# 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1—This test method replaces Test Methods C236, the Guarded Hot Box, and C976, the Calibrated Hot Box which have been withdrawn.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

[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
C1130 Practice for Calibrating Thin Heat Flux Transducers
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
C1371 Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers
C1373 Practice for Determination of Thermal Resistance of Attic Insulation Systems Under Simulated Winter Conditions
E230 Specification and Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples
E903 Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres[5]
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.

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.

[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.

3.2.9.1 *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
$\Delta t$ = temperature difference between two planes of interest, K or °C
$\Delta t_{a-a}$ = temperature difference—air to air, K or °C
$\Delta t_{s-env}$ = temperature difference—surface to the environment, K or °C
$\Delta t_{s-s}$ = temperature difference—surface to surface, K or °C
$U$ = thermal transmittance, $W/(m^2 \cdot K)$
$\lambda$ = apparent thermal conductivity, $W/(m \cdot K)$
$\varepsilon$ = total hemispherical surface emittance, (dimensionless)
$\sigma$ = Stefan-Boltzmann Constant for Thermal Radiation, $5.673 \times 10^{-8}\ W/(m^2 \cdot K^4)$
$\tau_{eff}$ = effective thermal time constant of the combined apparatus and specimen, s
$\Sigma e_i$ = 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:

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

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

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

$$1/U = (1/h_h) + (1/C) + (1/h_c) \quad (3)$$

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*:

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

3.4.4 *Thermal Conductance, C*:

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

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:

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

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

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:

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

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

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:

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

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, $\Delta t$, 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.

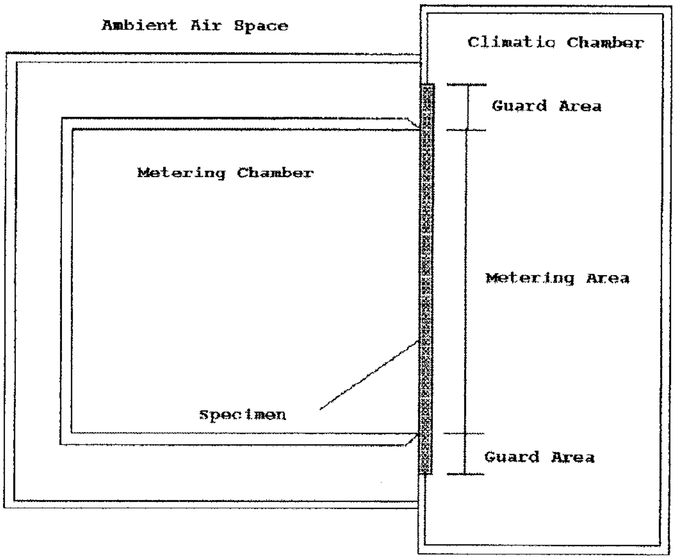


FIG. 1 Typical Hot Box Apparatus Schematic—Definition of Locations and Areas

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.

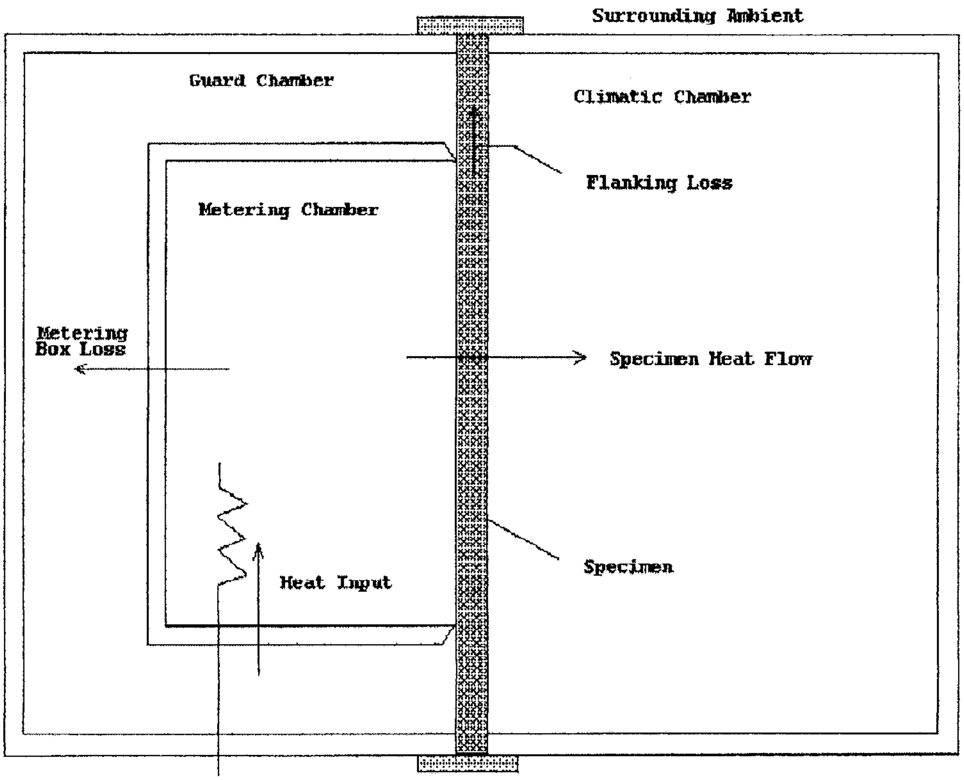


FIG. 2 Typical Guarded Hot Box Schematic

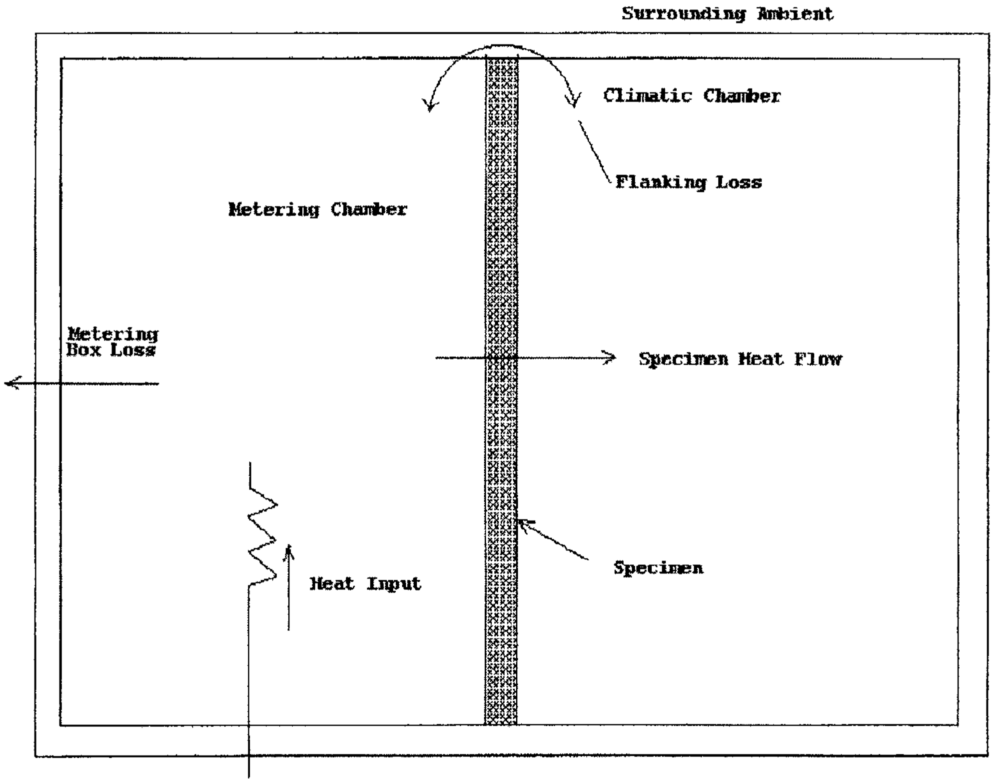


FIG. 3 Typical Calibrated Hot Box Apparatus

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 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. Test Methods C1371 and E903 are acceptable methods to measure emittance. Typically, a flat paint will meet this requirement.

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

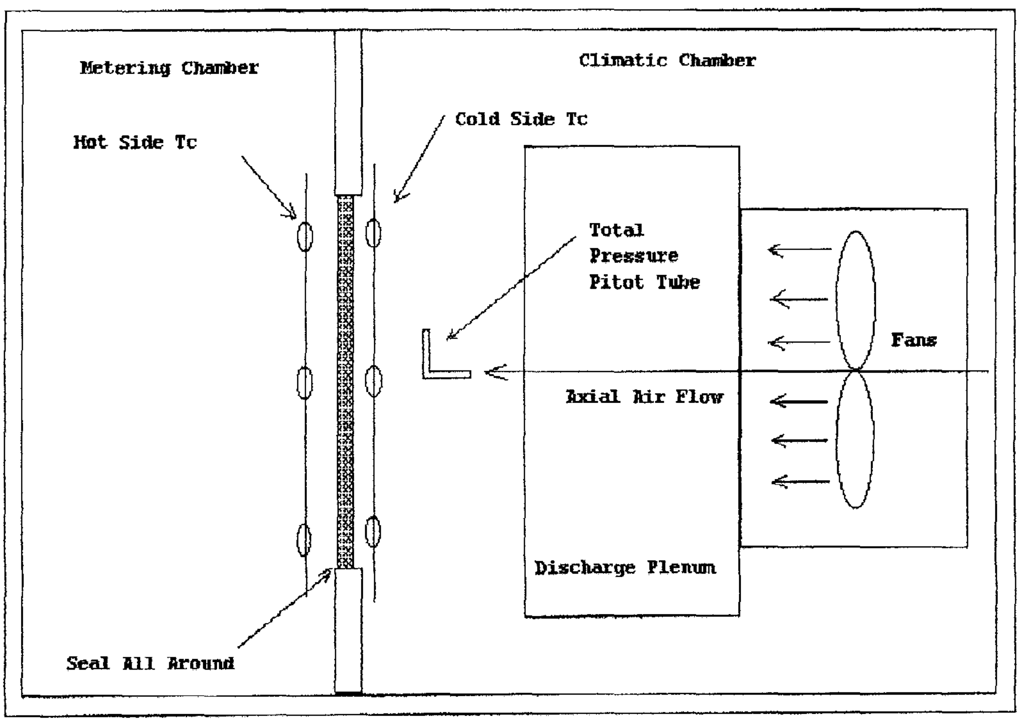


FIG. 4 Hot Box Arrangement for Perpendicular Air Flow

required temperature uniformity. Tangential fans have also been found to provide uniform temperatures.

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 % or the laboratory shall verify that the dew point temperature of the metering side air is 2 °C less than the minimum metering side surface temperature of the specimen.

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 temperature sensor systems may be used if comparative measurements or calculations show that the basic requirements are met.

NOTE 15—Metal foil tape, which has been painted to make the emittance greater than to 0.80, is an effective means to attach thermocouple sensors to most high emittance test specimens.

6.10.2 If the specimen construction, and therefore its thermal resistance, is uniform over its entire area, then a minimum number of sensors, spaced uniformly and symmetrically over the surface, are sufficient. The required minimum number of sensors per side shall be at least two per square meter of metering area but not less than nine **(24)**.

6.10.2.1 If each element of the specimen construction is relatively uniform in thermal resistance and is repeated several times over the entire surface, the number of sensors specified in 6.10.2 may still be sufficient. In this case, the sensors shall be located to obtain the average surface temperature over each type of construction element and, for each type of element, shall be distributed approximately uniformly and symmetrically over the specimen area. The average surface temperature of the specimen shall be calculated by area weighting of the averages for the different types of construction elements.

6.10.2.2 If the surface temperatures are expected to be, or found to be, greatly non-uniform, additional sensors shall be required. Often a great number, such as three or more times the normal amount as determined by trial and error, is required to adequately sample the different temperature areas so that a reliable area weighted mean surface temperature may be obtained. Some research has been published on the subject of testing highly conductive member that might be used as guidance for this determination. For example, see the work on steel framed buildings **(29)**.

6.10.2.3 If an accurate determination of the average surface temperatures cannot be obtained, the hot box apparatus can accurately measure only the thermal transmittance, $U$, or the overall thermal resistance, $R_u$. The average panel resistance, $R$, of the specimen can be estimated by subtracting off the previously determined surface film thermal resistances established using a transfer standard of equal thermal resistance, size, surface configuration and roughness. Note that the geometry, average temperatures, and energy exchange conditions must be similar for the calibration transfer standard (CTS) and test panel for this technique to have reasonable accuracy. (See Test Method C1199 for discussion on CTS design.)

NOTE 16—Tests on specimens containing thermal bridges require special care because of the possible great differences in thermal resistance and temperatures between the thermal bridge areas and those of surrounding insulated structures. Added complications arise when tests are run at higher air velocities since temperatures and energy transfer can depend significantly upon bridge geometry relative to the overall sample as well as the velocity and direction of air movement. If test results are to be comparable for competing systems, they must be run under similar conditions. This method does not attempt to standardize such conditions.

6.10.3 The temperature of the air on each side of the specimen shall be measured by thermocouples, temperature sensitive resistance wires, or similar temperature sensors.

6.10.3.1 The minimum number and locations of sensors used to measure air temperatures shall be that specified for surface temperature sensors in 6.10.2. These sensors must be radiation shielded or otherwise protected to provide an accurate indication of the temperature of the air curtain. Sensors shall be small to ensure fast response to changing temperatures. Resistance wires, if used, shall be distributed uniformly in the air curtain.

NOTE 17—One suitable radiation shield is made by using 12 mm diameter, 75 mm long pieces of thin walled plastic tubing covered on the outside with aluminum foil tape. The air thermocouple is placed at the center of the tube to measure the air stream temperature and yet be shielded from radiation sources.

6.10.3.2 The best location for temperature sensors depends upon the type of air curtain convection (natural or forced). In natural convection situations, it is usually possible to identify the temperature of still air outside the boundary layer. Consequently, when natural convection is established, air temperature sensors shall be located in a plane parallel to the specimen surface and spaced far enough away from it that they are unaffected by temperature gradients of the boundary layer. For minimum velocities required to attain temperature uniformities (see 6.8 and Note 12), the minimum spacing from the specimen surface is 75 mm. At velocities greater than 1 m/s, the required minimum spacing is greater. The boundary layer thickness increases sharply at the transition from laminar to turbulent flow. With fully developed turbulent flow, the boundary layer occupies the full space between the specimen and the baffle. When forced convection is established and the flow is fully developed, the sensors shall be located at a distance from the specimen surface corresponding to ⅔ up to ¾ of the specimen-to-baffle distance. This is to detect a temperature approaching the airflow bulk temperature.

6.10.3.3 Thermocouple sensors used for measurement of air temperatures shall meet the requirements of Items *(1)*, *(2)*, *(3)*, and *(5)* in 6.10.1. Other sensors are acceptable if they have similar time response and are calibrated so that the measurements are accurate within ± 0.5 K.

6.10.4 The surface temperature of the baffles in the metering and climatic chambers, where required, shall be measured by placing sensors on all surfaces seen by the specimen. A minimum area density of three sensors per square meter of baffle area, but not less than one sensor per baffle surface, is required. These data *(1)* can be used to determine any difference between the baffle surface and air curtain temperatures; *(2)* permits corrections to be made to the radiation component of the surface film conductance due to differences in these temperatures; and *(3)* is a necessary component of the data analysis for specimens such as windows which have a high thermal conductance. (See the discussion on the environmental temperature determination in Annex A9.)

6.11 *Specimen Pressure Difference*:

6.11.1 For some tests, it is necessary to establish and measure the air pressure differential between the faces of the test specimen. This is especially important for window and other samples where the airflow resistance between the specimen surfaces is low. The specimen pressure difference is defined as the difference in the local static pressure, on either side of the specimen, measured at a location at the geographic center of the metered area, at a distance 75 mm from the surfaces of the sample.

