Designation: C1363 – 05

Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus[1]

This standard is issued under the fixed designation C1363; 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.

1. Scope

1.1 This test method establishes the principles for the design of a hot box apparatus and the minimum requirements for the determination of the steady state thermal performance of building assemblies when exposed to controlled laboratory conditions. This method is also used to measure the thermal performance of a building material at standardized test conditions such as those required in material Specifications C739, C764, C1224 and Practice C1373.

1.2 This test method is used for large homogeneous or non-homogeneous specimens. This test method applies to building structures or composite assemblies of building materials for which it is possible to build a representative specimen that fits the test apparatus. The dimensions of specimen projections or recesses are controlled by the design of the hot box apparatus. Some hot boxes are limited to planar or nearly planar specimens. However, larger hot boxes have been used to characterize projecting skylights and attic sections. See 3.2 for a definition of the test specimen and other terms specific to this method.

NOTE 1—This test method replaces Test Methods C236, the Guarded Hot Box, and C976, the Calibrated Hot Box which have been withdrawn. Test apparatus designed and operated previously under Test Methods C236 and C976 will require slight modifications to the calibration and operational procedures to meet the requirements of Test Method C1363.[2]

1.3 A properly designed and operated hot box apparatus is directly analogous to the Test Method C177 guarded hot plate for testing large specimens exposed to air induced temperature differences. The operation of a hot box apparatus requires a significant number of fundamental measurements of temperatures, areas and power. The equipment performing these measurements requires calibration to ensure that the data are accurate. During initial setup and periodic verification testing, each measurement system and sensor is calibrated against a standard traceable to a national standards laboratory. If the hot box apparatus has been designed, constructed and operated in the ideal manner, no further calibration or adjustment would be necessary. As such, the hot box is considered a primary method and the uncertainty of the result is analyzed by direct evaluation of the component measurement uncertainties of the instrumentation used in making the measurements.

1.3.1 In an ideal hotbox test of a homogenous material there is no temperature difference on either the warm or cold specimen faces to drive a flanking heat flow. In addition, there would be no temperature differences that would drive heat across the boundary of the metering chamber walls. However, experience has demonstrated that maintaining a perfect guard/metering chamber balance is not possible and small corrections are needed to accurately characterize all the heat flow paths from the metering chamber. To gain this final confidence in the test result, it is necessary to benchmark the overall result of the hot box apparatus by performing measurements on specimens having known heat transfer values and comparing those results to the expected values.

1.3.2 The benchmarking specimens are homogeneous panels whose thermal properties are uniform and predictable. These panels, or representative sections of the panels, have had their thermal performance measured on other devices that are directly traceable or have been favorably compared to a national standards laboratory. For example, a Test Method C177 Hot Plate, a Test Method C518 Heat Meter or another Test Method C1363 Hot Box will provide adequate specimens. Note that the use of Test Method C518 or similar apparatus creates additional uncertainty since those devices are calibrated using transfer standards or standard reference materials. By performing this benchmarking process, the hot box operator is able to develop the additional equations that predict the magnitude of the corrections to the net heat flow through the specimen that account for any hot box wall loss and flanking loss. This benchmarking provides substantial confidence that any extraneous heat flows can be eliminated or quantified with sufficient accuracy to be a minor factor of the overall uncertainty.

1.4 In order to ensure an acceptable level of result uncertainty, persons applying this test method must possess a knowledge of the requirements of thermal measurements and testing practice and of the practical application of heat transfer

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

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[2] Footnotes in the text are supplied to clarify the discussion only, and as such, are not mandatory.

theory relating to thermal insulation materials and systems. Detailed operating procedures, including design schematics and electrical drawings, shall be available for each apparatus to ensure that tests are in accordance with this test method.

1.5 This test method is intended for use at conditions typical of normal building applications. The naturally occurring outside conditions in temperate zones range from approximately −48 to 85°C and the normal inside residential temperatures is approximately 21°C. Building materials used to construct the test specimens shall be pre-conditioned, if necessary, based upon the material's properties and their potential variability. The preconditioning parameters shall be chosen to accurately reflect the test samples intended use and shall be documented in the report. Practice C870 may be used as a guide for test specimen conditioning. The general principles of the hot box method can be used to construct an apparatus to measure the heat flow through industrial systems at elevated temperatures. Detailed design of that type of apparatus is beyond the scope of this method.

1.6 This test method permits operation under natural or forced convective conditions at the specimen surfaces. The direction of airflow motion under forced convective conditions shall be either perpendicular or parallel to the surface.

1.7 The hot box apparatus also is used for measurements of individual building assemblies that are smaller than the metering area. Special characterization procedures are required for these tests. The general testing procedures for these cases are described in Annex A11.

1.8 Specific procedures for the thermal testing of fenestration systems (windows, doors, skylights, curtain walls, etc.) are described in Test Method C1199 and Practice E1423.

1.9 The hot box has been used to investigate the thermal behavior of non-homogeneous building assemblies such as structural members, piping, electrical outlets, or construction defects such as insulation voids.

1.10 This test method sets forth the general design requirements necessary to construct and operate a satisfactory hot box apparatus, and covers a wide variety of apparatus constructions, test conditions, and operating conditions. Detailed designs conforming to this standard are not given but must be developed within the constraints of the general requirements. Examples of analysis tools, concepts and procedures used in the design, construction, characterization, and operation of a hot box apparatus is given in Refs (**1-34**).[3]

1.11 The hot box apparatus, when constructed to measure heat transfer in the horizontal direction, is used for testing walls and other vertical structures. When constructed to measure heat transfer in the vertical direction, the hot box is used for testing roof, ceiling, floor, and other horizontal structures. Other orientations are also permitted. The same apparatus may be used in several orientations but may require special design capability to permit repositioning to each orientation. Whatever the test orientation, the apparatus performance shall first be verified at that orientation with a specimen of known thermal resistance in place.

1.12 This test method does not specify all details necessary for the operation of the apparatus. Decisions on material sampling, specimen selection, preconditioning, specimen mounting and positioning, the choice of test conditions, and the evaluation of test data shall follow applicable ASTM test methods, guides, practices or product specifications or governmental regulations. If no applicable standard exists, sound engineering judgment that reflects accepted heat transfer principles must be used and documented.

1.13 This test method applies to steady-state testing and does not establish procedures or criteria for conducting dynamic tests or for analysis of dynamic test data. However, several hot box apparatuses have been operated under dynamic (non-steady-state) conditions after additional characterization (**1**). Additional characterization is required to insure that all aspects of the heat flow and storage are accounted for during the test. Dynamic control strategies have included both periodic or non-periodic temperature cycles, for example, to follow a diurnal cycle.

1.14 This test method does not permit intentional mass transfer of air or moisture through the specimen during measurements. Air infiltration or moisture migration can alter the net heat transfer. Complicated interactions and dependence upon many variables, coupled with only a limited experience in testing under such conditions, have made it inadvisable to include this type testing in this standard. Further considerations for such testing are given in Appendix X1.

