box variac power settings to 100%. This will allow full power to the heater to get up to operating temperature faster.
7. Adjust the output of the HP Triple Output Power Supply to full voltage for the guard and metering box fans.
8. After desired temperatures have been reached in both boxes. Adjust variacs to a setting that allows the maximum temperature to be maintained while still supplying power to the heaters. The red light on the controller tells you that the controller is supplying power to the heaters.

9. At this point turn on the main power switch to the AC unit on the cold side and adjust the controller temperature setting to the desired setting.

10. After variacs have been adjusted and steady state conditions have been reached, allow the boxes to set another four hours to normalize temperatures. ***Note:** Reaching steady state conditions could take up to 24 hours.

Data Collection

1. Using the data sheet, record guard box temperature, voltage and current using an appropriate meter. ***Note:** Guard box voltage and current measurement is not necessary to determine r-value.

2. Record metering box temperature, voltage and current. ***Note:** To determine metering box current, measure the voltage drop across the .1Ω resistor and solve for current. $I = V/R$

3. Record temperature readings for all 12 thermocouples using selector switch and reading on the temperature controller.

4. Record the voltage and current from the HP triple output power supply.

5. Convert Fahrenheit to Kelvin for the thermocouple temperature readings. *Note: The asterisks next to the thermocouple numbers denote the orientation of the metering area thermocouples and those opposite them (i.e., 1-4 Cold Side, 7-10 Hot Side).

6. Take area weighted average of the metering area thermocouples by multiplying the temperature (Kelvin) by thermocouple area.

7. Sum the 4 weighted averages for the cold side temperatures and divide by the metering box area. This value is t_1.
8. Sum the 4 weighted averages for the hot side temperatures and divide by the metering box area. This value is t_2.
9. Calculate total energy (W) into the metering box by combining fan energy and heater energy.
10. Plug these values into the formula and solve for R (thermal resistance).