6.12 *Instruments*:

6.12.1 All signal conditioning and data logging instruments shall be located outside of the apparatus. All instruments shall be calibrated to the specified accuracy, traceable to a national standards laboratory, and shall meet the following additional requirements:

6.12.1.1 All instrumentation shall have adequate sensor response so that the scanning speed does not adversely effect the measurement results.

6.12.1.2 Temperatures shall be readable to ± 0.05 K and be accurate within ± 0.5 K.

6.12.1.3 Heat flux transducer outputs shall be measured to the precision required to limit the error in estimation of the metering box wall loss to less than ± 0.5 % of the specimen energy transfer. This requires a heat flux transducer calibration accuracy of 5 percent or better.

6.12.1.4 Many methods of air velocity measurement are possible depending on the specific box design and test conditions. However, an accuracy of ± 5 % of the reading is required. A sensor whose signal can be processed by automatic data acquisition equipment is recommended.

6.12.1.5 Pressure difference measurements shall be accurate to within ± 5 % of reading or ± 1 Pa, whichever is greater.

6.12.1.6 Total average power (or integrated energy over a specified time period) to the metering box shall be accurate to within ± 0.5 % of reading under conditions of use. Power measuring instruments shall be compatible with the power supplied whether ac, dc, on off, proportioning, etc. Voltage stabilized power supplies are strongly recommended. Metered cooling instruments shall be calibrated together as a system to similar accuracy.

6.12.1.7 Temperature controllers for steady-state tests shall be capable of controlling temperatures constant to within ± 0.25 K (see 6.9).

## 7. Sampling and Test Specimens

7.1 Building elements shall be representative of typical field assemblies. As such, the metered specimen is usually a portion of a building assembly that has been selected for test due to the expectation that it will exhibit the same thermal behavior as the larger building element that it represents. Tests on apparatus requiring smaller than representative specimens shall be avoided. The construction details of the building elements to be investigated may be modified but only if necessary for test purposes. It must be recognized that modifications to the construction result in conditions that do not represent true field conditions. Conduction and convection paths that have considerable effect on the performance of the building elements must be left intact. During specimen design the following shall be considered.

NOTE 18—Reduced scale elements shall not be tested with the intent of extrapolating results to larger elements unless detailed modeling analysis clearly shows the validity of the extrapolations.

7.2 *Building Element Sizing:*

7.2.1 The building element shall be sized for the apparatus. Normally the outside dimensions of the building element shall match the dimensions of the metering chamber opening.

7.2.2 Wherever possible, the percent framing and insulated cavity space dimensions of the building element shall be the same as the building assembly it represents.

7.2.3 For elements such as an opaque envelope section, the building element is defined by an integral number of structural sections. For example, a residential wall section constructed of 0.41 m on center framing by 2.44 m wall height, would have a specimen size of at least 1.22 m wide by 2.44 m high. Metal building sections shall have a specimen width equal to the framing dimension, often 1.52 m.

7.2.4 When smaller elements must be tested, a surround panel shall be used to fill out the required size (See Annex A11 for additional details). The surround panel aperture for test purpose shall be sufficiently small relative to the metering area to ensure that extraneous heat loss (flanking loss) caused by the interaction of the metering box edge and surround panel is not greater than 1% of the total sample heat flow. Evaluate this extraneous heat loss using one of various techniques, including computer modeling or physical tests. A minimum distance from the specimen to the metering box edge equal to one half the thickness of the surround panel or 100 mm, whichever is greater, shall be considered acceptable without error evaluation.

7.2.5 For building elements having limited dimensions such as windows, doors, etc., the test specimen shall be the complete component plus the necessary surround panel.

7.2.6 For a building element having thermal behavior that is mostly independent of its horizontal and vertical dimensions, the test specimen size is at least that necessary to obtain an average performance for the material system. For example, insulated systems such as foam sandwich structure panels, are relatively uniform in the cross directions but may be nonuniform through the thickness. The test specimen for this type of material shall be large enough to obtain an average value which accounts not only for manufacturing variability but also includes the effect of joint details between adjacent panels when tested as a system.

7.2.7 For the characterization of homogeneous or nearly homogeneous materials that are self-supporting, the test specimen shall consist of a single layer of material. However, specimen assembly precautions such as sealing the surfaces shall be observed.

7.2.8 Three-dimensional structures may be tested if the apparatus size permits.

7.3 *Sensors*—The temperature sensors for the measurement of surface temperatures shall be installed as directed in 6.10. Additional sensors may be installed throughout the interior of the specimen for special investigations of local temperature variations.

7.4 *Mounting*—The building element shall be located in the same position in test frames as the specimen was during characterization tests so that flanking geometry is duplicated.

7.5 *Sealing*—The building element shall be gasketed, caulked, taped, or otherwise sealed in place to prevent air movement around its perimeter. The procedures and material for sealing shall be chosen to minimize flanking loss. If the building element is suspected of being porous so that a significant energy transfer results from air infiltration through the building element, then tests shall be run before and after sealing both faces. If the overall resistance changes significantly, then the building element does not possess unique properties independent of the imposed conditions. Results from all tests must be reported. Thin, air impervious sheets of paper or plastic, may be glued on to seal surfaces without significantly affecting thermal conduction. Some building elements are sealed with suitable paint. In all cases, the surface emittance of the sealed building element shall be within ± 0.1 of the emittance of the original unsealed building element.

7.6 *Perimeter Insulation*—Insulation shall be used at the building element perimeter. This insulation normally is incorporated into the re-usable specimen frame but may be newly installed for each building element. If newly installed, it shall be fully characterized in order to account for the surround panel flanking loss.

7.7 *Internal Air Barriers*—Testing of a building element, with uninterrupted internal air cavities that extend beyond the boundaries of the metering section is not permitted. To characterize building elements having uninterrupted air cavities that are larger than the metering chamber, it is necessary to alter the element by placing an internal convection barrier in each cavity where it crosses the boundary of the metering chamber. These barriers are required to prevent undesired air exchange between the metering and guard areas of the specimen. For example, such barriers are required for vertical wall cavities extending above or below the metered area when the cavity is insulated with reflective insulation having no internal air barriers. Any modifications to the building element shall be reported.

7.8 *High Lateral Conductance Building Elements*—For all building elements, it is necessary to maintain a near zero lateral energy flow between any guard and the metering areas of the specimen. This can be achieved by maintaining a near zero temperature difference on the building element surface between the metering and guard areas. However, in building elements incorporating an element of high lateral conductance, such as a metal sheet, it is necessary to separate the highly conductive element with a thermal break. One form of thermal break is a narrow gap caused by a saw cut at the metering chamber boundary.

7.9 When testing high thermal resistance specimens that are smaller than the metering area using a surround panel, the heat loss through the surround panel may approach or exceed the heat loss through the specimen. In this case, the operator shall determine the uncertainty of the test result and include that uncertainty value in the report.

## 8. Apparatus Characterization

8.1 All fundamental measurement devices used in the hot box control and data acquisition systems shall be individually maintained and calibrated to meet their design accuracy specifications. In general, this requires that each device be traceable to standards obtained from a national standards laboratory. Records of this calibration and periodic calibration verification checks shall be maintained in the laboratory files. Frequency of validation checks will be dependent on the purpose, style and stability of the equipment used.

8.2 Hot box apparatus characterization is necessary since the measured net heat input to the metering chamber includes not only the heat transfer through the specimen, but also metering box wall loss, flanking loss, and other such heat flows as through gaskets, penetrations for wires or pipes, mechanical fasteners, or other less obvious heat flow paths. Thus, the net metered specimen heat transfer shall be determined from the measured heat input by applying a correction for these flows. This correction, which is determined by characterization procedures, is different for each set of operating conditions and for metered specimens of different thickness or thermal resistance. The accuracy of the test results depends upon the accuracy of this correction. In a properly designed apparatus, however, the flows are a relatively small fraction of the metered specimen heat transfer under steady-state conditions and any error in the correction is reduced by a similar fraction in its effect upon the final result.

NOTE 19—A discussion of the characterization for the metering chamber walls is presented in Annex A3. A discussion of Flanking Loss characterization for one apparatus is given by Lavine et al. (**12**) and in Annex A7. The overall test matrix for the characterization is discussed in Annex A6. Examples of typical characterization matrices are presented in that section.

8.3 In principle, if all details of the hot box construction and all material thermal properties are known, it is possible to calculate all extraneous flows for a particular set of test conditions and then apply this calculated correction to measured data for unknown test specimens. However, because of the uncertainties involved, a wholly calculational characterization procedure, without experimental verification at the test conditions, shall not be used for this method. In general, such calculations are practical only with monolithic walls made of homogeneous material. If calculated corrections, after initial experimental verification, are used, then the chamber wall heat flow meter or thermopile outputs are used as a check to indicate any future changes in wall material properties. Calculations are useful in estimating the magnitude of the major heat flows so that characterization procedures may be better directed. Indeed, the most practical characterization technique uses corrections determined experimentally for a limited set of conditions, but modified on the basis of calculated estimates for use under somewhat different conditions of test. In general, the characterization procedure of 8.5, using a correction developed statistically from tests on standard reference materials shall be used. The choice of the characterization procedure details shall be made only after a review of the expected accuracy judged against the accuracy needed and against the practicability of the various procedures available.

8.4 *Characterization Specimens*—The accuracy of the characterization specimen measurements will depend upon the variability of the material, the means of sampling and the accuracy of the apparatus used to measure it. The accuracy required will depend upon the contemplated use. For highest accuracy, a characterization specimen having a known thermal resistance over the range of test mean temperatures is required. Such specimens shall be impervious to air and thermal radiation transfer, shall be free of internal air spaces that would affect the thermal resistance or allow internal convection, and shall be stable over the time period of use. Additionally, such specimens shall possess a thermal resistance that is essentially constant over all areas of the specimen so that properties determined on smaller areas will be representative of those of the whole area. Any joints necessary in large specimens shall be designed to minimize deviations in thermal resistance (as verified by small scale tests of specimens with and without joints). Characterization specimens shall be self-supporting and capable of being transported, repeatedly mounted and tested, and stored for future use without change in thermal resistance. These properties are also required for specimens used in inter-laboratory comparison tests (round robins). The thermal resistance of characterization specimens shall be determined by measurements in proven apparatus conforming to Test Methods C177 or C518 or another hot box that has been verified or calibrated by specimens traceable to a national standards laboratory. Generally, the hot box characterization specimen will be larger than the apparatus used in these measurements; thus, it will be necessary to measure smaller representative pieces. Such pieces are cut from the characterization specimen if they can be replaced without change in the average thermal properties, or they are selected from companion pieces of the same lot of material used to fabricate the specimen.

NOTE 20—Suitable characterization specimens have been constructed from molded glass fiberboard of approximately 100 to 125 kg/m$^3$ density or aged cellular polystyrene (XPS) board. During the tests both surfaces of the characterization panel shall be faced with an air impervious skins having an emittance greater than 0.8.

8.5 *Metering Box Wall Characterization—An Overview*—Since significant heat flows may exist which are not directly related to heat flow through the chamber walls and therefore not related to the voltage output of the wall energy flow meters or thermopiles, a full experimental characterization is necessary. This characterization involves running a series of tests over the expected operating temperature range using a characterization specimen of known thermal resistance (see 8.3). For each test, determination is made of the difference between the measured heat input to the metering chamber and the heat transfer through the characterization specimen, calculated from the measured temperature drop across it and its known resistance. It is impractical to run a sufficient number of tests to cover all possible sets of operating conditions. Since some of the extraneous heat flows included in the measurement are not metered separately (and indeed may be unknown), it is necessary to utilize statistical techniques to develop a usable correlation between the corrections and the test conditions. A useful procedure is to relate the correction to the test variables using a multiple linear regression. The significant test variables, or combinations of test variables, can often be determined from physical models. Those variables may include the mean temperature of the specimen and of the metering chamber walls, the temperature difference across the specimen, and across the metering chamber walls (related to the output of the chamber heat meters or thermopiles) and the temperature difference across any partial guards used. The regression correlation coefficients can be used to judge the statistical quality of the regression relation and the choice of variables. For greatest accuracy, it is necessary to run characterization specimens covering the expected range of specimen thickness and thermal resistance and to include these variables in the regression analysis.

NOTE 21—Examples of characterization procedures are given by Rucker and Mumaw (**9**), by Lavine, et al (**12**) and in Annex A3 through Annex A7.

8.6 In addition to the initial characterization sequence, it is necessary to repeat selected measurements at times dictated by either the known aging characteristics of the materials used in the metering chamber wall construction or, more often, as required by contractual or certification regulations. A single test may often be sufficient to verify that properties have not changed. The maximum time between verification of characterization shall be one year.

8.7 It is recommended that the performance of an apparatus be periodically confirmed by successful measurements on specimens traceable to a national standards laboratory, previously measured building specimens of known thermal performance or as part of a laboratory accreditation program. Participation in inter-laboratory round robin programs and comparisons with another proven hot box apparatus are other methods to demonstrate continued satisfactory operation.

## 9. Conditioning

9.1 Conditioning requirements specified by code or construction specifications shall govern for the test, where available. Normally pre-test conditioning shall be in ambient air, for a period long enough to come to practical equilibrium. If the requester does not provide specific conditioning instructions, use Practice C870 as a guide for conditioning. The recommended condition is in air at 24 ± 2°C with 50 ± 5 % relative humidity. To avoid abnormally long conditioning periods, building materials may be preconditioned at laboratory conditions prior to specimen assembly. Other conditioning may be used as, for example, long term exposure to cold dry (outside winter) air on one side and warm, moderately humid (inside) air on the other to investigate the effects of moisture or ice build up.

## 10. Test Procedure

10.1 Detailed written operating procedures for each test apparatus shall be developed and shall be available to ensure that the tests are conducted in accordance with the requirements of this test method.

10.2 *Test Conditions*:

10.2.1 Whenever available, product or system specifications or applicable code requirements for all test conditions shall be used.

10.2.2 Specimen orientation and direction of heat transfer, hot-side and cold-side air temperature and velocities and differential pressure, when not specified, shall be chosen to meet requirements of the building element investigation, usually to match in-use conditions.

10.2.3 When not otherwise directed, the air velocities shall be the minimum required to achieve the desired temperature uniformity under the requirements of 6.8.4, be in the direction of natural convection, and the metered specimen pressure differential shall be essentially zero.

10.2.4 Whenever the temperature conditions are not otherwise specified, Practice C1058 shall be used as a guide for selecting the appropriate test temperature conditions.

10.2.5 When testing fenestration products, Test Method C1199 and Practice E1423 shall be used as a guide for selecting the appropriate test environmental conditions.

10.3 Construct the building element in the specimen frame opening as specified in Section 7 including installation of all required sensors.

10.3.1 Some metered specimens require adequate time to come to thermal and moisture equilibrium after assembly. These shall be conditioned at laboratory conditions as long as necessary to establish equilibrium, that is, constant weight. One example would be concrete walls or wet applied insulations in a frame wall.

10.4 Place the test frame, with the metered specimen installed, in the opening between the climatic and metering chambers.

10.5 Make all necessary electrical connections and check out the data acquisition system for measurement continuity.

10.6 Complete sealing of the hot box system in preparation for the test. Check the installed metered specimen for air leakage, if possible (see 7.5 and Note 24).

10.7 Start conditioning systems and set temperature controls to the appropriate temperature set points to yield the desired temperature conditions.

10.8 Begin data acquisition scanning of the test apparatus and continue the operation until the steady conditions described in 10.10 are obtained.

10.9 As specified in 6.9.6, avoid test conditions that cause condensation on the metered specimen surfaces during the test. This requirement becomes more difficult to satisfy when testing building elements with highly conductive components such as steel stud walls or single glazed windows. For example, the National Fenestration Rating Council (NFRC) window test operators have observed that the relative humidity in the metering chamber must be below 15 % to prevent the formation of frost on highly conductive window frames tested at −18°C cold side and 21°C hot side air temperatures.