1.15 *This standard does not purport to address all of the safety concerns, 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.*

2. Referenced Documents

2.1 *ASTM Standards:*[4]

C168 Terminology Relating to Thermal Insulation

C177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus

C236 Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box[5]

C518 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus

C739 Specification for Cellulosic Fiber Loose-Fill Thermal Insulation

C764 Specification for Mineral Fiber Loose-Fill Thermal Insulation

C870 Practice for Conditioning of Thermal Insulating Materials

C976 Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box[5]

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[3] The boldface numbers in parentheses refer to the list of references at the end of this standard.

[4] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[5] Withdrawn. The last approved version of this historical standard is referenced on www.astm.org.

C1045 Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions

C1058 Practice for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation

C1114 Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus

C1130 Practice for Calibrating Thin Heat Flux Transducers

C1132 Practice for Calibration of the Heat Flow Meter Apparatus[5]

C1199 Test Method for Measuring the Steady-State Thermal Transmittance of Fenestration Systems Using Hot Box Methods

C1224 Specification for Reflective Insulation for Building Applications

C1373 Practice for Determination of Thermal Resistance of Attic Insulation Systems Under Simulated Winter Conditions

C1558 Guide for Development of Standard Data Records for Computerization of Thermal Transmission Test Data for Thermal Insulation

E230 Specification and Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples

E283 Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen

E1423 Practice for Determining Steady State Thermal Transmittance of Fenestration Systems

E1424 Test Method for Determining the Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure and Temperature Differences Across the Specimen

2.2 *Other Documents:*

ASHRAE Handbook of Fundamentals, Latest Edition, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.[6]

ISO Standard 8990 Thermal Insulation Determination of Steady State Thermal Properties—Calibrated and Guarded Hot Box, ISO 8990-1994(E)[7]

ISO Standard 12567 Thermal Performance of Windows and Doors—Determination of Thermal Transmittance by Hot Box Method, ISO 12567-2000[7]

3. Terminology

3.1 *Definitions*—The definitions of terms relating to insulating materials and testing are governed by Terminology C168, unless defined below. All terms discussed in this test method are those associated with thermal properties of the tested specimen, unless otherwise noted.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *building element*—a portion of a building assembly, selected for test, in the expectation that it will exhibit the same thermal behavior as the larger building assembly that it represents. Guidance for the selection process is given in Section 7. For purposes of this method, a single material whose properties are being evaluated is also defined as a building element.

3.2.2 *metered specimen*—the element that fills the boundary of the metering chamber opening. The metered specimen can be: *(1)* the entire building element when it is the same size as the metering chamber opening dimensions; *(2)* the building element and the surround panel in the case when the building element is smaller than the opening; *(3)* a portion of the building element when the building element is larger than the opening.

3.2.3 *test specimen*—that portion of the metered specimen for which the thermal properties are to be determined. The test specimen can be: *(1)* the entire building element when it is the same size as the metering chamber dimensions; *(2)* the building element only in the case when the building element is smaller than the opening; *(3)* that portion of the building element that is within the metered area when the building element is larger than the opening.

3.2.4 *surround panel*—the surround panel, often called the mask, is a uniform structure having stable thermal properties that supports the building element within the metering area. The material shall be homogeneous and low thermal conductivity that both supports the test specimen and provides a uniform, reproducible heat flow pattern at the edges of the metering chamber perimeter.

3.2.5 *self-masking*—a hot box configuration which occurs when the metering chamber opening is less than the building element dimensions. This configuration may be used when the thermal behavior of the building element is such that it is "self-masking." This means that the lateral heat flow at the edges of the metering chamber can be minimized. With proper design and control of the metering chamber, this condition is easily obtained for test specimens that are homogeneous, or while not homogeneous, do not contain highly conductive elements that extend beyond the boundary of the metering chamber. This configuration was previously known as a "guarded hot box."

3.2.6 *masked*—a hot box configuration which occurs when the metering chamber opening is the same or greater than the test specimen dimensions. This configuration must be used when the test specimen cannot be "self-masking." Here, the perimeter of the test specimen requires a separate mask, called a surround panel, constructed to eliminate lateral heat flow. Note that the hot box wall acts as a mask when the test specimen and the metering chamber dimensions are the same. The case where the hot box walls act as the mask was previously known as a "calibrated hot box."

3.2.7 *heat transfer*—the energy transfer that takes place between material bodies as a result of a temperature difference.

3.2.8 *metering box wall loss, Q_{mw}*—the time rate of heat exchange through the walls of the metering box.

3.2.8.1 *Discussion*—The metering box wall loss must be subtracted from, or added to, the heat input to the metering chamber as part of the determination of the net heat flow through the metered specimen. A more complete discussion of the Metering Box Wall Loss is provided in Annex A3.

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[6] Available from American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE), 1791 Tullie Circle, NE, Atlanta, GA 30329.

[7] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036.

3.2.9 *flanking loss, Q_{fl}*—the time rate of heat exchange from the metering chamber to the climatic chamber and or guard chamber that is due to the two-dimensional heat transfer at the interface of the test specimen and the surround panel or metering box wall.

3.2.9.1 *Discussion*—The flanking loss must also be subtracted from, or added to, the heat input to the metering chamber as part of the determination of the net heat flow through the metered specimen. A more complete discussion of the Flanking Loss is provided in Annex A4.

3.3 *Symbols*—The following are symbols, terms, and units used in this test method.

3.3.1 Some of these symbols can be modified for a particular application by the subscript attached.

A = metering box opening area, m^2
A_{eff} = effective area of the metering box wall, m^2
A_{in} = inside surface area of the metering chamber, m^2
A_s = effective area of the test specimen, m^2
C = surface to surface thermal conductance, $W/(m^2{\cdot}K)$
E = voltage output of heat flux transducer or thermocouple, V
$h_{c,env}$ = surface to environment heat transfer coefficient, cold side, $W/(m^2{\cdot}K)$
h_{conv} = convective surface heat transfer coefficient, $W/(m^2{\cdot}K)$
$h_{h,env}$ = surface to environment heat transfer coefficient, hot side, $W/(m^2{\cdot}K)$
h_{rad} = radiative surface heat transfer coefficient, $W/(m^2{\cdot}K)$
HC = equivalent heat capacity of an object, $(W{\cdot}h)/(kg{\cdot}K)$
L = length of the heat flow path (usually, the thickness of the test panel), m
m = the slope of the metering box thermopile equation, W/V
M = mass of an object, kg
q = time rate of heat flow through a unit area, W/m^2
Q = time rate of net heat flow through the metering box opening, W
Q_{cp} = time rate of heat flow through a known calibration panel, W
Q_{conv} = time rate of heat flow to a surface by convection, W
Q_{cool} = time rate of heat input to the metering chamber by the cooling coils, W
Q_f = time rate of heat input to the metering chamber by the fans, W
Q_{fl} = time rate of heat flow from the metering chamber to the climatic chamber, other than that through the metering box walls or metered specimen, W
Q_h = time rate of heat input to the metering chamber by the heaters, W
Q_{in} = the net time rate of heat flow into the metering chamber, equals the algebraic sum of the heat from the fans, heaters and cooling coils, W
Q_{mw} = time rate of heat flow from the metering chamber to the guard chamber through the metering box walls, W
Q_{rad} = time rate of heat flow to a surface by radiation, W
Q_s = time rate of heat flow through the metered specimen, W
Q_{sp} = time rate of heat flow through the surround panel, W
R = surface to surface thermal resistance, $m^2{\cdot}K/W$
$R_{c,env}$ = surface to environment thermal resistance, cold side, $(m^2{\cdot}K)/W$
$R_{h,env}$ = surface to environment thermal resistance, hot side, $(m^2{\cdot}K)/W$
R_s = surface to surface thermal resistance, $(m^2{\cdot}K)/W$
R_u = overall thermal resistance, $m^2{\cdot}K/W$
S = heat flux transducer calibration factor (a function of temperature), $W/(m^2{\cdot}V)$
t_a = volume averaged temperature of ambient air, K or °C
t_b = area weighted average temperature of the baffle surface, K or °C
t_c = volume averaged air temperature 75 mm or more from the cold side surface, K or °C
t_{env} = the effective environmental temperature including radiation, conduction, and convection effects, K or °C (see Annex A9)
t_h = space averaged air temperature 75 mm or more from the hot side surface, K or °C
t_m = average specimen temperature, average of two opposite surface temperatures, K or °C
t_1 = area weighted average temperature of specimen hot surface, K or °C
t_2 = area weighted average temperature of the specimen cold surface, K or °C
th = panel thickness at the location of the flanking loss path, m
Δt = temperature difference between two planes of interest, K or °C
$\Delta t_{a\text{-}a}$ = temperature difference—air to air, K or °C
$\Delta t_{s\text{-}env}$ = temperature difference—surface to the environment, K or °C
$\Delta t_{s\text{-}s}$ = temperature difference—surface to surface, K or °C
U = thermal transmittance, $W/(m^2{\cdot}K)$
λ = apparent thermal conductivity, $W/(m{\cdot}K)$
ε = total hemispherical surface emittance, (dimensionless)
σ = Stefan-Boltzmann Constant for Thermal Radiation, 5.673×10^{-8} $W/(m^2{\cdot}K^4)$
τ_{eff} = effective thermal time constant of the combined apparatus and specimen, s
Σe_i = total edge length on the inside walls of the metering chamber, m