10.10 *Stabilization and Test Times*:

10.10.1 *Thermal Steady-State*—For purpose of this test procedure the definition of thermal steady-state is identical to that described as steady-state (thermal) in Terminology C168.

10.10.2 The required time to reach stability for a steady-state test depends upon the properties of both the metered specimen and of the apparatus as well as upon the initial and final conditions of the test. Since these factors can vary over wide ranges, a single specification of required stabilization time and the test period for data acquisition couldn't be provided. A combined apparatus and metered specimen time constant, $\tau_{eff}$, calculated from dimensions and estimated physical properties, can be helpful in estimating stabilization times.

NOTE 22—The thermal time constant, $\tau_{eff}$, of the system is the time required to come to within 1/e (37 %) of the final value of the thermal resistance after a step temperature disturbance of the system. This time is strongly dependent on the mode of operation. Two modes of operation have been used for a hot box operation. They are *(1)* constant power to the metering chamber and *(2)* constant temperature control of the metering chamber. The constant temperature operation mode is usually used since it has a considerably shorter time constant because it is not significantly dependent on the thermal mass of the metering chamber. For the constant power mode, the thermal time constant is the time required to come within 37 % of the final temperatures. The thermal time constant of the constant temperature mode is the time required to come to within 37 % of the final power level. The thermal time constant of a simple system can be estimated from knowledge of the thermal diffusivities of the components of the system, but it is more readily determined experimentally for complex systems.

10.10.3 Annex A10 contains a suggested procedure for estimating the thermal time constant of a test system.

10.10.4 Normally, the thermal capacity of either the apparatus or metered specimen will be the controlling factor. However, since this test method is applicable to low conductance specimens, the time to reach steady state is on the order of hours. Even with this information, it may be difficult to judge whether stability has been reached and the operator shall rely upon previous test experience and observations or upon computer assisted statistical prediction of trends. The following guidelines are recommended but shall not be regarded as sufficient criteria in all cases.

10.11 *Test Data Acquisition and Completion*:

10.11.1 *Data Acquisition*—After the final test temperature conditions are reached, five successive repeated data acquisition sets shall be obtained. These sets shall be obtained at a data set time interval equal to the approximate time constant, $\tau_{eff}$, of the measured system but not less than 30 minutes. In some laboratories, an individual data set is developed from the average value for each variable obtained from multiple, evenly spaced, data scans during the permitted time interval.

10.11.2 *Test Completion Criteria*—This combination of five data acquisition runs shall constitute a valid test if the datum obtained for each measured variable differs from its mean by no more than the uncertainty of that variable. If the data obtained during this period is changing monotonically with time, the test shall also be considered incomplete and further repeated runs shall be conducted until the steady drift is no longer observed. Such a drift, even at low levels, indicates that the specimen characteristics are changing or that the system is not at steady state within its test capabilities. In either event, serious errors may result. (See Note 23 for an example of the criteria for stabilization.)

10.11.3 *Continued Testing*—For the purpose of determining test completion, it is necessary to repeat the testing in five time constant blocks ($5 \cdot \tau_{eff}$) until all the required criteria have been satisfied. For test analysis, a sliding $5 \cdot \tau_{eff}$ time range shall be used. Upon acquisition of each additional data set, an analysis of the last five sets shall be performed to see if the criteria of 10.11.2 are met. As soon as these criteria are met, the test is judged complete and the reported result is determined from the averages of the last five readings.

NOTE 23—Operator experience on different types of wall sections has shown that the time to stabilized conditions can range from several hours for lightweight building components to several days for thick massive constructions. Specific test practices have been written and used that reference the hot box test procedure. In these cases, alternate procedures have been written that specify specific requirements for steady state determination and frequency of data collection intended to meet the intent of these sections. An example of a modified stabilization procedure developed for fenestration testing is presented below:

"After essentially steady state temperature and heat flow conditions have been reached, a measurement period of five continuous time constants shall produce five successive measured data sets in which the following conditions exist:

*(1)* The average room side and exterior test specimen individual surface temperatures (if measured) do not change by more than ± 0.25°C over the entire test period.

*(2)* The average metering box ambient air temperatures do not vary by more than ± 0.25°C over the test period.

*(3)* The average metering box wall heat flow does not vary more than ± 1 % of the specimen heat flow and does not change monotonically over the entire test period.

*(4)* The net energy input to the metering box shall be recorded by automated data acquisition equipment at five minute intervals or less and shall not deviate more than ± 1 % from the average net energy readings at any time during the entire test period. The net energy input to the metering box also shall not change monotonically during the test period.

*(5)* The thermal transmittance, as calculated from the data, for the sample shall not vary more than ± 1 % when comparing any time period with any other period within the five data sets. The data sets shall not overlap.

*(6)* The final, calculated test result shall be the average result calculated for the last five time constant periods of the stabilized test period."

10.12 *Recorded Test Data*:

10.12.1 The data acquired during the testing period shall include, but not be restricted to, the following items.

10.12.1.1 The total net energy or average power transferred through the metered specimen, during a measurement interval. This includes all metering box heating and cooling, power to fans or blowers, any significant power to transducers, corrections for metering chamber wall energy transfer and flanking loss, any other extraneous flow, and corrections for the enthalpy of infiltration air entering the metering chamber.

10.12.1.2 All air and surface temperatures specified in 6.10.

10.12.1.3 The average air velocity on each side of the metered specimen (see 6.8.11).

10.12.1.4 The pressure differential across the metered specimen, if different from zero, (see 6.11), and the infiltration flow rate required to maintain it.

NOTE 24—For either parallel or perpendicular forced air velocity conditions, care shall be taken to quantify the amount of air leakage between the climatic and metering chambers. This may be done by several techniques, including: *(1)* tracer gas methods or *(2)* calibration of the airflow rate as a function of the pressure difference using Test Method E1424.

10.12.1.5 The effective test specimen dimensions and metered area (the projected area perpendicular to the direction of energy flow). It may also be helpful to determine and report the hot and cold side surface areas if they are different from the projected areas. For example, detailed windows have surface areas as much as 50 % greater than the projected areas.

10.12.1.6 The metering area of the hot box.

10.12.1.7 Any other conditions specific to this test such as modifications to the normal specimen design required to assemble the test specimen for test purpose.

## 11. Calculations

11.1 For steady-state tests, the average thermal transmission properties appropriate for metered specimen are calculated by using one of the equations given in 3.4.2, using the average data obtained in 10.10 and 10.11. Practice C1045 should be used to resolve the test results for variable temperature difference testing.

11.2 *Average Temperature Determination*:

11.2.1 When operated under steady-state conditions with temperatures held constant during a test, the results shall be expressed as thermal resistance $R$, thermal conductance $C$, overall thermal resistance $R_u$, or thermal transmittance $U$. This method permits use of either of two procedures for determining the average surface temperatures used in the calculations. The choice between the two procedures depends, to some extent, upon the uniformity of the specimen and thus upon whether sufficiently uniform surface temperatures exist that can be measured by temperature sensors and a representative average obtained. For some specimens, the choice shall be arbitrary and must be made by the user of the method, by the sponsor of the test, or it may be specified in applicable regulations or specifications. In all cases, the procedure used shall be fully reported. The two procedures are:

11.2.1.1 For uniform and nearly uniform metered specimens the average surface temperatures shall be determined from area-weighted measurements from the temperature sensors installed as directed in 6.10. The thermal resistance, $R$, is then calculated using the measured energy transfer and the difference in the average temperatures of the two surfaces.

11.2.1.2 For very non-uniform metered specimens (see 6.10.2.3), meaningful average surface temperatures will not exist. In this case the thermal resistance, $R$, is estimated by subtracting the surface resistances for the two surfaces from the measured overall thermal resistance, $R_u$. These surface resistances shall be determined from tests conducted under similar conditions (see Note 25), but using a uniform metered specimen of approximately the same overall thermal resistance.

NOTE 25—Surface resistances have been found to depend significantly on the magnitude of the energy flux as well as the ambient conditions affecting the surface. When using the procedure of 11.2.1.2, it is important that the energy flux for the uniform metered specimen be similar to that through the non-uniform metered specimen and that air temperature, air velocity, and the temperature of surfaces that exchange radiation with the specimens also be similar.

11.3 *Calculation of Thermal Properties*:

11.3.1 Generally, the overall thermal resistance, $R_u$, or the thermal transmittance, $U$, shall be determined for the specimen under the conditions of interest.

11.3.2 For very non-uniform specimens where the energy transfer is greatly different from one area to another, for example, metal frame building section or windows, and if detailed temperatures profiles are not known, only the net energy transfer through the specimen (see 10.11) shall be meaningful. In these cases, only the overall resistance, $R_u$, and transmission coefficient, $U$, are permitted.

11.3.3 For a relatively uniform specimen having only minor thermal bridging such as wood framed walls, floors, ceilings, etc., the thermal properties that shall be calculated are: the resistance $R$, conductance $C$, overall resistance $R_u$, transmittance $U$, surface resistances $R_{c,env}$ and $R_{h,env}$, and surface conductances $h_{c,enc}$ and $h_{h,env}$.

11.3.4 For a homogeneous specimen of insulation material, the apparent thermal conductivity, λ, shall also be calculated if the specimen meets the uniformity requirements of Terminology C168. Available test data shall demonstrate that the thermal resistance of the material under test is linearly proportional to thickness within the range of temperatures and thicknesses under consideration. An expected error of these assumptions shall be assigned to the thermal conductivity result as part of the report.

11.3.4.1 Where there is a question as to the uniformity of the tested material, multiple tests at the same temperature conditions but at different thicknesses shall be made. If the material has been tested at thicknesses greater than the representative thickness, the calculation of the apparent thermal conductivity for those tests will yield the same result within the uncertainty of the measurements. If the result is not the same within the uncertainty for these tests, then the test results are applicable only at the thickness of the test at that thickness. This fact shall be included as part of the report.

11.3.5 For a specimen smaller than the metering chamber opening, the properties that apply to that specimen, as per the distinctions of 11.3.1 through 11.3.4, shall be calculated if surround panel calibration tests have been run that permit the specimen energy transfer to be determined. Annex A8 presents considerations for these calculations.

11.3.6 When directed by applicable agreements or regulations, the overall resistance at standardize conditions, $R_u$, shall be determined from the estimate of the thermal resistance, $R$, obtained as directed in 11.2.1.2 by adding standardized surface resistances. One source of standardized resistances is the ASHRAE Handbook of Fundamentals.

NOTE 26—Overall resistances, $R_u$, obtained from measured resistances, $R$, by adding standardized surface resistances typical of different conditions, may not agree with overall resistances that would be measured directly under those conditions. Discrepancies are especially likely for non-uniform specimens with high conductance surface elements connected to thermal bridges when measured resistances, $R$, are obtained under nearly still air conditions on one or both sides, and the standardized outside surface resistances are typical of high wind velocities. The user is cautioned to be aware of such possible discrepancies.

## 12. Report

12.1 The report shall include information on the following:

NOTE 27—The primary units used in this method are SI, but either SI or inch-pound units may be used in the report, unless otherwise specified. Table 1 provides conversion factors between inch-pound and SI units.

12.1.1 Identification of the test laboratory with address and telephone number, the responsible person in charge, the test operator (optional), the date and duration of test, and the test sponsor, if appropriate.

12.1.2 Name, and any other identification or description of the test construction, including if necessary, a drawing showing important details, dimensions, and all modifications made to the construction, if any, and specimen orientation. Photographs and drawings are helpful as are statements explaining how the specimen represents or differs from typical constructions. It is also desirable to include in the description of the test construction a complete and detailed description of all materials. This includes the generic names of all construction materials and their densities. For hygroscopic materials, such as concrete and wood, the moisture content shall also be given. If the thermal conductivity of these materials, at the test conditions, has been measured, these values shall also be included.

NOTE 28—A detailed description of the test materials in addition to the brand name shall be reported, where possible. For example: preformed, cellular polystyrene, Type II with a density of 22 kg/m$^3$; spruce-pine-fir with moisture content of 12 % and a dry density of 486 kg/m$^3$.

12.1.3 Any pertinent information regarding the specimen preconditioning.

**TABLE 1 Thermal Properties Conversion Factors (International Table)**

NOTE 1—Conversion factors for thermal resistivity and thermal conductance or transmittance can be found by using these tables in reverse direction.

NOTE 2—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.

NOTE 3—Example of table use: To convert from thermal conductivity of 0.05 W/mK (SI units) to thermal conductivity (IP units), multiply by 6.9330 to yield 0.35 (Btu in./h ft$^2$ F).

Thermal Conductivity

| | W/m K | W/cm K | cal/s cm K | kcal / h m K | Btu / h ft F | Btu in/hr ft$^2$ F |
|---|---|---|---|---|---|---|
| W/m K | 1.0000 | 0.0010 | 2.388E-3 | 0.8598 | 0.5778 | 6.9330 |
| W/cm K | 100.0000 | 1.0000 | 0.2388 | 85.9800 | 57.7800 | 693.3000 |
| W/cm K | 418.7000 | 4.1870 | 1.0000 | 360.0000 | 241.9000 | 2,903.0000 |
| cal/s cm K | 1.1630 | 1.163E-2 | 2.7788E-3 | 1.0000 | 0.6720 | 8.0640 |
| Btu/h ft F | 1.7310 | 1.731E-2 | 4.134E-3 | 1.4880 | 1.0000 | 12.0000 |
| Btu in/h ft$^2$ F | 0.1442 | 1.442E-3 | 3.445E-4 | 0.1240 | 8.333E-2 | 1.0000 |

Thermal Resistance

| | K m$^2$/ W | K cm$^2$/W | K cm$^2$ s/cal | K m$^2$ h/kcal | F ft$^2$ h/Btu |
|---|---|---|---|---|---|
| K m$^2$/ W | 1.0000 | 1.0000E4 | 4.187E4 | 1.1630 | 5.6780 |
| K cm$^2$/W | 1.000E-4 | 1.0000 | 4.1870 | 1.163E-4 | 5.678E-4 |
| K cm$^2$ s/cal | 2.388E-5 | 0.2388 | 1.0000 | 2.778E-5 | 1.356E-4 |
| K m$^2$ h/cal | 0.8598 | 8.598E3 | 3.600E4 | 1.0000 | 4.8820 |
| F ft$^2$ h /Btu | 0.1761 | 1.761E3 | 7.272E3 | 0.2048 | 1.0000 |

12.1.4 Information shall be provided that describes the test apparatus, apparatus number, test configuration, mode of operation, etc. including the dimensions of the metered area and its relationship to the overall test specimen dimensions and to principle elements of the specimen.

12.1.5 Test specimen orientation and the direction of energy transfer during the test.

12.1.6 Average air velocity and direction on both sides of the test specimen and air velocity distribution, if non-uniform.

12.1.7 Latest apparatus characterization verification date and procedure used. References for the characterization report(s) shall also be included.

12.1.8 Average pressure differential across the test specimen and the average airflow volume rate, if applicable.

12.1.9 Report temperatures, both air and surface, on each side of the test specimen as follows:

12.1.9.1 For uniform test specimens, report the average temperatures over the test specimen area.

12.1.9.2 For non-uniform test specimens, including test elements, separate measured temperature averages for each different area or element must be given. Areas for each element shall also be reported.

12.1.10 The net heat transfer through the test specimen, steady-state average rate. Include values for metering box loss, flanking loss, surround panel heat flow, surround panel opening flanking loss, and other energy flows included in the net energy calculation.

12.1.11 Any thermal transmission properties calculated in 11.3, and their estimated uncertainty (see 13.1 and Note 29).

12.1.12 A full description of test procedures and data analysis techniques used.

12.1.13 The test-start date and time, the time required to establish steady temperature conditions, the time to reach steady state, the data acquisition time period and frequency, and the test-end date and time.