3.3.2 *Subject Modifiers*:

1 = hot side surface
2 = cold side surface
a = ambient condition

a-a = air to air difference
ap = apparatus
b = baffle
c = cold
conv = convection
cool = cooling energy
eff = effective or equivalent property
env = environment
fl = flanking path
h = hot
i = index
in = inside
m = mean or average value
mw = metering box wall
o = null or zero condition
out = outside
rad = radiation
s = surface
sp = surround panel
s-a = surface to air difference
s-env = surface to the environment difference
s-s = surface to surface difference
t = test
u = overall

3.4 *Equations*—The following equations are listed here to simplify their use in the Calculations section of this test method.

3.4.1 *Overall Thermal Resistance, R_u*—The overall thermal resistance is equal to the sum of the resistances of the specimen and the two surface resistances. It is calculated as follows:

$$R_u = \frac{A \cdot (t_{env,h} - t_{env,c})}{Q} = R_c + R + R_h \tag{1}$$

3.4.2 *Thermal Transmittance, U*—(sometimes called overall coefficient of heat transfer). It is calculated as follows:

$$U = \frac{Q}{A \cdot (t_{env,h} - t_{env,c})} \tag{2}$$

$$I/U = (1/h_h) + (1/C) + (1/h_c) \tag{3}$$

NOTE 2—Thermal transmittance, U, and the corresponding overall thermal resistance, R_u, are reciprocals, that is, their product is unity.

3.4.3 *Thermal Resistance, R*:

$$R = \frac{A \cdot (t_1 - t_2)}{Q} \tag{4}$$

3.4.4 *Thermal Conductance, C*:

$$C = \frac{Q}{A \cdot (t_1 - t_2)} \tag{5}$$

NOTE 3—Thermal resistance, R, and the corresponding thermal conductance, C, are reciprocals; that is, their product is unity. These terms apply to specific bodies or constructions as used, either homogeneous or heterogeneous, between two specified isothermal surfaces.

3.4.5 *Surface Resistance, $R_{i,env}$*—The surface resistance is the resistance, at the surface, to heat flow to the environment caused by the combined effects of conduction, convection and radiation. The subscripts *h* and *c* are used to differentiate between hot side and cold side surface resistances respectively. Surface resistances are calculated as follows:

$$R_{h,env} = \frac{A \cdot (t_{env,h} - t_1)}{Q} \tag{6}$$

$$R_{c,env} = \frac{A \cdot (t_2 - t_{env,c})}{Q} \tag{7}$$

3.4.6 *Surface Heat Transfer Coefficient, $h_{i,env}$*—Often called surface conductance or film coefficient. The subscripts *h* and *c* are used to differentiate between hot side and cold side surface heat transfer coefficients respectively. The coefficients are calculated as follows:

$$h_{h,env} = \frac{Q}{A \cdot (t_{env,h} - t_1)} \tag{8}$$

$$h_{c,env} = \frac{Q}{A \cdot (t_2 - t_{env,c})} \tag{9}$$

NOTE 4—The surface heat transfer coefficient, $h_{i,env}$, and the corresponding surface resistance, $R_{i,env}$, (see 3.4.5) are reciprocals, that is, their product is unity.

3.4.7 *Surface Coefficient Determination*—An expanded discussion of the interactions between the radiation and convective heat transfer at the surfaces of the test specimen is included in Annex A9. The material presented in Annex A9 must be used to determine the magnitude of the environmental temperatures. These temperatures are required to correct for the radiation heat flow from the air curtain baffle.

3.4.8 Whenever the heat transfer is greatly different from one area to another or the surface area of one surface of the test specimen is significantly larger than the projected area, or the detailed temperatures profiles are unknown, only the net heat transfer through the specimen is meaningful. In these cases, only the calculation of the overall resistance, R_u, and transmission coefficient, U, are permitted.

3.4.9 *Apparent Thermal Conductivity of a Homogeneous Specimen*, λ:

$$\lambda = \frac{Q \cdot L}{A \cdot (t_1 - t_2)} \tag{10}$$

NOTE 5—Materials are considered homogeneous when the value of the thermal conductivity is not significantly affected by variations in the thickness or area of the specimen within the range of those variables normally used.

4. Summary of Test Method

4.1 This test method establishes the principles for the design of a hot box apparatus and the minimum requirements for the determination of the steady state thermal performance of building assemblies when exposed to controlled laboratory conditions. At the minimum, the hot box apparatus shall be able to measure the rate of heat flow through a building element of known area for known test conditions while limiting extraneous heat flows. The apparatus is required to establish and maintain a desired steady temperature difference across the test specimen for the period of time. The elapsed time required is that necessary to ensure constant heat flow and steady temperatures, and, for an additional period adequate to measure these quantities to the desired accuracy.

4.2 To determine the conductance, C, the transmittance, U, or the resistance, R, of any specimen, it is necessary to know the area, A, the net heat flow,Q and the temperature differences, Δt, all of which shall be determined under such conditions that the flow of heat is steady.

4.3 The area and temperatures are measured directly. The ent heat flow Q, however, cannot be directly measured. To determine the net heat flow through the metered specimen, a five-sided metering box is placed with its open side against one face of the metered specimen.