12.1.14 Include a statement of laboratory accreditation of the test facility used, if applicable.

12.2 **Precaution:** Where this test method might be 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 accompany such published information: "This test did not fully comply with following provisions of Test Method C1363." (followed by a listing of specific deviations from this test method and any special test conditions that were applied)

## 13. Precision and Bias

13.1 *Uncertainty Estimation*—The precision and bias of this method depends upon the test equipment and operating procedures, and upon the test conditions and specimen properties **(24, 34)**. For this reason, no simple quantitative statement can be made that will apply to all tests; however, in order to comply with the requirements of 12.1.11, it is necessary to estimate the uncertainty of results for each test to be reported. Such estimates of uncertainty can be based upon an analysis using the propagation of errors theory discussed in textbooks on engineering experimentation and statistical analysis; see for example Schenck **(13)** or ISO Standard 8990. These estimates can be augmented by the results of interlaboratory test comparisons (round robins), and by the results of experiments designed to determine repeatability of the effect of deviations from design test conditions and by measurements of transfer standards from appropriate standards laboratories. In general, the best overall accuracy will be obtained in apparatus with low metering box wall loss and with low flanking loss. Low metering box wall loss is achieved by using highly insulated walls subjected to low temperature differences. Low flanking loss, in relation to metering box heat input, is achieved by using large boxes where the ratio of perimeter to area is less, and by minimizing of any highly conductive layers or skins flanking the specimen at its perimeter. Also in general, for a particular apparatus, the uncertainty will decrease as the heat transfer through the specimen increases.

NOTE 29—As an example, an outline of the procedure for an uncertainty analysis for thermal resistance, *R*, is as follows:

From 3.4.3, $R = (t_1 - t_2)A / Q$ where, $Q$, is the power through the specimen. The net energy input to the metering box is, $Q_{in} = Q_h + Q_f + Q_{cool}$; the energy into the metering box through its walls is, $Q_{mw}$; and the flanking loss power is, $Q_{fl}$; such that $Q = Q_{in} + Q_{mw} + Q_{fl}$ (other terms such as blower input or cooling may be added as needed). Combining these equations, the relation for resistance is $R = (t_1 - t_2)A / (Q_h + Q_f + Q_{cool} + Q_{mw} + Q_{fl})$. The individual uncertainty for each item in this equation must be estimated. Such estimates shall be made from knowledge of individual instrument and transducer uncertainty or from the results of characterization experiments designed to investigate such uncertainties. Then, following the propagation of errors theory that assumes the errors to be independent and not systematic, the uncertainties are combined by adding in quadrature (square root of the sum of the squares) the absolute uncertainties for sums and the relative uncertainties (fractional or percentage of the variable) for the products or quotients.

NOTE 30—Uncertainty estimates for existing apparatus range from 1 to 10 %. Published estimates include 0.75 to 1.0 % according to Mumaw **(2)** and to Miller et al **(4)** and from 1.5 to 3 % according to Rucker and Mumaw **(9)**. A 5 % agreement with guarded hot boxes was also reported by Miller et al **(4)**. Unpublished estimates range from less than 2 % for a large box operated with a temperature difference of 56°C to 10 % when the same box is operated with a temperature difference of 14°C for a high resistance (5.3 K m²/W) specimen. Also see Refs **(29)** and **(32)** for recent discussions of the uncertainty determination.

13.2 *Interlaboratory Comparison Results*:

13.2.1 *Background*—During the 1980's, a round robin for guarded and calibrated hot boxes was conducted with 21 laboratories participating, 15 boxes were guarded while 6 were calibrated hot boxes. The design of the round robin is described by Powell and Bales **(14)**. Data were reported for 100 mm thick homogenous specimens of expanded polystyrene board. Each laboratory received material from a special lot whose production was specially controlled to ensure a uniform product density. At a mean temperature of 24°C, the average R-value was determined to be 2.81 K m²/W. The regression equation for each data set was:

$$R_{guarded} = 3.146 - 0.016 \cdot T_{mean} \tag{11}$$

$$R_{calibrated} = 3.265 - 0.016 \cdot T_{mean} \tag{12}$$

over a mean temperature range of 4 to 43°C. The mean specimen density ranged from 20.2 to 23.9 kg/m³. The report of this round robin was prepared by Bales **(19)**.

NOTE 31—These results are for hot boxes built to C236 and C976 specifications. These two standards were combined in the development of this test method. Additional refinements were added here in hopes of improving testing performance.

13.2.2 *Precision*—At a specimen thermal resistance of $R$ = 2.81 K m²/W and on the basis of test error alone, the difference in absolute value of the test results obtained from two laboratories on this same specimen material lot will be expected to exceed the reproducibility interval only 5 % of the time. The reproducibility intervals based upon this round robin are presented in Table 2. For example, measurements from two different laboratories using a calibrated hot box on this same specimen lot would be expected to differ less than 14.4 % at a mean temperature of 24°C, 95 % of the time.

13.2.3 *Bias*—Based on guarded hot plate data, (see Test Method C177), from the National Institute of Standards and Technology and supported by measurements from other laboratories, the average value for the round robin specimen is a thermal resistance of 2.81 K m²/W at an average density of 20.8 kg/m³ **(19)**. The mean value as measured by the composite of the calibrated hot boxes was 2.88 (K m²/W) or 2.7 % greater than expected from the hot plate tests. The mean value as measured by the composite of the guarded hot boxes was 2.78 (K m²/W) or 1.1 % less than the expected value. All measurements were made at a mean temperature of 24°C.

NOTE 32—Both round robins used quasi-homogeneous specimens assembled from multiple pieces of the polystyrene board stock. While this specimen approximates an ideal wall section, it cannot be represented by the homogeneous board stock material due to the presence of joints and surface treatment. The precision and bias statement above gives an indication of those values expected for this specimen lot only and may not represent the values expected for either a non-homogeneous wall section (that is, real walls) or for a specimen that is truly uniform in density and material properties.

**TABLE 2 Reproducibility Test Results—Homogeneous Specimens—ASTM Hot Box Round Robin (19)**

| Mean Temperature (°C) | Reproducibility Interval (%) | | Difference in Resistance (m²K/W) |
|---|---|---|---|
| | Calibrated | Guarded | |
| 4 | 13.6 | 14.6 | ± 0.22 |
| 24 | 14.4 | 15.6 | ± 0.22 |
| 43 | 15.4 | 17.2 | ± 0.22 |

13.2.4 The precision and bias of the hot box apparatus has not been confirmed for building sections, such as a metal building panel, which contains large thermal bridges. The accuracy of the results of the overall thermal transmission, $U$, at the test conditions are expected to be equal to that of other specimens. The problem is with the determination of the surface-to-surface thermal resistance, $R$, which is expected to have greater uncertainty due to problems with defining the true surface temperatures **(30)**.

13.2.5 The precision and bias of the hot box apparatus used for testing windows has been evaluated and the results published by the National Fenestration Research Council (NFRC). These results are from their annual round robin testing of the NFRC accredited laboratories which perform testing using the C1363 and C1199 test procedures. The results of the most recent published survey show an uncertainty (two standard deviations units) of ± 0.23 W/m²K for a non-thermally broken, aluminum framed, horizontal slider window having an average thermal transmission of 3.2 W/m²K. The 2001 results on a thermally improved, aluminum fixed window with high performance glazing ($U_{st}$ = 2.3 W/m²K, showed a reproducibility limit of 13.8 % at 95 % confidence level and a coefficient of variance of 4.92 %. Eight testing laboratories participated in these round robins. No bias was calculated since the "true" value was not known **(28, 32)**.

13.3 No interlaboratory comparison exists for this latest version of the hot box method. An interlaboratory comparison of this test method is planned as soon as it is available and the laboratories have had time to modify their apparatus to meet the requirements of this test method, if necessary.

## 14. Keywords

14.1 building assemblies; building materials; hot box; test method; thermal properties; thermal resistance

# ANNEXES

**(Mandatory Information)**

## A1. INTRODUCTION TO THE ANNEXES

A1.1 This introduction provides a brief description of each of the Annexes provided.

A1.1.1 *Annex A1: Introduction to the Annexes*—Provides a brief summary of all the Annexes.

A1.1.2 *Annex A2: Heat Balance in a Hot Box Apparatus*—Provides a general overview of the heat balance within a hot box apparatus.

A1.1.3 *Annex A3: Estimating the Metering Box Wall Loss*—Describes the physics of the metering box wall loss. Also describes the characterization tests required to determine the heat flow through the metering box walls in relation to the metering box wall transducer output.

A1.1.4 *Annex A4: Estimating the Flanking Loss*—Defines the concept of the flanking loss. Also describes methods for modeling and model verification of the flanking loss in a hot box apparatus.

A1.1.5 *Annex A5: Preliminary Hot Box Characterization*—Outlines the initial testing required for the initial setup of the metering box wall transducers.

A1.1.6 *Annex A6: Experimental Determination of the Flanking Loss and Metering Box Wall Loss Model Coefficients*—Describes the development of the testing matrix for establishing the relationships between the hot box heat flows and the instrumentation output signals.

A1.1.7 *Annex A7: An Example of a Hot Box Characterization Test Program*—Provides an example of characterization test results used to determine the metering box wall transducer output and flanking loss coefficients.

A1.1.8 *Annex A8: Using the Hot Box To Determine the Heat Transfer Through Specimens Smaller Than the Metering Area*—Explains how to use a surround panel to measure the thermal resistance of specimens smaller than the metering area of the hot box.

A1.1.9 *Annex A9: Determination of the Environmental Temperature in the Hot Box Environment*—Describes how to calculate the environmental temperature in both chambers of the hot box. These values are used to determine the thermal resistance of all specimens.

A1.1.10 *Annex A10: Recommended Practice for Estimation of the Testing System Time Constant*—Provides a methodology in which the time constant of the thermal chamber and specimen can be estimated and measured.

A1.1.11 *Annex A11: Design and Construction of the Hot Box Characterization and Surround Panels*—Specifies how to assemble and instrument characterization and surround panels. These panels are used in the characterization tests specified in Annex A5 through Annex A7 and in testing specimens smaller than the metering area as described in Annex A8.

## A2. HEAT BALANCE IN A HOT BOX APPARATUS

A2.1 Hot boxes are designed to measure the heat transfer through a specimen when the environmental conditions on both sides of the specimen are held constant. Tests are typically performed with a significant temperature difference across the specimen, and with the air temperatures on both sides being held at fixed values. In addition, the air velocities on both sides of the specimen are measured and held constant during the test. Once the environmental conditions are stable, as defined by the steady state criteria, the net heat flow into the metering box is carefully measured.

A2.2 The measured value of heat flow is then adjusted based on the results from characterization tests described in these Annexes. Annex A2-Annex A4 describe the basics relating to the metering box wall heat flow and the flanking loss, respectfully. Annex A5 outlines the tests necessary to initialize the metering box wall transducers. Annex A6 describes the development of a testing matrix for characterization and then Annex A7 provides an example of the use of a text matrix to obtain the characterization coefficients. Annex A8 describes the additional steps required to measure specimens smaller than the metering area. Annex A11 describes the design and construction of the characterization and surround panels required for testing in this apparatus.

A2.3 The tests described in Annex A5 through Annex A8 depend upon establishing a heat balance between the metering chamber and the surrounding environment. These tests are performed using homogeneous characterization panels, which are instrumented on both sides to determine the surface temperature difference across them. A schematic of the heat flows in a hot box and their sources is shown in Fig. A2.1.

A2.3.1 The equation that describes the total heat balance of the metering box is:

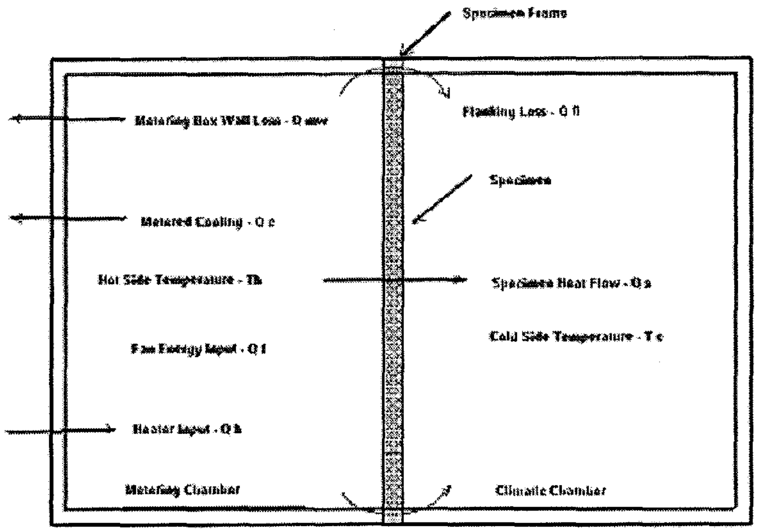


FIG. A2.1 Hot Box Heat Flow Diagram

$$Q_{aux} + Q_{mw} + Q_{fl} = Q = A \cdot \Delta t / R \quad \text{(A2.1)}$$

where:

$Q_{aux}$ = net heat flow due to the fan, heater, and cooling coil, W,
= $Q_c + Q_h + Q_f$, W,
$Q_c$ = net heat removed by the cooling coil, W,
$Q_h$ = net heat added by the heaters, W,
$Q_f$ = net heat added by the fans, W,
$Q_{mw}$ = metering box wall loss, W,
$Q_{fl}$ = flanking loss, W,
= $Q_{fl,\ m\text{-}g} + Q_{fl,\ m\text{-}c}$, W,
$Q_{fl,\ m\text{-}g}$ = flanking loss from the metering chamber to the guard, W,
$Q_{fl,\ m\text{-}c}$ = flanking loss from the metering chamber to the climate chamber, W,
$Q$ = heat flow through the specimen, W,
$R$ = thermal resistance of the specimen, $m^2 \cdot K/W$,
$A$ = metered area of heat flow, $m^2$, and
$\Delta t$ = surface temperature difference across the specimen, K.

A2.3.2 Recall that $Q_{mw}$ is a function of the transducer output, $E$, described by Eq A2.2. From an operational standpoint, the objective of proper metering box operation is to make $Q_{mw}$ equal to or nearly zero.

$$Q_{mw} = f(E) = m \cdot E + E_o \quad \text{(A2.2)}$$

where:

$E$ = thermopile voltage, V,
$m$ = slope of the metering box loss versus thermopile output relationship, and
$E_o$ = zero offset for the thermopile output, V.

A2.4 *Metering Box Wall Loss Determination*:

A2.4.1 To quantify m in Eq A2.2, three, or more, test runs shall be performed with differing levels of $E$. In practice, the adjustment of the value of $E$ is accomplished by adjusting the guard temperature while holding the other temperatures constant. The level of change required for analysis of the relationship will depend upon the transducer sensitivity and the metering box wall thermal resistance. One of these tests shall be performed with the guarding temperature above the metering box air temperature. The second test has the guarding temperature approximately equal to the metering box air temperature. And finally, one test shall be performed with the guarding temperature below the metering box air temperature. All control parameters shall be held constant during each test.

A2.4.2 Once the value for $Q_{mw}$ is determined for each test using Eq A2.1; the results are plotted versus the transducer output $E$. The slope of the line, $m$, and the $y$-intercept, $E_o$, as described by Eq A2.2 are determined from the plot or by fitting the data to Eq A2.2.

A2.4.3 Ideally, a set of tests shall be performed where the heat flow through the specimen was negligible ($\Delta t$ across the specimen is zero), and any heat flow measured in the metering box is attributed to the metering box wall heat flow. Unfortunately, not all hot boxes operate at environmental conditions where the temperature differences across the specimen are close to zero. Therefore, this test method specifies a characterization methodology in Annex A6 where the coefficients representing the metering box wall loss and flanking loss are combined, and may not be individually identified.