4.4 If there were no net heat exchange across the walls that of the metering box and the flanking loss around the metered specimen is negligible, then the heat input from the fan and heaters minus any cooling coil heat extraction from the metering box is a measure of the net heat flow through the metered specimen.

4.5 Since it is difficult to achieve the condition described in 4.4, the hot box apparatus must be designed to obtain an accurate measure of the net metered specimen heat flow. The net heat transfer through the metered specimen is determined from the net measured heat input to the metering chamber, corrected for the heat flow through the metering chamber walls and flanking loss for the specimen at the perimeter of the metering area. Where the metering chamber opening contains a building element smaller than the opening masked by a surround panel, the net heat transfer through the surround panel is subtracted from the metered specimen heat flow in order to determine the net heat flow through the building element.

4.6 The heat flow rate through the metering chamber walls is limited by the use of highly insulated walls, by control of the surrounding ambient temperature, or by use of a temperature-controlled guard chamber.

4.7 The portion of the building element or specimen frame outside the boundary of the metering area, exposed to the guarding space temperature, constitutes a passive guard to minimize flanking heat flow in the building element near the perimeter of the metering area (see Annex A2).

4.8 Both the metering chamber wall flow and the flanking loss corrections are based upon a series of characterization tests, using specimens of known thermal properties. These tests cover the range of anticipated performance levels and test conditions. While it is possible to estimate the magnitude of these corrections using numerical techniques and material properties of the components, the accuracy of those corrections must be verified by characterization measurements. (See Annex A2 through Annex A11 for details.)

5. Significance and Use

5.1 A need exists for accurate data on heat transfer through insulated structures at representative test conditions. The data are needed to judge compliance with specifications and regulations, for design guidance, for research evaluations of the effect of changes in materials or constructions, and for verification of, or use in, simulation models. Other ASTM standards such as Test Methods C177 and C518 provide data on homogeneous specimens bounded by temperature controlled flat impervious plates. The hot box test method is more suitable for providing such data for large building elements, usually of a built-up or composite nature, which are exposed to temperature-controlled air on both sides.

5.2 For the results to be representative of a building construction, only representative sections shall be tested. The test specimen shall duplicate the framing geometry, material composition and installation practice, and orientation of construction (see Section 7).

5.3 This test method does not establish test conditions, specimen configuration, or data acquisition details but leaves these choices to be made in a manner consistent with the specific application being considered. Data obtained by the use of this test method is representative of the specimen performance only for the conditions of the test. It is unlikely that the test conditions will exactly duplicate in-use conditions and the user of the test results must be cautioned of possible significant differences. For example, in some specimens, especially those containing empty cavities or cavities open to one surface, the overall resistance or transmittance will depend upon the temperature difference across the test specimen due to internal convection.

5.4 Detailed heat flow analysis shall precede the use of the hot box apparatus for large, complex structures. A structure that contains cavity spaces between adjacent surfaces, for example, an attic section including a ceiling with sloping roof, may be difficult to test properly. Consideration must be given to the effects of specimen size, natural air movement, ventilation effects, radiative effects, and baffles at the guard/meter interface when designing the test specimen.

5.5 For vertical specimens with air spaces that significantly affect thermal performance, the metering chamber dimension shall match the effective construction height. If this is not possible, horizontal convection barriers shall be installed inside the specimen air cavities at the metering chamber boundaries to prevent air exchange between the metering and guarding areas. The operator shall note in the report any use of convection barriers. The report shall contain a warning stating that the use of the barriers might modify the heat transfer through the system causing significant errors. For ceiling tests with low density insulations, the minimum lateral dimension of the specimen shall be at least several times the dimension of the expected convection cells.

5.6 Since this test method is used to determine the total heat flow 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 is independently determined. See Annex A8 for the general method.

5.7 Discussion of all special conditions used during the test shall be included in the test report (see Section 12).

6. Apparatus

6.1 *Introduction*—The design of a successful hot box apparatus is influenced by many factors. Before beginning the design of an apparatus meeting this standard, the designer shall review the discussion on the limitations and accuracy, Section 13, discussions of the energy flows in a hot box, Annex A2, the metering box wall loss flow, Annex A3, and flanking loss, Annex A4. This, hopefully, will provide the designer with an appreciation of the required technical design considerations.

6.2 *Definition of Location and Areas*—The major components of a hot box apparatus are *(1)* the metering chamber on one side of the specimen; *(2)* the climatic chamber on the other; *(3)* the specimen frame providing specimen support and perimeter insulation; and *(4)* the surrounding ambient space. These elements shall be designed as a system to provide the desired air temperature, air velocity, and radiation conditions for the test and to accurately measure the resulting net heat transfer. A diagram of the relative arrangement of those spaces is shown in Fig. 1.

6.2.1 The basic hot box apparatus has been assembled in a wide variation of sizes, orientations and designs. Two configurations have been historically used for a majority of the designs. The first is the self-masking hot box which has a controlled "guard" chamber surrounding the metering box. An example of this configuration is presented in Fig. 2.

6.2.2 The second configuration is the masked hot box. This configuration can also be considered as a special case of the guarded hot box in which the surrounding ambient is used as the guard chamber. An additional design consideration for the masked hot box design is that the metering chamber walls shall have sufficient thermal resistance to reduce the metering box wall loss to an acceptable level. The masked design is generally used for testing of large specimens. Fig. 3 shows an example of a masked apparatus for horizontal heat transfer.

NOTE 6—The two opposing chambers or boxes are identified as the metering chamber and the climatic chamber. In the usual arrangement, the temperature of the metering chamber is greater than that of the climatic chamber and the common designations of "hot side" and "cold side" apply. In some apparatus, either direction of heat flow may apply.

6.3 *Apparatus Size*—The overall apparatus shall be sized to match the type of specimens anticipated for testing (see 7.2). For building assemblies, it shall accommodate representative sections. Generally, the maximum accuracy is obtained when the specimen size matches that of the metering chamber while the climatic chamber also matches or is larger.

NOTE 7—A large apparatus is desirable in order to minimize perimeter effects in relation to the metered area, but a large apparatus may also exhibit longer equilibrium times, thus, a practical compromise must be reached. Typical heights for wall hot boxes are 2.5 to 3 m with widths equal to or exceeding the height. Floor/ceiling hot boxes up to 4 by 6 m have been built.

6.4 *Construction Materials*—Materials used in the construction of the hot box apparatus shall have a high thermal resistivity, low heat capacity and high air flow resistance. Polystyrene or other closed cell foam materials have been used since they combine both high thermal resistivity, good mechanical properties, and ease of fabrication. One potential problem with some foam is that they exhibit time dependent thermal properties that would adversely affect the thermal stability of the apparatus. Problems associated with the use of these materials are avoided by using materials that are initially aged prior to assembly, or by periodic chamber verification, or by using impermeable faced foam materials with sealed edges to greatly minimize the aging effects.

6.5 *Metering Chamber*:

6.5.1 The minimum size of the metering box is governed by the metering area required to obtain a representative test area for the specimen (see 7.2) and for maintenance of reasonable test accuracy. For example, for specimens incorporating air spaces or stud spaces, the metering area shall span an integral number of spaces (see 5.5). The depth of the metering box shall be no greater than that required to accommodate the air curtain, radiation baffle and the equipment required to condition and circulate the air. Measurement errors in testing with a hot box apparatus are, in part, proportional to the length of the perimeter of the metering area and inverse to metering area. The relative influence of the perimeter length diminishes as metering area is increased. Experience on testing homogeneous materials, has demonstrated that for the "guarded," self-masking hot box configuration, the minimum size of the metering area is 3 times the square of the metered specimen thickness or 1 m^2, whichever is larger (**18**). From the same experience base, for the "calibrated," masked box configuration, a minimum metering area size is 1.5 m^2. For non-homogeneous specimens, the size requirements are more significant.

6.5.2 The purpose of the metering chamber is to provide for the control and measurement of air temperatures and surface coefficients at the face of the specimen under prescribed conditions and for the measurement of the net heat transfer through specimen. The usual arrangement is a five-sided

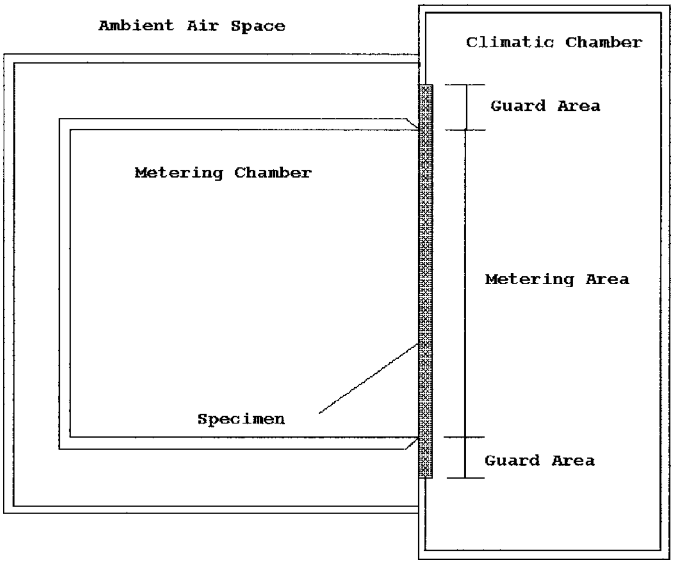

FIG. 1 Typical Hot Box Apparatus Schematic—Definition of Locations and Areas

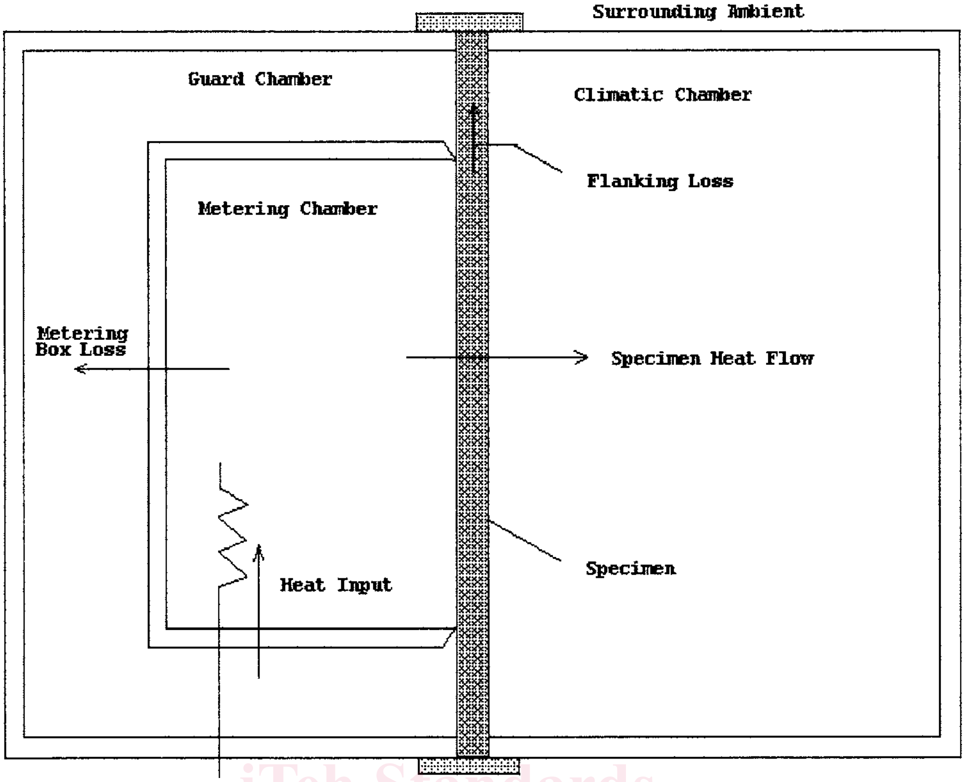

FIG. 2 Typical Guarded Hot Box Schematic

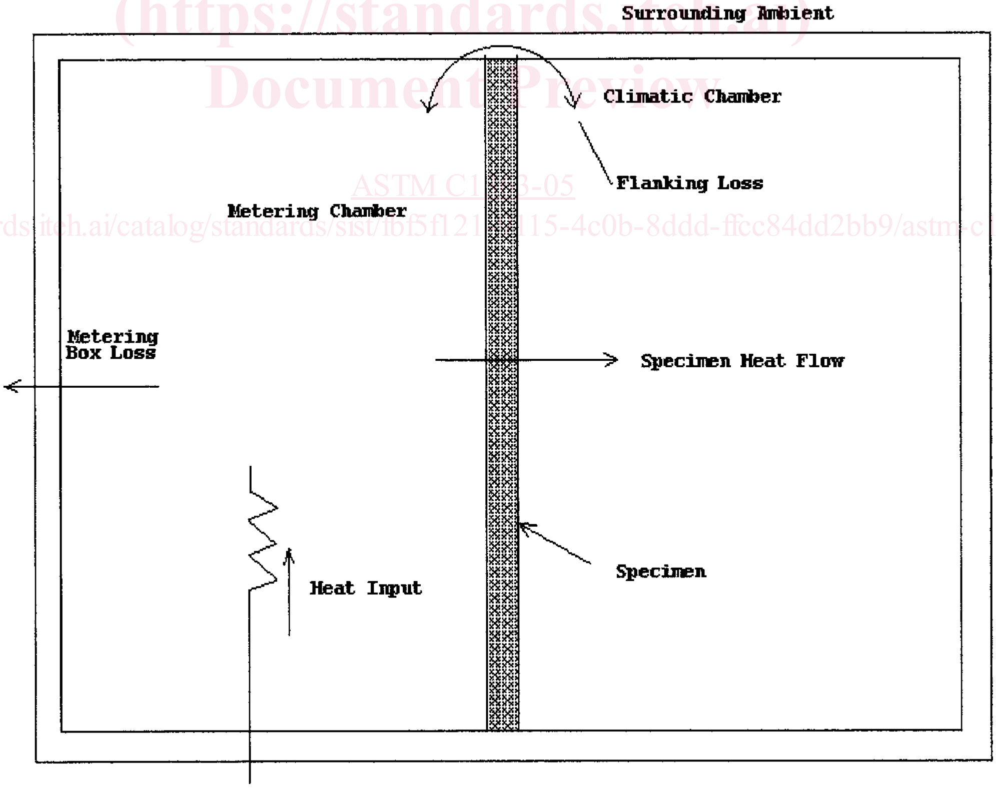

FIG. 3 Typical Calibrated Hot Box Apparatus

chamber containing airflow baffles, electrical heaters, cooling coils (if desired), and an air circulation system. At steady state conditions, the heat transfer through the specimen equals the electrical power to the heaters and blowers minus the cooling energy extraction, corrected for the heat passing through the chamber walls and flanking the specimen. Both the metering box wall loss and flanking loss are determined from characterization measurements (see Section 8 and Annex A2-Annex A9).