A2.4.4 For those hot boxes that have metering boxes with active metered refrigeration, the thermopile zero offset is determined separately from the thermal chamber flanking loss coefficient. Hot boxes with active metered refrigeration can determine the thermopile zero offset by setting the temperature difference across the specimen surface equal to zero ($Q = 0$). Substituting Eq A2.2 into Eq A2.1 and setting $Q = 0$ reduces Eq A2.1 to:

$$Q_{aux} = -(m \cdot E + E_o) \quad \text{(A2.3)}$$

A2.4.4.1 Notice that setting the temperature difference across the test specimen to zero also forces the flanking loss $Q_{fl,\ m\text{-}c}$ to be equal to zero.

A2.4.5 Those thermal chambers that cannot perform the metering box wall heat flow test with zero temperature difference across the specimen, shall use the procedure outlined in Annex A6 to determine a combined metering box wall heat flow and flanking loss coefficient. The coefficient is valid only at the environmental conditions at which the tests were performed. Therefore, separate tests shall be performed at the environmental conditions expected during actual testing.

A2.5 *Flanking Loss Determination*:

A2.5.1 Typically, flanking losses can occur at two locations in a hot box. One source of flanking loss is the heat transfer between the metering box and the guard or climate chambers around the contact point where the metering box wall touches the specimen. Examples of this flanking loss are shown in Fig. A2.2, for thermal chambers with a guard chamber, and in Fig. A2.3, for hot boxes where the metering box has the same sized aperture as the climate chamber. This extraneous heat flow is considered to be the flanking loss associated with that specific metering chamber at that environmental condition, and determining its value is the primary focus of Annex A4. The second area where flanking loss occurs is between the metering box and the climate chamber through the edge of the aperture of the surround panel holding a specimen smaller than the metering area. This flanking loss only occurs when a test specimen smaller than the metering aperture is mounted in a surround panel. Although the specimen flanking loss can be estimated by computer simulation or testing, typically the heat flow associated with test specimen flanking loss is included with the test specimen heat flow, which slightly decreases the measured thermal resistance of the test specimen (**33**). See A8.4 for a more detailed discussion of test specimen flanking loss.

A2.5.2 The metering box wall flanking loss is a source of error when measuring the heat flow through a metered specimen. This method requires that the flanking loss be determined using the tests described in Annex A6. Unfortunately, the heat flow due to flanking loss cannot be measured directly. In addition, the flanking loss has been shown to vary with the test conditions. In some of these hot boxes, the flanking loss varies more with the change in air velocities than with the change in air temperatures. In these circumstances, a series of tests shall be performed at all the environmental conditions experienced during testing to properly quantify the heat flow due to flanking loss.

A2.5.3 As previously mentioned in A2.4.2, many hot boxes are not configured to measure the flanking loss separately from the thermopile zero offset. The process used to establish the combined flanking loss and metering box wall thermopile coefficients is similar to the procedure used to establish the metering box wall transducer coefficients when the temperature difference across the specimen surface is equal to zero. When the temperature difference across the specimen is not zero, the flanking loss coefficient and the heat flow through the specimen shall be included in Eq A2.3 to produce a new heat balance equation shown in Eq A2.4. By solving Eq A2.4 at the range of testing conditions using a variety of panels, temperatures, and wind speeds, the hot box flanking loss can be fully characterized. As a minimum, solving Eq A2.4 requires a minimum of three tests for each characterization panel. At each environmental condition, the guarding temperature is set to different levels, but all other temperatures remain constant.

$$(A \cdot \Delta t / R) - Q_{aux} = m \cdot E + [E_o + Q_{fl}] \quad \text{(A2.4)}$$

A2.5.4 The results from performing numerous tests at the range of heat flows, temperatures and wind speeds experienced during testing will generate different values of the combined coefficient, $[E_o + Q_{fl}]$ in most hot boxes. The slope of the linear equation, $m$, remains relatively constant throughout these tests, but the flanking loss may vary with changes in the environmental conditions or heat flow. The values of $m$, and $[E_o + Q_{fl}]$ shall be analyzed in relation to the changes in environmental conditions and heat flow to establish a unified and consistent methodology to adjust the measured heat flow of actual specimens based on these tests. Since the actual specimen will have a significantly different construction than the relatively homogeneous characterization panels, the test operator shall have to make a judgment as to which values of $m$, and $[E_o + Q_{fl}]$ should be used for a particular test. In some cases, it shall be necessary to interpolate between different values of $m$, and $[E_o + Q_{fl}]$ based on the assembly of the specimen or test conditions.

A2.5.5 One of the consequences of using the results from the characterization tests to adjust the results from testing actual specimens is that any systematic errors present in the hot

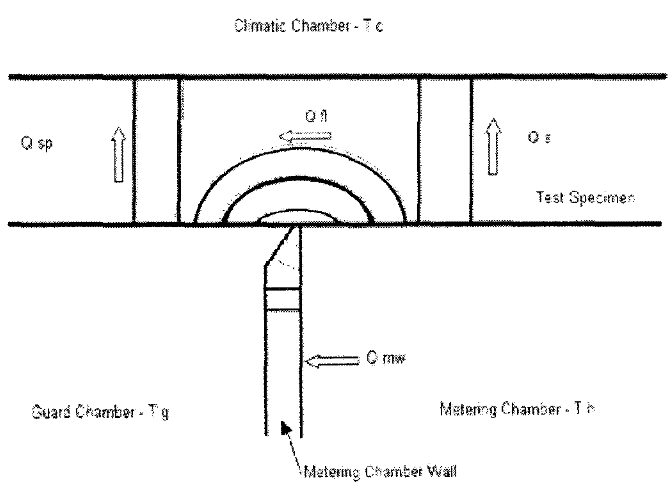


**FIG. A2.2 Guard Chamber/Metering Box Interface**

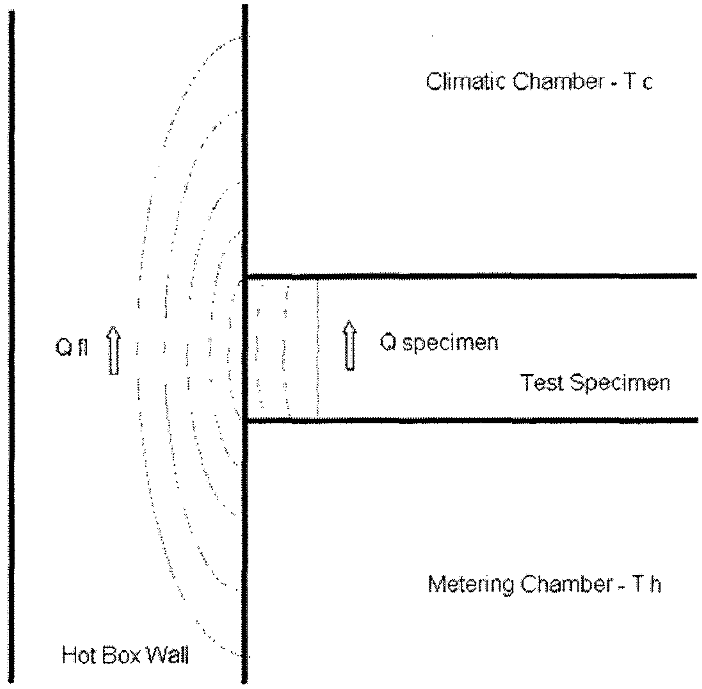


**FIG. A2.3 Hot Box Wall or Frame Interface with Specimen**

box and instrumentation shall be included in the combined flanking loss and thermopile zero offset coefficient, $[E_o + Q_{fl}]$. For this reason, it is critical to accurately measure the heat input into the metering chamber by the heaters, fans or instrumentation, $Q_{aux}$. Not only is it important to have a combined coefficient that is relatively small compared to the net heat flow, but also the test operator should try to understand the cause of the flanking loss and thermopile zero offset within their specific thermal chamber. To help understand the reasons for flanking loss, compare the heat flow that is calculated using the procedures outlined in A7.4 to the results generated by the test analysis as shown in Fig. A7.3. The reason for any differences shall be identified.

## A3. ESTIMATING THE METERING BOX WALL LOSS

A3.1 The heat flow through the metering box walls is estimated by various means, which differ in accuracy and the level of effort required. The heat flow of the metering box shall be estimated during the design of the hot box to refine the final construction. In addition, the predicted heat flow shall then be compared to the actual values measured in Annex A6 as a gauge of meeting the design goals. The procedures described below assume that the hot box apparatus is designed to have generally uniform airflow and temperatures at each surface of the metering chamber walls.

A3.2 *Model Prediction*:

A3.2.1 The following equations represent one method of estimating the heat flow through the walls of a five-sided rectangular metering box made of homogeneous material. Langmuir (**15**) estimates the metering chamber wall heat flow to be equivalent to one-half that of a closed six sided box formed by placing two of the open sided boxes together. The heat flow per unit time for the five-sided box is given by:

$$q = \frac{\lambda_{eff} \cdot A_{eff} \cdot (t_{in} - t_{out})}{L} \qquad \text{(A3.1)}$$

where, the effective area normal to heat flow, m$^2$, is given by:

$$A_{eff} = A_{in} + 0.54 \cdot L \cdot \Sigma\, e_i + 0.60 \cdot L^2 \qquad \text{(A3.2)}$$

where:

$A_{in}$ = metering chamber inside surface area, m$^2$,
$L$ = metering chamber wall thickness, m,
$\lambda_{eff}$ = metering chamber effective wall thermal conductivity, W/mK,
$t_{in}$ = metering chamber inside wall surface temperature, K,
$t_{out}$ = metering chamber outside wall surface temperature, K, and
$\Sigma\, e_i$ = sum of all (total of 8) metering chamber interior edge lengths formed where two walls meet, m.

A3.2.2 There are numerous two-dimensional computer analysis tools that can be used to estimate the heat flow through the metering box walls. Typically, these computer programs require detailed cross sections of the metering box wall at all locations that are representative of the metering box wall construction. The thermal conductance and emittance of all the building components in those cross sections are input into the computer models to determine the heat flow through those sections. The total heat flow through the metering chamber walls is determined by area weighting the computed heat flow through the various cross sections.

A3.2.3 The most accurate method of calculating the heat flows in and out of the metering box is by using three-dimensional computer analysis tools. These computer programs allow detailed analysis of the convection and radiation environments encountered in the hot box. Typically, these computer programs require detailed three-dimensional computer drawings of the metering box wall construction, as well as the thermal conductance and surface heat transfer coefficients of all the building components.

## A4. ESTIMATING THE FLANKING LOSS

A4.1 The flanking loss is defined to be the quantity of heat, which flows between the metering and climatic chambers through the surround panel or test frame, which holds the specimen. The flanking loss from the metering chamber to the guard chamber that passes through the specimen, Figs. A2.2 and A2.3, have been discussed in A2.5. This analysis is applicable to the flanking loss through the surround panel at its interface with the specimen, Fig. A4.1. This loss also occurs at the opening when the surround panel thickness is different from the specimen thickness. The flanking loss is expected to be a function of the construction through which the flanking loss passes, the temperatures, the air velocities in both chambers, and the thickness and construction of the specimen.

A4.2 Before the flanking loss tests are performed, a preliminary analysis must be made to predict the magnitude of the flanking loss as a function of the appropriate variables. For example, the air-to-air temperature difference between the chambers; associated mean temperature; surface heat transfer coefficients; and the specimen construction and thickness all may be significant.

A4.3 Fig. A4.1 shows a cross-section of the joint between the surrounding panel opening and the specimen. The primary direction of the flanking heat flow is parallel to the surround panel opening surface skin. Since the skin has a fairly high thermal conductivity compared to the internal insulation, it cannot be ignored as a heat flow path. The flanking loss occurs through both the skin and the insulation beneath. For this analysis, the use of a two-dimensional or three-dimensional finite element or finite difference model is recommended.

A4.4 *Modeling the Flanking Loss*:

A4.4.1 By modeling the flanking loss, a better understanding of the mechanisms of extraneous heat flows for a particular hot box is achieved. The objective is to characterize the flanking loss using a simplified representation of the extraneous heat flow based on actual measurements. Typically, the flanking loss shall be represented using regression equations based on known thermodynamic properties.

A4.4.2 For ease of calculation of the flanking loss correction, the heat flow along two paths is lumped together and described as a single path with an effective thermal conductivity, length, and area. The exact form of this equation will be guided by the modeling results. In thermal chambers where the air velocities on both sides are always constant, the flanking loss has been successfully predicted using the following equation form:

$$Q_{fl} = \lambda_{eff} \cdot (A/L)_{eff} \cdot \Delta t_{a-a} \quad \text{(A4.1)}$$

where:

$Q_{fl}$ = flanking loss, W,
$\lambda_{eff}$ = effective thermal conductivity of base insulation and the skin material, W/(m · K),
$(A/L)_{eff}$ = effective area/path length of entire frame around its perimeter, m, and
$\Delta t_{a-a}$ = air-to-air temperature difference, K.

A4.4.3 Strictly speaking, the effective thermal conductivity is a function of temperature, since the thermal conductivity of the base insulation and skin vary with temperature. The effective path length and area will clearly be a function of specimen thickness, since varying the specimen thickness will change the geometry of the problem. As the specimen thickness is increased, the path length for flanking loss will increase. So, the function $(A/L)_{eff}$ will decrease with increasing specimen thickness.

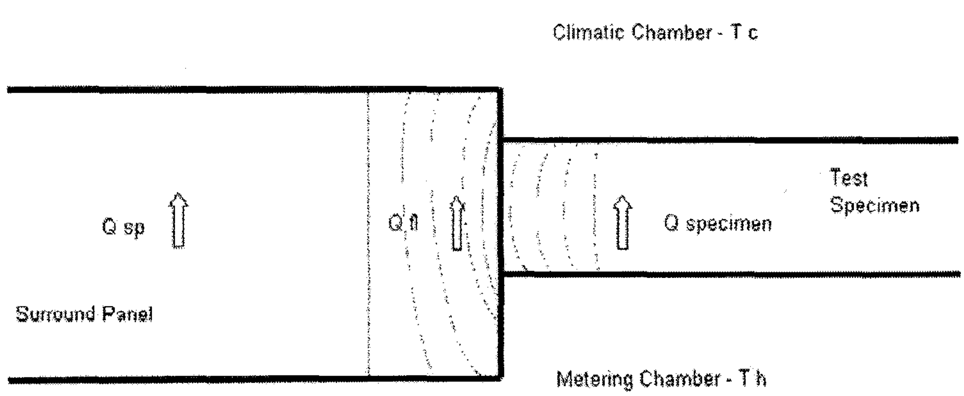


FIG. A4.1 Specimen—Surround Panel Opening Interface

A4.4.4 The model above presupposes one-dimensional heat flow through the specimen. In actuality, the heat flow will be two-dimensional or three-dimensional near the frame. For this reason, a two-dimensional or three-dimensional model is preferred. There are numerous two-dimensional and three-dimensional computer analysis tools that can be used to model and estimate the flanking loss. These models typically require that a representation of the metering box wall construction be input into the computer including the thermal conductivity, surface emittance, air temperatures and surface heat transfer coefficients of all the appropriate components. Much of the difficulty in modeling the flanking loss is assigning the proper air temperatures and surface heat transfer coefficients to use in the analysis.

A4.4.5 Once the computer models are operational, a sensitivity analysis shall be performed to determine the effects of variation in the specimen construction, air temperatures, and surface heat transfer coefficients on the flanking loss heat flow.

A4.5 *Experimental Model Verification*:

A4.5.1 Once the relationships between the various factors controlling the magnitude of flanking loss is determined, it is necessary to conduct a series of tests on known specimens in order to determine the equation coefficients for the various factors. An example of this analysis is presented in Annex A7. Each variable shall be tested at its range of expected values. This would include, as a minimum, tests at several thicknesses, mean temperatures, temperature differences and air speeds.

A4.6 *Limitations*—Consideration shall be given to various possible sources of errors in the flanking loss calibration procedure (**33**). The three listed below are highlighted for consideration.

A4.6.1 The flanking loss equation developed using one particular frame may differ slightly for other frames of the same general construction.

A4.6.2 The data analysis assumed that the specimen heat flow can be calculated as $Q = C \cdot A \cdot \Delta t_{s\text{-}s}$. This presupposes one-dimensional heat flow through the specimen. In reality, the heat flow is two-dimensional near the interface.

A4.6.3 Finally, the testing and analysis are generally performed on homogeneous specimens. It is not known whether flanking loss would be greatly different for a non-homogeneous specimen. It is conceivable that a multi-layer wall, in which the layers vary significantly in thermal conductivity, would behave differently. The model used in this calibration can be used to investigate these concerns for the particular box construction.

## A5. PRELIMINARY HOT BOX CHARACTERIZATION

A5.1 The procedure given in this section outlines the steps required to verify the proper output of the metering box wall thermopile, and to obtain the initial relationship between metering chamber wall heat flow, metering box loss, and its transducer output. The latter series of tests addresses the technique that will yield the heat flow relationship as a function of the transducer output including a zero offset, if present. In addition to the verification tests described in this Annex, the flanking loss characterization tests described in Annex A6 shall be performed before testing actual specimens.

NOTE A5.1—Alternate procedures to evaluate the slope and offset of the metering box heat flow and flanking loss are acceptable, if documented and verified experimentally.

A5.2 To perform the required tests, a characterization panel, as described in Annex A11, shall be instrumented and installed in the hot box. This panel shall fill the available dimensions of the test frame. The metering wall characterization cannot be performed using a test specimen smaller than the metering chamber opening.

A5.3 It is essential that the air velocities, power inputs and temperatures for the metering, guard and climatic chambers be held constant throughout each test. By holding all the control parameters constant, the operator decreases the variability of the surface heat transfer coefficients on the panel during the test.

A5.4 *Verifying Metering Box Wall Transducer Null Offset*:

A5.4.1 This procedure outlines a verification test required to confirm that the metering chamber wall transducer output is zero when there is no heat flow through the metering chamber walls. This method helps determine if the thermopile used to measure the temperature difference (and heat flow) across the metering box wall is wired properly. The construction of the metering box wall thermopile is described in 6.5.4, and the proper operation of the thermopile shall be verified before additional calibration tests are performed.

A5.4.2 Install a characterization panel, as specified in Annex A11, in the thermal chamber. Do not start any fans, heaters, or instrumentation, which generates heat (that is, hot wire anemometers). Record the ambient laboratory air temperature, the temperatures of the air, baffle surfaces, and surround panel in the hot box, and the output from the metering box wall transducer (thermopile) for at least 24 h after the hot box has reached steady state conditions with the surrounding laboratory environment.

A5.4.3 Once the hot box has reached steady state conditions with the ambient environment (this may take days to achieve); the surface and air temperatures in the climate chamber, metering chamber, and guard chamber (if present) should be close to each other. Therefore, the output from the metering box wall transducer should be close to zero. There may be a small cyclic output from the metering box wall transducer based on the diurnal fluctuation of temperature in the surrounding laboratory, but the average output over 24 h shall be nearly zero. If the average output from the metering box wall transducer is not close to zero, then the wiring of the metering box wall thermopile shall be checked and repaired, if necessary, before additional tests are performed.

A5.5 *Preliminary Characterization of Metering Wall Transducer*:

A5.5.1 This describes the process to determine the relationship between the output from the metering box wall transducer and the heat flow through the metering box walls when the temperature difference across the characterization panel is close to zero. The environmental conditions generated during this test are significantly different from actual test conditions, and therefore the results from these tests are only used to establish the initial value of the coefficient that is multiplied by the output from the metering box wall transducer to determine the metering box wall loss. Any offset due to flanking loss or other anomalies is determined by the tests are described in Annex A6.

A5.5.2 Hot boxes that do not have the capacity to cool the metering chamber with a metered, active refrigeration system will have difficulty performing the test described in this section. For this reason, it is not mandatory to perform this test, but it is recommended. If active metering chamber cooling is not available, then it is possible to reach steady state conditions by installing a characterization panel with a low thermal resistance. This panel shall be installed and instrumented as specified in Annex A11. An alternate procedure to determine the relationship between the output from the metering box wall transducer and the heat flow through the metering box walls is described in Annex A7.

A5.5.2.1 Perform a minimum of three tests with the metering box air temperature equal to the climate chamber air temperature, but with the guarding temperature set to different values. If so equipped, the metering box air temperature shall be controlled with the assistance of a metered refrigeration system. Otherwise the metering box controls shall be adjusted such that the fans operate at minimum levels and the heaters are barely activated. Use the minimum heat in the metering box to maintain temperature control. Adjust the climatic chamber temperature to match the metering chamber temperature. In this configuration, no heat, $Q$, is flowing through the specimen, and thereby, all the net heat into the metering box is lost (or gained) through the metering box walls.

A5.5.2.2 As described in A2.4 and A2.5, separate tests shall to be performed with the guarding temperature set at different values, but with the metering room air temperature held constant. The fans generating the airflow on both sides of the thermal chamber shall also be set at constant speeds. It is recommended that, as a minimum, one test be performed with the guarding temperature above the metering chamber air temperature, one test with the guarding temperature equal to the metering room air temperature, and one test be performed with the guarding temperature below the metering box air temperature.

A5.5.2.3 For the condition where the surface temperature difference across the known panel is close to zero, the flanking loss is also zero, and the heat balance can be determined by Eq A2.3. By plotting the heat flow versus the output from the metering box wall thermocouple, the slope and the zero offset as described by A2.2 can be determined.

A5.5.3 The measured metering box wall heat flow shall also be compared to the theoretical value calculated in Annex A3. If there is a significant discrepancy between the measured and calculated heat flow, conduct an investigation to identify the reason for this discrepancy. If all systems are operating satisfactorily, use the measured coefficients when performing the calibration tests specified in Annex A6.

## A6. EXPERIMENTAL DETERMINATION OF THE FLANKING LOSS AND METERING BOX WALL LOSS MODEL COEFFICIENTS

A6.1 Characterization of the hot box apparatus is required before testing of products can begin. The complete characterization of the apparatus serves to verify the assumptions made in the design and to quantify the extraneous heat transfer paths seen during operation of the apparatus. The objective of this annex is to provide examples for the test condition combinations of the metering chamber, surround chamber and climatic chamber temperatures that are required to fully characterize the apparatus. The choice of the test matrix is based upon the style of apparatus construction, the mode of operation and the test conditions anticipated. The example in Table A6.1 is for a window test apparatus having a window smaller than the metering chamber opening. The apparatus is to be used only at one set of temperature conditions and only one mode of operation but for three different surround panel thicknesses. For this matrix the set of calibration tests is small. For the example presented in Table A6.1 as few as 6 tests may be adequate. If only one surround panel thickness is used, fewer

TABLE A6.1 Recommended Test Matrix for Characterization of an ASTM C1363 Hot Box —For Fenestration Testing

| Test No. | Metering Chamber Air Temperature, °C | Guard Chamber[A] Air Temperature, °C | Climate Chamber Air Temperature, °C | Metering Wall Thermopile Output, Volts | Surround Panel Thickness, mm |
|---|---|---|---|---|---|
| Nul | Ambient | Ambient | Ambient | 0 | 114. |
| 1 | 21.1 | 21.1 | −17.8 | 0 | 114 |
| 2 | 21.1 | 18.3 | −17.8 | + | 114 |
| 3 | 21.1 | 23.9 | −17.8 | − | 114 |
| 4 | 21.1 | 21.1 | −17.8 | 0 | 152 |
| 5 | 21.1 | 21.1 | −17.8 | 0 | 203 |
| 6 | 21.1 | 18.3 | −17.8 | + | 203 |
| 7 | 21.1 | 23.9 | −17.8 | - | 203 |

[A] Guard chamber or surrounding laboratory environment.

tests are possible. On the other hand, in the example of Table A6.2, for an apparatus used for walls and windows over a wide range of temperatures, air velocities, and specimen and specimen thicknesses, many more tests are required for full characterization. The examples given below are intended to provide an outline for the concept only. Each hot box shall have its own characterization matrix that will depend upon its design and planned operation.

A6.2 Of interest here is how to measure the combined flanking loss and metering box thermopile coefficient. As discussed in Annex A2, the heat flow due to flanking loss is difficult to measure and quantify. By solving Eq A2.1 at the range of testing conditions using a variety of characterization panels, temperatures, and wind speeds, the hot box flanking loss shall be fully characterized. The results from performing a minimum of three tests at different guarding temperatures can be used to solve for the coefficients in Eq A2.2 for a simple hot box. This matrix shall be repeated when operating the hot box with different panels and at different environmental conditions to fully characterize the apparatus at the conditions at which testing takes place.

A6.3 It is essential that the air velocities, power inputs and temperatures for the metering, guard and climatic chambers be held constant throughout each test. By holding all the control parameters constant, the operator reduces the variability of the surface heat transfer coefficients on the specimen during the test.

A6.4 The first step in characterizing a hot box is to develop a matrix identifying all the test conditions and specimens anticipated for testing in the apparatus. If testing includes fenestration products or other specimens that are smaller than the metering aperture, all the surround panels constructions and thicknesses to be used shall be identified. Next, arrange the

**TABLE A6.2 Test Matrix for Calibration of an ASTM C1363 Hot Box**

| Test No. | Metering Chamber Air Temperature, °C | Guard Chamber[A] Air Temperature, °C | Climate Chamber Air Temperature, °C | Metering Wall Thermopile Output, Volts | Calibration Panel Thickness,[B] mm | Metering Chamber Air Velocity, m/s | Climate Chamber Air Velocity, m/s |
|---|---|---|---|---|---|---|---|
| Hot box used for general testing at different environmental conditions including multiple air velocities. | | | | | | | |
| 1 | 21.1 | 21.1 | −17.8 | 0 | 50 | 0.2 | 5.4 |
| 2 | 21.1 | 18.3 | −17.8 | + | 50 | 0.2 | 5.4 |
| 3 | 21.1 | 23.9 | −17.8 | − | 50 | 0.2 | 5.4 |
| 4 | 21.1 | 21.1 | −17.8 | 0 | 50 | 0.4 | 5.4 |
| 5 | 21.1 | 18.3 | −17.8 | + | 50 | 0.4 | 5.4 |
| 6 | 21.1 | 23.9 | −17.8 | − | 50 | 0.4 | 5.4 |
| 7 | 21.1 | 21.1 | −17.8 | 0 | 50 | 0.2 | 1.3 |
| 8 | 21.1 | 18.3 | −17.8 | + | 50 | 0.2 | 1.3 |
| 9 | 21.1 | 21.1 | −17.8 | − | 50 | 0.2 | 1.3 |
| 10 | 21.1 | 21.1 | −17.8 | 0 | 50 | 0.4 | 1.3 |
| 11 | 21.1 | 18.3 | −17.8 | + | 50 | 0.4 | 1.3 |
| 12 | 21.1 | 23.9 | −17.8 | − | 50 | 0.4 | 1.3 |
| 13 | 21.1 | 21.1 | −17.8 | 0 | 114 | 0.2 | 5.4 |
| 14 | 21.1 | 18.3 | −17.8 | + | 114 | 0.2 | 5.4 |
| 15 | 21.1 | 23.9 | −17.8 | − | 114 | 0.2 | 5.4 |
| 16 | 21.1 | 21.1 | −17.8 | 0 | 152 | 0.2 | 5.4 |
| 17 | 21.1 | 18.3 | −17.8 | + | 152 | 0.2 | 5.4 |
| 18 | 21.1 | 23.9 | −17.8 | − | 152 | 0.2 | 5.4 |

| Test No. | Metering Chamber Air Temperature, °F | Guard Chamber[A] Air Temperature, °F | Climate Chamber Air Temperature, °F | Metering Wall Thermopile Output, Volts | Calibration Panel Thickness,[B] in. | Metering Chamber Air Velocity, mph | Climate Chamber Air Velocity, mph |
|---|---|---|---|---|---|---|---|
| Hot box used for wall and fenestration testing at different environmental conditions. | | | | | | | |
| 19 | 21.1 | 21.1 | −17.8 | 0 | 203 | 0.2 | 5.4 |
| 20 | 21.1 | 18.3 | −17.8 | + | 203 | 0.2 | 5.4 |
| 21 | 21.1 | 23.9 | −17.8 | − | 203 | 0.2 | 5.4 |
| 22 | 37.8 | 37.8 | 10.0 | 0 | 50 | 0.2 | 1.3 |
| 23 | 37.8 | 35.0 | 10.0 | + | 50 | 0.2 | 1.3 |
| 24 | 37.8 | 40.6 | 10.0 | − | 50 | 0.2 | 1.3 |
| 25 | 37.8 | 37.8 | 10.0 | 0 | 50 | 0.4 | 1.3 |
| 26 | 37.8 | 35.0 | 10.0 | + | 50 | 0.4 | 1.3 |
| 27 | 37.8 | 40.6 | 10.0 | − | 50 | 0.4 | 1.3 |
| 28 | 37.8 | 37.8 | 10.0 | 0 | 114 | 0.2 | 1.3 |
| 29 | 37.8 | 35.0 | 10.0 | + | 114 | 0.2 | 1.3 |
| 30 | 37.8 | 40.6 | 10.0 | − | 114 | 0.2 | 1.3 |
| 31 | 37.8 | 37.8 | 10.0 | 0 | 152 | 0.2 | 1.3 |
| 32 | 37.8 | 35.0 | 10.0 | + | 152 | 0.2 | 1.3 |
| 33 | 37.8 | 40.6 | 10.0 | − | 152 | 0.2 | 1.3 |
| 34 | 37.8 | 37.8 | 10.0 | 0 | 203 | 0.2 | 1.3 |
| 35 | 37.8 | 35.0 | 10.0 | + | 203 | 0.2 | 1.3 |
| 36 | 37.8 | 40.6 | 10.0 | − | 203 | 0.2 | 1.3 |

[A] Guard chamber or surrounding laboratory environment.
[B] Or continuous surround panel.

matrix so that the environmental conditions and surround panels are ordered from the lowest to highest or least conductive to most conductive. This matrix shall be used to identify the range of environmental conditions and characterization panels that will be used to perform the tests.

A6.5 For the example illustrated in Table A6.1, the apparatus is assumed to operate only at a 21.1°C metering chamber air temperature and a −17.8°C climatic chamber air temperature. The air velocities are held constant on both sides as specified in Test Method C1199. The fenestration specimens are always mounted in one of three surround panels, but of different thickness. The thinnest and thickest surround panel shall be tested first, and if the differences between the metering box wall transducer and flanking loss coefficients are negligible, then the middle thickness of surround panel may not have to be tested. Note that for Test Method C1199 the flanking loss at the interface between the window or door and the surround panel is assigned to the U-factor of the fenestration unit and therefore does not need to be evaluated separately.

A6.6 For the test matrix illustrated in Table A6.2, the apparatus is operated over a wide range of temperatures, air velocities and specimens. This would be the case for a hot box used for testing walls at one set of temperatures and air velocities, and then testing windows installed in multiple thicknesses surround panels at different environmental conditions. For this configuration, the metering chamber heat flow, and thermal chamber flanking loss shall be evaluated over a wide range of test conditions. This is a most complex system and shall require a matrix of tests up to or exceeding the 36 listed in Table A6.2. Completion of all the tests in the matrix is not necessary if it can be shown that there is no significant variation in the metering box wall transducer and flanking loss coefficients seen upon testing at the extremes values of a particular environmental condition.

A6.7 Hot boxes operating in many commercial laboratories need a testing matrix between these two examples. A careful examination of the testing conditions anticipated might limit the number of tests required. For a research apparatus, full characterization of the apparatus is required since the exact conditions of the test cannot always be anticipated.