6.5.3 To minimize measurement errors, several requirements are placed upon the metering chamber walls and the adjoining ambient space:

6.5.3.1 The metering chamber heat flow corrections, which are estimated for design purpose using the equations of Annex A2-Annex A4, must be kept small, by making the metering box wall area small, keeping its thermal resistance high or by minimizing the temperature difference across the wall (see Note 8).

6.5.3.2 With proper design, the metering box wall loss are controlled to be as low as 1 or 2 % of the heat transfer through the specimen. The metering box wall loss shall never be greater than 10 % of the specimen heat transfer. In any case, the minimum thermal resistance of the metering chamber walls shall be greater than 0.83 m^2K/W.

NOTE 8—The 10 % limit is based upon design analysis of existing hot boxes. The choice of construction of the metering chamber can only be made after review of the expected test conditions in which metering box wall loss and associated uncertainties are considered in relation to the anticipated energy transfer through the metered specimen and its desired maximum uncertainty. The influence of the guarding temperature upon the ability to maintain steady temperatures within the metering chamber must also be considered in choosing between highly insulated walls and a tightly controlled guard space conditioning.

6.5.3.3 However large the metering box wall loss is, the uncertainty of the resulting metering box wall loss correction to the net heat flow shall not exceed 0.5 % of the net heat flow through the specimen. In some designs, it has been necessary to use a partial guard to reduce the metering chamber box wall loss.

6.5.3.4 For best results, the heat transfer through the metering chamber walls shall be uniform so that a limited number of heat flux transducers or differential thermocouples can be used to characterize the heat flow from each representative area. This goal is best approximated by the use of a monolithic, uniform insulation uninterrupted by highly conducting structural members, and by eliminating any localized hot or cold sources from the adjoining space. No highly conductive structural members shall be within the insulation. Thermal bridges, structural cracks, insulation voids, air leaks and localized hot or cold spots from the conditioning equipment inside the metering chamber walls shall be avoided.

NOTE 9—One method of constructing satisfactory chamber walls is by gluing together large blocks of an aged, uniform low thermal conductivity cellular plastic insulation such as extruded polystyrene foam. A thin covering of reinforced plastic or coated plywood is recommended to provide durability, moisture and air infiltration control. In addition to using a high thermal resistance, the designer must also recognize that wall heat storage capacity is also a governing factor in hot box wall design.

6.5.3.5 To ensure uniform radiant heat transfer exposure of the specimen, all surfaces which exchange radiation with the specimen shall have a total hemispherical emittance greater than 0.8.

6.5.3.6 In applications where the metering chamber contacts the specimen, an airtight seal between the specimen and metering wall shall be provided. The cross section of the contact surface of the metering chamber with the specimen shall be narrowed to the minimum width necessary to hold the seal. A maximum width of 13 mm, measured parallel to the specimen surface plane, shall be used as a guide for design. Periodic inspection of the sealing system is recommended in order to confirm its ability to provide a tight seal under test conditions.

6.5.4 Since one basic principle of the test method is to measure the heat flow through the metering box walls, adequate controls and temperature-monitoring capabilities are essential. Small temperature gradients through the walls 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 specimen, these small temperature gradients through the walls cause substantial heat flows totaling a significant fraction of the heat input to the metering box. For this reason, the metering box walls shall be instrumented to serve as a heat flow transducer so that heat flow through them can be minimized and measured. A correction for metering chamber wall loss shall be applied in calculating test results. The use of one of the following methods is required for monitoring metering box wall loss.

NOTE 10—The choice of transducer types and mounting methods used to measure the heat flow through the metering chamber walls is guided by the hot box design. However, they must provide adequate coverage and output signal to quantify the metering box wall loss during testing (see 6.5.3.3).

6.5.4.1 The walls may be used as heat flow transducers by application of a large number of differential thermocouples connected between the inside and outside surfaces of the metering chamber walls. Care must be taken 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 climatic chamber air velocities and temperatures. Care must also be taken when determining the number of differential thermocouples. Based upon a survey of hot box operators (**18**), a minimum of five differential thermocouple pairs per m^2 of metering box wall area shall be used. The thermocouple junctions shall be located directly opposite each other and, preferably, located at the centers of approximately equal areas. Small pieces of foil, having surface emittance matching the remainder of the box walls, may be attached to the thermocouples to facilitate the thermal contact with the wall surface. The junctions and the attached thermocouple wires shall be flush with, and in thermal contact with, the surface of the wall for at least a 100 mm distance from the junctions. The thermocouple pairs are connected in series to form a thermopile in which the individual voltages are summed to give a single output or read out individually in cases where significant differences may occur or be expected in the local heat flow levels.

6.5.4.2 As an alternative, separate heat flux transducers are placed on the metering chamber walls. Care must be taken in choosing and installing the transducers to ensure that the thermal resistance of the wall and its surface emittance remain essentially unchanged. The transducers shall be initially calibrated separately to ensure that the relative sensitivities are approximately the same. Since the transducer sensitivity is also temperature sensitive, temperature sensors shall be installed at the same or adjacent location. The outputs from these transducers are measured separately or as a group. If measured separately, the transducers shall be detachable from the surface so their calibrations, at energy flux levels typical of use, may be checked periodically (see Practice C1130). If the measurement procedure is to calibrate the chamber with the heat flux transducers in place, the transducer outputs shall be connected in series to provide a single reading. The designer must recognize that the calibration factors for the heat flux transducer will be different due to shunting effects when calibrated in-situ versus calibrated alone.

6.5.4.3 Regardless of the method of hot box metering wall instrumentation used, the metering box wall heat flow shall be correlated with the signal outputs during the characterization process. See Section 8 and Annex A5 and Annex A6 for this process.

6.6 *Climatic Chamber*:

6.6.1 The purpose of the climatic chamber is to provide controlled conditions on the side of the specimen opposite the metering chamber. The test conditions specified are generally those associated with standardized or normal outdoor conditions. The instrumentation shall be capable of the control and measurement of the air temperature and velocity and surrounding surface temperatures in order to maintain the desired surface heat transfer coefficient. In the usual arrangement, it consists of a five-sided insulated chamber with internal dimensions matching or greater than the metering chamber opening and with sufficient depth to contain the required cooling, heating and air circulation equipment. An acceptable alternate is to utilize a large environmental chamber with an opening matching the metering chamber opening size. This arrangement is especially suited for a floor/ceiling test apparatus in which large roof/attic structures are to be tested.

6.6.2 The walls of the climatic chamber shall be well insulated to reduce the refrigeration capacity required and to prevent the formation of condensation on the outside of the chamber walls.

6.6.3 Heaters, fans and cooling coils shall be shielded or placed behind an air baffle to maintain the uniformity of the surface temperatures radiating to the surface of the specimen. The internal surfaces of the climatic chamber shall also meet the criteria of 6.5.3.4 for surface emittance.