A6.8 Perform a test at each of the environmental conditions in the characterization matrix. As a minimum, one test, in the matrix, is performed with the guarding temperature above the metering chamber air temperature, the second test has the guarding temperature equal to the metering room air temperature, and the third test is performed with the guarding temperature below the metering box air temperature. All other temperatures and air velocities shall be held constant during a test. Each test must meet steady state conditions as specified by Section 10.

A6.9 Solve Eq A2.4 for the metering box wall transducer and flanking loss coefficients at each environmental condition. By plotting the heat flow versus the output from the metering box wall thermocouple, determine the slope, $m$, and the $y$-intercept, $[E_o + Q_{fl}]$.

A6.10 Test the parameter values at the extremes of the test matrix first. The test laboratory operator can then identify those environmental conditions that do not have significant influence on the metering box wall transducer and flanking loss coefficients. Any parameters, which are shown to not significantly change the metering box wall transducer and flanking loss coefficients can then be removed from the calibration testing matrix.

A6.11 The measured metering box wall heat flows and flanking loss shall also be compared to the theoretical values calculated in Annex A3 and Annex A4. If there is a significant discrepancy between the measured and calculated heat flow, conduct an investigation to identify the reason for this discrepancy.

## A7. AN EXAMPLE OF A HOT BOX CHARACTERIZATION TESTING PROGRAM

A7.1 The following example of the application of Annex A4 through Annex A6 to an actual hot box is presented here for illustration purposes. More detailed information is available in the referenced materials. This is only an example of the process required and not a specific guideline for its application.

A7.2 *Test Apparatus*—This example is based upon the flanking loss discussion by Lavine et al (**12**) that was used for the calibrated hot box described by Mumaw (**2**). That hot box is a vertical wall tester with a metering area of 2.7 by 4.3 m. The chambers and specimen frame are constructed of urethane foam (0.5 m thick) with glass fiber reinforced polyester (GRP) skins (1 to 3 mm thick). The example is specific to that facility, however the development procedure and calibration results are useful as a guide for other hot box users.

A7.3 *Perspective*—It is informative to note the approximate magnitude of the flanking loss relative to the heat flow through the specimen for some typical conditions. Consider a 110 mm thick wall with an overall thermal resistance of 2.5 $m^2K/W$, tested at a 10°C mean temperature. Under these conditions, for the example hot box, the flanking loss $(Q_{fl})$ is estimated to be 6 % of the specimen heat flow $(Q)$. This is a small percentage, but is not negligible. If $Q_{fl}$ could be calculated to within 10 % error, then the resultant error in $Q$ would be 0.6 %. The magnitudes of $Q_{fl}$ and $Q$ are strongly related, since both are proportional to the $\Delta t$ across the specimen. For this example, the value of 6 % is typical for $Q_{fl}$ relative to $Q$. This magnitude could be significantly different for another test construction or a different specimen area. In contrast to this example, if a plywood skin were used as the skin for the frame, it will provide a low thermal resistance flanking path for the flanking loss. For a 13 mm thick, continuous plywood skin, the flanking loss would exceed 10 % of the specimen heat flow under many test conditions.

A7.4 *Effect of Specimen Thickness*—For the example, the thickness dependence of the flanking loss was investigated theoretically using HEATING 5, a finite difference heat conduction program (17). A cross-section at the joint between the frame and the specimen was modeled. The metering chamber, climatic chamber, and room air temperatures were taken to be 24, −4, and 24°C, respectively. Since the metering chamber and room air temperatures were chosen to be equal, there was no metering box wall loss, and all heat leaving the metering chamber ended up in the climatic chamber. Thus, the flanking loss was simply the quantity of heat leaving the metering chamber through the frame, integrated over the perimeter of the frame.

A7.4.1 Modeling runs were made on the example facility to determine the effect of thickness. The thickness of the specimen ranged from 19 to 300 mm, and the specimen thermal conductivity was held constant. (A few runs were made which determined that varying the specimen thermal conductivity did not strongly affect the flanking loss.) Fig. A7.1 illustrates the shape of flanking loss per unit temperature difference as a function of specimen thickness, as predicted by the model. Since $\Delta t_{a-a}$ and $\lambda_{eff}$ were constant for these runs, this plot can be used to define the thickness dependence of the flanking loss, $(A/L)_{eff}$. Once the functions $\lambda_{eff}$ and $(A/L)_{eff}$ had been defined, the predicted flanking loss equation was complete. It could then be compared to experimental results to determine the exact coefficients for the equation.

A7.4.2 Using the model, the temperature dependence of the materials was estimated to have less than a 10 % effect on the flanking loss. Since the flanking loss for the example hot box was on the order of 6 % of the specimen heat flow, temperature dependence of the effective frame thermal conductivity has only a minor influence on the specimen heat flow. It was, however, included in the final characterization equations.

A7.5 *Characterization Tests*—For the example characterization procedure, a series of hot box tests was run on homogeneous specimens with known thermal characteristics. Single thickness (35 mm) and triple thickness (105 mm) specimens were constructed for flanking loss as a function of specimen thickness. To investigate the temperature dependence of flanking loss, a series of tests was performed on each specimen. Temperature differences across the specimen ranged from 28 to 58 K, and mean temperatures varied from −13 to 49°C.

A7.6 *Variation with Effective Thermal Conductivity*—From the tests, a strong linear trend, Fig. A7.2, can be observed for both of the specimens. Since the flanking loss had been predicted to be proportional to the independent variable, straight lines were fit through the data, constrained to go through the origin. This was done separately for the single and triple thickness specimens. A statistical analysis indicated acceptable agreement between the data and the regression lines. Thus, the predicted temperature dependence of the flanking loss had been validated. In this series, however, the slopes of the two regression lines indicated two values of $(A/L)_{eff}$, one for each specimen thickness. This demonstrates the predicted thickness dependence of the flanking loss.

A7.7 *Thickness Variation*—Notice that the regression of $Q_{fl}$ versus $\lambda_{eff} \cdot \Delta t_{a-a}$ may also provide an experimental estimate of the function $(A/L)_{eff}$. In Fig. A7.3, the experimental flanking loss and the theoretically predicted flanking loss are now plotted versus specimen thickness. If the general shape of the experimental and theoretical results is in agreement, then the appropriate coefficients can be determined by regression. In this example, the theoretical model results and the two experimental estimates of $(A/L)_{eff}$ do not fall on the theoretical curve, but that the general shape of the curve appears to be correct. Observe that the theoretical curve predicts flanking loss to be inversely proportional to thickness for large thicknesses (150 to 300 mm). For smaller thicknesses, the flanking loss curve becomes very steep. The difference between the tested results and the model results was attributed to differences between the assumed and actual physical properties and dimensions.

A7.7.1 From the modeling results, it is probable that the flanking loss dependence on thickness has the general equation form of Eq A7.1:

$$(A/L)_{eff,\,th} = \frac{a}{(b + th)} \tag{A7.1}$$

where:

$a$ and $b$ = model constants, and
$th$ = the specimen thickness.

A7.7.2 The two constants were solved for using the two experimental estimates of $(A/L)_{eff}$. The regression curve, also

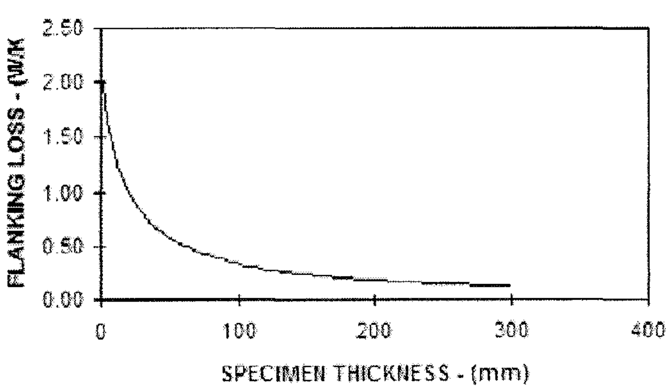


**FIG. A7.1 Relationship of Flanking Loss to Specimen Thickness (Estimated with Modeling)**

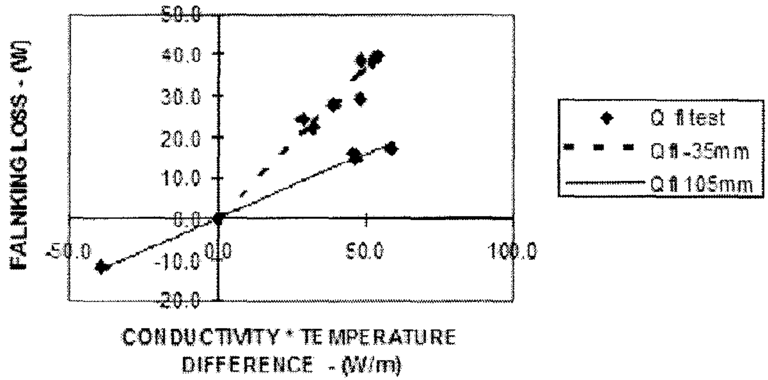


FIG. A7.2 Relationship of Flanking Loss to Conductivity/Temperature Difference

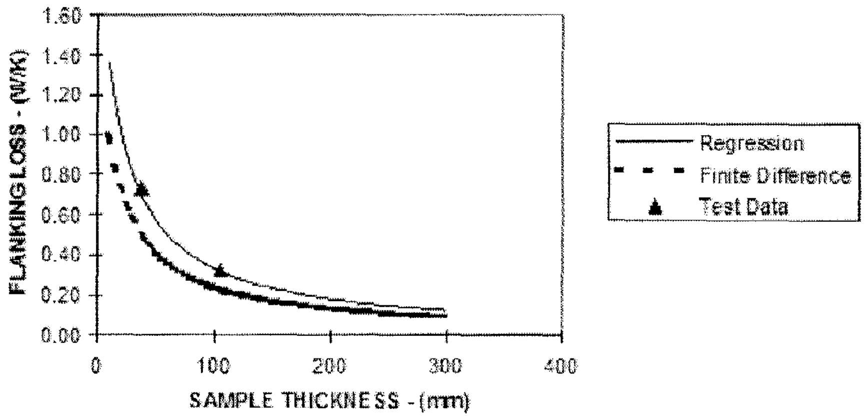


FIG. A7.3 Relationship of Flanking Loss to Specimen Thickness (Estimated vs. Tested)

plotted in Fig. A7.3, gives a reasonable representation of flanking loss as a function of thickness.

A7.8 *Final Results*—Combining the results of the regressions on the individual effects from our experiments yields the final equation for correction of the flanking loss as a function of the experimental variables. Thus, for the example hot box, the flanking loss can be described by an equation of the form:

$$Q_{fl} = \lambda_{eff} \cdot (a / (b + th)) \cdot \Delta t_{a-a} \quad \text{(A7.2)}$$

where:

$\lambda_{eff}$ = a function of mean temperature.

A7.9 *Summary*—The results of the analysis for the example hot box are plotted versus mean specimen temperature for the two test specimens, CS1 And CS2, in Fig. A7.4. The known curve of conductance versus temperature is also shown. The root mean square of the percentage error between the test and known values was only 0.8 %.

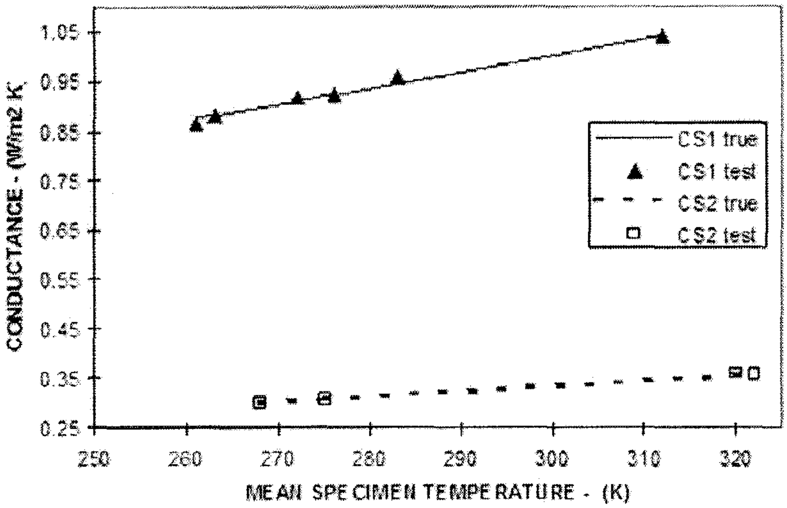


FIG. A7.4 Relationship of Conductance to Mean Specimen Temperature

## A8. USING THE HOT BOX TO DETERMINE THE HEAT TRANSFER THROUGH SPECIMENS SMALLER THAN THE METERING AREA

A8.1 *General Considerations*:

A8.1.1 Hot boxes are also used to measure the thermal resistance of specimens that are smaller than the metering area. For this type of testing, the specimen consists of the specimen installed and sealed in a surround panel built in accordance with Annex A11. In this use, the specimen of area $A_s$ is located centrally in the metering area, $A$, and is surrounded by a homogeneous surround panel of area $A_{sp} = A - A_s$. The total heat flow rate, $Q$, is determined by the hot box measurement. Assuming no interaction between the two heat flow rates in parallel, the relationship between the individual heat flows is described by Eq A8.1:

$$Q = Q_s + Q_{sp} \quad \text{(A8.1)}$$

where:

$Q_s$ = the total heat flow through the specimen area $A_s$, and
$Q_{sp}$ = the heat flow through the surround panel area $A_{sp}$.

A8.1.1.1 To determine $Q_s$, measurement is made of $Q$, using the regular hot box procedure. The surround panel heat flow, $Q_{sp}$, is calculated from measurements of the temperature difference between the surround panel surfaces and multiplying that value by the ratio of the area and thermal resistance of the surround panel. The surround panel thermal resistance is determined by means of hot box tests of the same surround panel either before the aperture for the specimen is cut out or with a blank of identical thermal conductance and thickness as the surround panel installed in place of the specimen. The characterization tests shall be performed on the surround panel at similar environmental conditions that the specimen is tested. The method of performing characterization tests on surround panels is described in Annex A5.

A8.1.2 As specified in Annex A11, the surround panel is the same thickness or somewhat thicker than the specimen (see A11.3.4.3). In addition, the materials around the perimeter of specimen may have a greater thermal conductance than the surround panel material. For both of these reasons, specimen will have a flanking loss associated with its installation in that particular surround panel. Flanking loss is shown in Fig. A8.1. Although the heat flow associated with the test specimen flanking loss is typically assigned to the heat flow through the test specimen, there are means of estimating its magnitude, and adjusting the final measured results. If the heat flow associated with test specimen flanking loss is subtracted from the specimen heat flow to calculate the reported thermal resistance of the specimen, that test specimen flanking loss shall be clearly identified in the test report.

A8.2 *Surround Panel Construction*—The construction details for the surround panels are presented in Annex A11.

A8.3 *Characterization of the Surround Panel as a Heat Flow Transducer*—The need to determine the surround panel heat flow, $Q_{sp}$, accurately requires that the surround panel be designed to act as a heat flux transducer with a temperature difference, $\Delta t$, proportional to the total heat flow through it. Before surround panels are used for testing actual specimens, the surround panel wall heat flow transducer and flanking loss coefficients shall be determined for that surround panel using the characterization tests described in Annex A4 through Annex A6. These tests require that the surround panel first be instrumented and calibrated with the specimen aperture filled with material of the same thickness, conductance and assembly as the surround panel as described in Annex A11. After the tests specified in Annex A6 are performed, then the surround panel opening flanking loss tests described in A8.4 can be performed.