6.7 *Specimen Frame*:

6.7.1 A specimen frame shall be provided to support and position the specimen and to provide the needed perimeter insulation. The frame opening shall have dimensions at least of those of the metering chamber opening. In the direction of heat flow, the frame shall be at least as thick as the thickest specimen to be tested. In the outward direction perpendicular to the normal energy flow direction, the wall thickness of the specimen frame shall be at least equal to that of the metering chamber walls or 100 mm, whichever is greater.

6.7.2 Care must be taken in the design and construction of specimen frames so that flanking losses are minimized. Conductive plates, fasteners or structural members shall not be used in the flanking paths. The thickness and conductance of skins shall be limited to minimize the flanking loss potential.

6.8 *Air Circulation*:

6.8.1 The measured overall resistance, R_u, and, when applicable, the surface resistances, R_h or R_c, depend in part upon the velocity, temperature uniformity, and distribution patterns of the air circulated past the specimen surfaces.

6.8.2 Air temperature differences of several degrees exist from air curtain entrance to exit due to heating or cooling of the air curtain as it passes over the specimen surface. The magnitude of this difference is a function of the heat flow through the specimen and the velocity and volume of the air flow. When natural convection is desired, the temperature differences will be larger. A forced air flow reduces the magnitude of this difference. Specific airflow conditions are established by the specification requirements for the material being tested. The paragraphs below describe some specific details required for maintenance of an acceptable air circulation within the hot box.

6.8.3 Test specifications sometimes require that near natural convection conditions be used in a wall test apparatus or in a floor/ceiling test apparatus. When required, these tests shall be run using forced convection at near natural convection conditions. However, the air velocity shall be below 0.5 m/s if natural convective air conditions are to be approximated with some forced airflow to maintain temperature control.

6.8.4 The design of the air circulation system will have an impact on the entrance to exit air temperature difference. Tradeoffs during design must be made between the desired uniformity of the air curtain temperatures and the operational mode of convective flow. A velocity of approximately 0.3 m/s has proven satisfactory for a wall test apparatus of 3 m height when testing wall systems.

6.8.5 When more uniform air temperatures are desired, it is necessary to provide curtains of forced air moving past the specimen surfaces. For test purposes, the curtain air velocities shall be measured 75 mm away from the surface at the center of the specimen in the direction of airflow as specified in 6.8.11.3.

6.8.6 For uniform test results, the maximum point to point air temperature variation across the test panel, perpendicular to the air flow direction at the center of the test panels, shall be less than 2 % of the overall air to air temperature difference, or 2 K, whichever is greater.

6.8.7 The direction of airflow in a hot box apparatus is determined by the test design and may be parallel, that is, up, down, or horizontal, or perpendicular to surface. However, less fan power is required to maintain air movement in the direction of natural convection (down on the hot side, up on the cold) and that direction is recommended. In some situations the test specification requires a specific direction to evaluate the system performance.

6.8.8 Air velocities greater than 1m/s are permissible when their effect upon heat transfer is to be determined. Velocities commonly used to simulate parallel or perpendicular wind conditions on the exterior side are 2.75 m/s for summer conditions and 5.5 m/s for winter conditions.

NOTE 11—Distinction is made between the effects and requirements of air velocity parallel to the specimen surface and those for velocity perpendicular to it. Parallel velocities simulate the effect of the cross winds, and may be achieved by moving a small amount of air confined in a narrow baffle space and therefore require relatively little blower power. Perpendicular velocities, simulating direct wind impingement, require moving larger amounts of air with corresponding larger power requirements. The baffles in the second case must be placed further from the specimen surface and should have a porous section (a set of screens or a honeycomb air straightener) that directs the air stream to the specimen surface. Fig. 4 shows an example of climatic chamber arrangement for perpendicular flow.

6.8.9 *Air Baffles*—For parallel flow, a baffle, parallel to the specimen surface, shall be used to confine the air to a uniform channel, thus aiding in maintaining an air curtain with uniform velocities.

6.8.9.1 The baffle thermal resistance shall be adequate to shield the specimen surface from radiative heat exchange with any energy sources located behind it. A baffle thermal resistance of 1 (m^2 K /W) is recommended for this purpose. Other baffle designs that maintain temperature uniformity of the baffle surface seen by the test specimen are acceptable.

6.8.9.2 An adjustable baffle-to-specimen spacing is one means of adjusting the airflow velocity. For purpose of maintaining a well-mixed and characterized air curtain, a spacing of 140 to 200 mm is recommended.

6.8.9.3 A baffle also serves as a radiation exchange surface with a uniform temperature only slightly different than that of the air curtain. The baffle surface facing the specimen shall have an emittance greater than 0.8.

6.8.10 *Air Velocity Uniformity*—Uniform air flow profile across the specimen width, perpendicular to the air flow direction, is achieved by use of multiple fans or blowers or by use of an inlet distribution header across one edge of the baffle and an outlet slot across the opposite. The inlet header shall incorporate adjustable slots or louvers to aid in obtaining uniform distribution.

6.8.10.1 After construction of an air circulation system, the air velocity profile shall be measured across the area perpendicular to the direction of airflow in the proximity of the specimen. The test shall be conducted with a flat, homogeneous panel in place so that the surface of the test panel has minimum effect on the velocity profile. The air velocity profile shall be defined as uniform if all measurements from the profile scan are within 10 % of the mean of all measurements. For parallel air curtains, the air flow measurements shall be made at 0.3 m intervals across the specimen face, perpendicular to the air flow direction, at the centerline of the metering chamber. For air flow perpendicular to the specimen face, the air flow measurements shall be made in the radial direction at a density of one per every 30 degrees around the outlet of the diffuser at a distance from the center of the metering area equal to the outlet diameter of the air supply diffuser. If the profile is not uniform, additional adjustments shall be made to the inlet header slot or louvers or in the placement of fans or blowers to achieve an air curtain with uniform velocity across the face of the specimen. The velocity profiles shall be verified, whenever modification or repairs of the distribution system are made that might cause a change in flow patterns. Also, the profiles shall be verified during characterization checks.

NOTE 12—Linear air diffusers designed for ceiling air distribution systems have been found satisfactory to use as distribution headers. For large floor/ceiling testers it may be necessary to use more than one set of fans or inlet and outlet headers creating opposing zones to obtain the required temperature uniformity. Tangential fans have also been found to provide uniform temperatures.

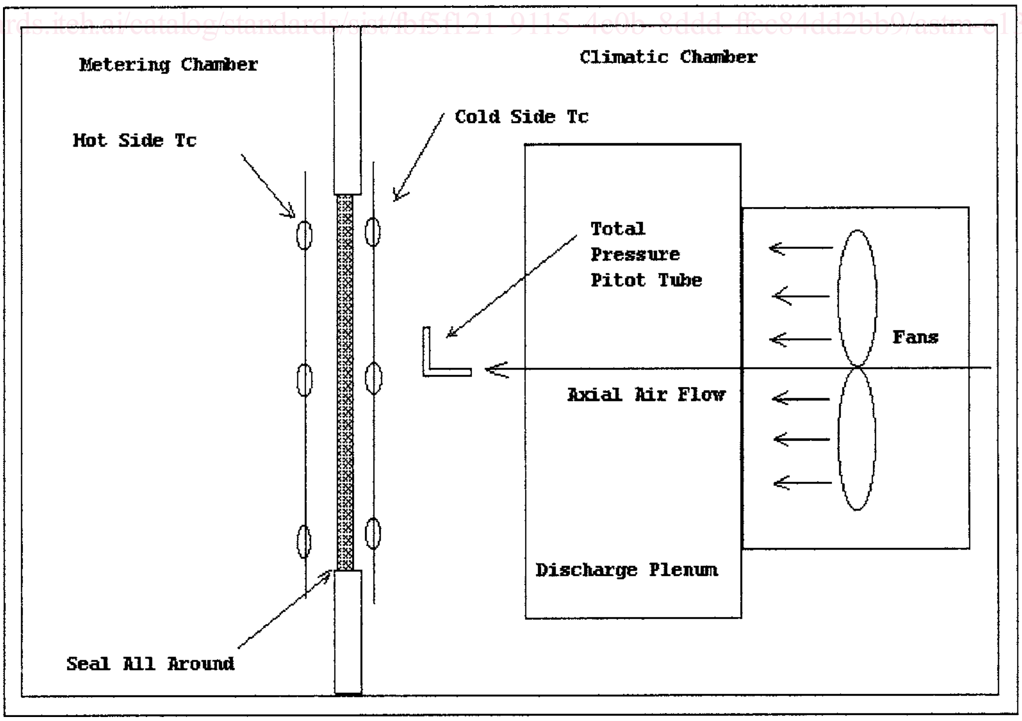

FIG. 4 Hot Box Arrangement for Perpendicular Air Flow

6.8.11 *Air Velocity Measurement*—The apparatus design shall provide a means for determining mean air velocity past both the hot and cold faces of the specimen during each test. Acceptable methods are as follows:

6.8.11.1 One method is to measure the volumetric airflow in the duct to the inlet distribution header by using a calibrated orifice or other flow-measuring device. The average baffle space velocity is then calculated from the volume flow and the size of the space between the specimen and the parallel baffle. The baffle must be well sealed for this technique to work.

6.8.11.2 Another method is to calculate the velocity from an energy balance. The rate of loss, or gain, of heat by the air as it moves through the baffle space, as indicated by its temperature change, will match the rate of heat transfer through the metering chamber opening, average values of which can be determined from the test data.

6.8.11.3 The best method is to locate velocity sensors directly in the air curtain. For test purpose, wind velocity shall be measured at a fixed location that represents the average free stream condition. For both perpendicular and parallel flow patterns, this location shall be a distance out in the air stream such that the wind speed sensor is not in the test specimen surface boundary layers or wakes. A distance of 75 to 150 mm out from the test specimen surface at the center point is typically used. On the room side, where low circulation velocities are generally used, a properly located sensor is also required. The operator's experience and knowledge of the air distribution system obtained in the profiles from 6.8.10 shall be used to determine the optimum sensor location.

6.9 *Air Temperature Control*:

6.9.1 The temperature of the air entering the air curtains shall be within ± 1 K of the setpoint temperature across its width and, for steady-state tests, shall not change during the measurement period.

6.9.2 One method of providing controlled, heated air is to install open wire, low thermal mass electrical heaters in an insulated, low emittance section of the blower duct or other part of the air circulation system and to control these heaters using a sensor located at the inlet to the air curtain.

NOTE 13—Another method of heater control is to use several individual heaters that are switched on to provide fixed levels of energy. Fine-tuning is provided by an additional heater modulated by a controller. Another satisfactory method is to use a controller that varies the power to all the heaters.

6.9.3 Methods for cooling the climatic chamber include the installation of a refrigeration system evaporator inside the chamber, ducting in chilled air from an external source or injecting liquid nitrogen. Usually the evaporator or external chilled air is controlled at a constant temperature a few degrees (typically < 5°C) below the desired setpoint. Then, a reheat and control system, similar to that for obtaining heated air (see 6.9.2) is used to achieve fine control of the temperature at the inlet to the specimen air curtain. When liquid nitrogen is used a valve regulating its flow is pulsed or modulated to obtain fine temperature control.

NOTE 14—One proven configuration for a climatic chamber utilizes two air circuits created by suitable baffles. The evaporator fan creates one circulation path that includes a mixing chamber from which air is circulated by a separate blower to the specimen air curtain and returned. An air reheat and control system provides fine control of air temperature at the distribution header inlet. Other proven configurations utilize only a single air circuit containing both cooling and reheat elements. Under certain conditions, a desiccant may be needed to remove moisture from the air stream.

6.9.4 Metering chamber blowers shall be small and efficient since, without cooling, they determine the least possible net energy input to the metering chamber. If large fans or blowers are necessary, then compensatory cooling with inherent loss in accuracy shall be used. Some heat is removed by locating the blower motor outside of the metering chamber and accurately measuring the heat equivalent of the shaft power. Precautions shall be taken to prevent air leakage around the shaft.

6.9.5 When cooling of the metering chamber is required, it must be done in a manner in which the amount of heat extracted can be measured accurately. One method is to circulate a chilled liquid through a heat exchanger located in the metering chamber air circuit. The rate of heat extraction is controlled by the inlet to chamber air temperature difference, the airflow rate, the liquid properties, and the heat exchanger efficiency. The amount of cooling used shall be limited to that necessary to overcome any excess blower or other heating loads since test accuracy will be lost if excessive heating must be used to compensate for large cooling. For example, assume that the heater input was 400 Btu/h out of an overall heater capacity of 2000 Btu/h and is known to within 1 % of capacity or ± 20 Btu/h. Also assume a concurrent cooling load of 320 Btu/h out of an overall cooling capacity of 1600 Btu/h which is known to within 1 % of capacity or ± 16 Btu/h. Since these loads oppose each other, the net load is 80 Btu/h but the uncertainty of the net could be as large as ± 36 Btu/h or 45 % of the net load. For this reason, care must be observed in obtaining the correct test setup.

6.9.6 *Special Considerations, Humidity Control*—Moisture migration, condensation, and freezing within the specimen can also cause variations in heat flow. To avoid this, the warm side relative humidity shall be kept below 15 %.

6.10 *Temperature Measurement*:

6.10.1 When surface temperatures are required, specimen surface temperature sensors shall typically be located opposite each other on the two faces of the specimen. However, when placement opposite each other is not possible, the sensors shall be placed to represent the correct area weighting for each surface. These sensors shall be chosen and applied to the surface in a manner such that the indicated temperature is within ± 0.2 K of the temperature that would exist if the sensor had not been applied. This requirement is met by thermocouples if: *(1)* the wire is no larger in diameter than 0.25 mm (No. 30 AWG.); *(2)* the wire meets, or is calibrated to, the special limits of error as specified in the Tables E230; *(3)* the junctions, not larger than two times the wire diameter, are twisted and welded or soldered; *(4)* 100 mm of adjoining wire are taped, cemented or otherwise held in thermal contact with the surface using materials of emittance close (± 0.05) to that of the surface; and *(5)* they are electrically insulated, or otherwise protected, so that the electrical junction is at the location of the thermocouple bead. Application of alternate