A8.4 *Estimating the Surround Panel Opening Flanking Loss*:

A8.4.1 As described in Annex A3 and Annex A4, there are numerous two-dimensional and three-dimensional computer

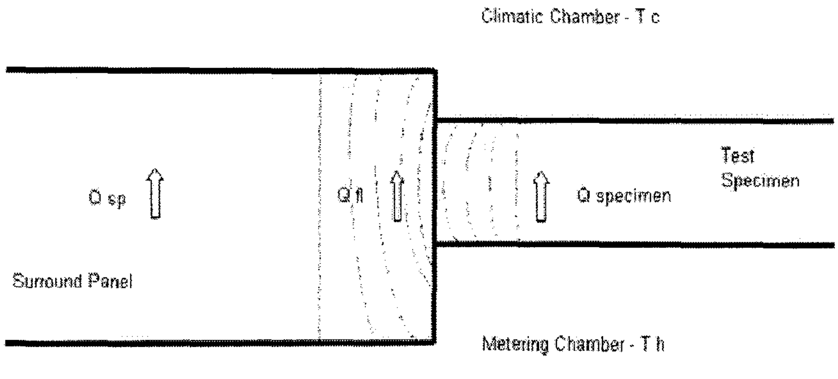


**FIG. A8.1 Test Specimen/Surround Panel Interface**

analysis tools that can be used to model and estimate the surround panel opening flanking loss. These models typically require that a representation of the surround panel and the specimen be input into the computer including the thermal conductivity, emittance, air temperatures and surface heat transfer coefficients of all the appropriate components. Much of the difficulty in modeling the flanking loss is assigning the proper air temperatures and surface heat transfer coefficients to use in the analysis.

A8.4.2 The surround panel opening flanking loss shall be estimated by performing a test on a transfer standard of known thermal properties, which is the same thickness as the specimen to be tested. An example of such a transfer standard is described in detail in Annex A1 of Test Method C1199. The transfer standard of known thermal properties is instrumented, installed and sealed into the hole in the surround panel, and a characterization test is performed at the same environmental conditions, as the test specimen will be tested. It is recommended that the transfer standard be positioned in the same position as the test specimen at the juncture with the surround panel aperture. An estimate of the surround panel opening flanking loss is calculated by first subtracting the expected heat flow through the transfer standard, as determined by multiplying the temperature difference across the panel by its area and thermal conductance, from the measured heat flow through the metering chamber opening. The final result is then determined by subtracting the heat transfer through the surround panel from the first result. An example of a characterization matrix for a single thickness surround panel is given in Table A8.1.

NOTE A8.1—Additional uncertainty may arise due to the possible influences of the specimen in causing two or three dimensional heat flow at its boundary with the surround panel. The surround panel heat flow, determined under a given set of conditions with a transfer standard in place, may change when the actual specimen is installed, even though the test conditions remain unchanged. The user of this procedure shall attempt to evaluate the impact of this uncertainty on the desired accuracy of the test.

A8.5 *Uncertainty Estimation of Measuring Specimens Smaller Than the Metering Area*:

A8.5.1 From Eq A8.1, the uncertainty in $Q_s$ is equal to the difference of the uncertainty in $Q$ and $Q_{sp}$. The fractional uncertainty is given by:

$$\Delta Q_s / Q_s = (\Delta Q - \Delta Q_{sp}) / (Q - Q_{sp}) = [(\Delta Q / Q) - (\Delta Q_{sp} / Q)] / (1 - Q_{sp} / Q) \quad (A8.2)$$

where:

$\Delta Q_s$ = the uncertainty in $Q_s$, etc.

A8.5.1.1 An estimate of the fractional uncertainty, $\Delta Q_{sp}/Q$, is dependent upon the method used to calibrate the surround panel. If the characterization is made before the aperture for the specimen is cut out then:

$$\Delta Q_{sp} / Q = (\Delta Q_t / Q) \times (A_{sp} / A) \quad (A8.3)$$

**TABLE A8.1 Test Matrix for Characterization of an ASTM C1363 Hot Box for a Single Thickness Surround Panel (Includes Flanking Loss)**

| Test No. | Metering Chamber Air Temperature, °C | Guard Chamber[A] Air Temperature, °C | Climate Chamber Air Temperature, °C | Metering Wall Thermopile Output, Volts | Surround Panel Thickness, mm | Transfer Panel Thickness,[B] mm |
|---|---|---|---|---|---|---|
| Nul | Ambient | Ambient | Ambient | 0 | 152 | No Opening |
| 1 | 21.1 | 21.1 | -17.8 | 0 | 152 | No Opening |
| 2 | 21.1 | 18.3 | −17.8 | + | 152 | No Opening |
| 3 | 21.1 | 23.9 | −17.8 | − | 152 | No Opening |
| 4 | 21.1 | 21.1 | −17.8 | 0 | 152 | 25 |
| 5 | 21.1 | 21.1 | −17.8 | 0 | 152 | 76 |
| 6 | 21.1 | 21.1 | −17.8 | 0 | 152 | 127 |

[A] Guard chamber or surrounding laboratory environment.
[B] Installed in the surround panel opening.

where:

$\Delta Q_{sp}$ = the uncertainty in heat flow measured during the characterization test.

A8.5.1.2 If a blank of known thermal conductance is used to calibrate the surround panel then:

$$\Delta Q_{sp} / Q = (\Delta Q_t - \Delta Q_{cp}) / Q \quad \text{(A8.4)}$$

where:

$\Delta Q_{cp}$ = the uncertainty in determination of heat flow through the characterization panel.

A8.5.1.3 Little can be said in general about the magnitudes of the fractional uncertainties $\Delta Q_t/Q$ and $\Delta Q_{sp}/Q$ since these depend on the quality and management of the particular hot box apparatus and upon the accuracy of determination of heat flow through the blank, but it is evident that the systematic portion of the uncertainty $\Delta Q_s/Q_s$ is reduced as $\Delta Q_{sp}/Q_t$ is made small. Also, as $Q_{cp}$ is made small, the term $\Delta Q_{cp}/Q_t$ is presumably also made less significant. Thus, the fractional systematic uncertainty possible in the determination of $Q_s$ is reduced by increasing either the area of the specimen (if feasible), or the total thermal resistance of the surround panel.

## A9. DETERMINATION OF THE ENVIRONMENTAL TEMPERATURE IN A HOT BOX ENVIRONMENT

A9.1 *General Considerations*:

A9.1.1 *Background*—The heat transfer environment seen by the specimen surfaces within a hot box apparatus are generally controlled by two types of heat transfer, convection and radiation. The air conduction heat transfer is small and can be neglected when compared to radiation and convective heat transfer at the surface boundary. For purposes of this method, it is lumped with the convective component. The measured surface and air temperatures control the convective heat transfer. The radiation heat transfer is a function of the measured surface temperatures of the surrounding enclosure, including the baffle. Although it is desirable to have the surrounding surface temperatures as close to the air temperature as possible, that condition does not always exist, especially if the specimen contains highly conductive components (that is, steel studs, single glazed window, etc.). Therefore, it is more accurate to describe the heat flow (or thermal transmittance) through a specimen in terms of the environmental temperature difference as opposed to the air temperature difference alone.

A9.1.2 *Need*—Calculation of the environmental temperature for a hot box test is important where the average surface temperature is not easily defined. Generally, this is due to the presence of thermal bridging within the specimen. The definition of environmental temperature permits the surface coefficient to be defined as a function of one temperature variable, $T_{env}$, which replaces both the air and equivalent radiative surface temperatures. The determination of environmental temperature is required to enable the use of this Test Method's (C1363) test results in calculating the heat transfer parameters required by the equivalent ISO 8990 Hot Box Procedure.

A9.1.3 *Introduction*—The following equations are expressed in general terms. These equations are used for both the climatic side and the metering side of the specimen surfaces in the hot box by inserting the appropriate surface and environmental parameters.

NOTE A9.1—Eq A9.2 assumes that the view factor between the baffle surfaces and the specimen is unity, and therefore the specimen surfaces are assumed to only "view" the baffle and other surfaces in the chamber on which surface temperatures are measured. If the specimen views a relatively large areas of the surround panel or itself (that is, the metering side of a curb mounded skylight), the view factor, the radiation exchange of specimen and the surfaces in view of the specimen must be determined by a more detailed analysis. See ISO 12567 for a more detailed analysis of how to determine the radiation exchange between the specimen and the surround panel edge.

A9.2 *Heat Flow Components*:

A9.2.1 *Convective Heat Transfer*—The convective heat transfer is an exchange of heat from the surface to the surrounding air by convective means. This heat flow is a function of the system geometry, air flow properties, and air velocity, and is generally expressed by Eq A9.1:

$$Q_{conv} = h_{conv} \cdot A_s \cdot \Delta t_{s-a} \quad \text{(A9.1)}$$

where:

$Q_{conv}$ = heat flow by convection from the specimen surface, W,

$h_{conv}$ = convective heat flow coefficient, W/m$^2$ K,

$A_s$ = specimen projected surface area., m$^2$, and

$\Delta t_{s-a}$ = the temperature difference between the specimen area weighted average surface temperature ($t_s$), and the surrounding average air temperature ($t_a$); where, for the metering side: $\Delta t_{s-a} = (t_h - t_1)$, and for the climatic side: $\Delta t_{s-a} = (t_2 - t_c)$.

A9.2.2 *Radiation Heat Transfer*—The radiation heat transfer is an exchange of heat between the specimen surface and the surrounding enclosure by radiation. This heat flow, is also a function of the system geometry, and the surrounding surface temperatures, and is generally expressed by Eq A9.2:

$$Q_{rad} = h_{rad} \cdot A_s \cdot \Delta t_{s-b} \quad \text{(A9.2)}$$

where:

$Q_{rad}$ = heat flow by radiation from the specimen surface to that of the surrounding enclosure, W,

$\Delta t_{s-b}$ = the temperature difference between the average test specimen surface ($t_s$) and the surrounding enclosure surfaces area weighted average temperature ($t_b$), K; where, for the metering side: $\Delta t_{s-b} = (t_{b1} - t_1)$, and for the climatic side: $\Delta t_{s-b} = (t_{b2} - t_2)$, and

$h_{rad}$ = radiation heat transfer coefficient for the surface as defined in Eq A9.3 if temperatures are in °C, W/m$^2$ K.

$$h_{rad} = \varepsilon_{eff} \cdot \sigma \cdot [(273.15 + t_s)^2 + (273.15 + t_b)^2] \cdot [(273.15 + t_s) + (273.15 + t_b)] \quad (A9.3)$$

or, in Eq A9.4, if temperatures are in absolute K,

$$h_{rad} = \varepsilon_{eff} \cdot \sigma \cdot [t_s^{\,2} + t_b^{\,2}] \cdot [t_s + t_b] \quad (A9.4)$$

and:

$\sigma$ = Stefan-Boltzmann constant = 5.673 × $10^{-08}$ W/m² K⁴,

$\varepsilon_{eff}$ = effective emittance of the specimen surface and surrounding enclosure surface as defined in Eq A9.5,

$$\varepsilon_{eff} = \frac{1}{(1/\varepsilon_s + 1/\varepsilon_b - 1)} \quad (A9.5)$$

$\varepsilon_b$ = area weighted emittance of the surrounding enclosure and baffle surfaces as seen by the specimen surface. For the metering side, $\varepsilon_b = \varepsilon_{b1}$, and for the climatic side, $\varepsilon_b = \varepsilon_{b2}$, and

$\varepsilon_s$ = area weighted emittance of the specimen surface, or the metering side, $\varepsilon_s = \varepsilon_1$, and for the climatic side, $\varepsilon_s = \varepsilon_2$.

A9.3 *Total Heat Flow*:

A9.3.1 *Total Heat Flow*—The total heat exchange from the specimen surface is then the sum of the two modes of heat flow from the surfaces defined in Eq A9.6.

$$Q_{total} = Q_{conv} + Q_{rad} \quad (A9.6)$$

A9.4 *Environmental Temperature*:

A9.4.1 *Calculation of Effective Environmental Temperature*—Eq A9.7 defines the effective environmental temperature as that temperature that yields the same net heat exchange in the simple convective mode as the combination of convective and radiation exchange seen in the test situation.

$$Q_{total} = (h_{rad} + h_{conv}) \cdot A_s \cdot \Delta t_{s-env} \quad (A9.7)$$

where:

$\Delta t_{s\text{-}env}$ = temperature difference between the average test specimen surface ($t_s$) and the effective environmental temperature ($t_{env}$); where, for the metering side, $\Delta t_{s\text{-}env} = t_{env1} - t_1$, and for the climatic side, $\Delta t_{s\text{-}env} = t_2 - t_{env2}$.

A9.4.1.1 By substituting Eq A9.1, Eq A9.2, and Eq A9.6 into Eq A9.7:

$$\Delta t_{s-env} = [h_{conv} \cdot \Delta t_{s-a} + h_{rad} \cdot \Delta t_{s-b}] \,/\, (h_{rad} + h_{conv}) \quad (A9.8)$$

NOTE A9.2—Additional discussion of the environmental temperature is found in ISO Standard 8990.

## A10. RECOMMENDED PRACTICE FOR ESTIMATION OF THE TESTING SYSTEM TIME CONSTANT

A10.1 *General Considerations*:

A10.1.1 The time required to conduct a hot box test is determined, in part, by the speed of response of the testing apparatus and the specimen's response to changes in its environment. One measure of this response to change is the time constant, $\tau$, of the system. As defined in Note 22, the time constant of the system is the time required for the system to respond to within 37 % (1/e) of its final value of response, usually heat flow, after a step change in forcing condition, usually temperature difference. As specified in 10.11, a minimum of five time constants of consecutive, uniform data shall be collected to determine if steady state conditions exist. Therefore, it is necessary that an accurate measure of the effective time constant, $\tau_{eff}$, of the operating hot box system be determined.

A10.1.2 The operation of the hot box apparatus is an heat transfer problem. Therefore, it appears logical that the time controlling factors for the hot box test would include:

*(1)* The heating and cooling capacity for the apparatus;

*(2)* The air circulation patterns and velocity;

*(3)* The internal heat storage capacity of the test chamber equipment;

*(4)* The thermal diffusivity and resistance of the materials used to construct the chambers;

*(5)* The specimen geometry;

*(6)* The specimen thermal diffusivity and resistance; and

*(7)* The specimen heat storage capacity.

A10.1.2.1 Also, any transient effects such as residual moisture change, latent heat effects, or the onset of convection within specimen will increase the time for stabilization for a test.

A10.2 *Testing System Time Constant Evaluation*—The hot box apparatus time response is controlled by either the apparatus design or the assembled properties of the specimen. For test purposes, if the apparatus time constant, $\tau_{ap}$, is greater than specimen time constant, $\tau_s$, the test will be controlled by the value of $\tau_{ap}$. If however, $\tau_{ap} < \tau_s$, then the specimen response will be the controlling factor in determining whether the test is complete. The apparatus time constant, $\tau_{ap}$, is determined by experimental measurement as described in A10.3, and the specimen time constant, $\tau_s$, is calculated as specified in A10.4. Note, however, that the two time constants may not be completely distinct and independent.

A10.3 *Response of the Apparatus*:

A10.3.1 The design of the apparatus shall include consideration of the speed of response of the test chambers to changing test conditions and the thermal lag caused by the heat capacity of the internal equipment. The speed of response of the apparatus, or time constant, $\tau_{ap}$, is fixed by the design and, for a properly designed system will be less than the specimen time constant. Since the test apparatus is generally complex compared to the specimen, and since it does not change with the specimen, the apparatus time constant, $\tau_{ap}$, can be determined by experimental means.

A10.3.2 *Experimental Determination of the Apparatus Time Constant*:

A10.3.2.1 The time constant of the apparatus, $\tau_{ap}$, can be empirically determined by measuring the speed of response of the hot box with a specimen installed. As discussed in A10.1.2, for any experimental setup, the measured system time response is the sum of the time responses of the individual parts. Any attempt to measure, experimentally, the effective time constant, $\tau_{eff}$, will, in fact, be determining the combined response of the apparatus constant, $\tau_{ap}$, and the specimen time constant, $\tau_s$. Therefore, if the time constant of the specimen can be forced to be significantly less than the time constant of the apparatus, then the apparatus time constant, $\tau_{ap}$, can be approximated using the simple experiment outlined in A10.3.3.

A10.3.2.2 Although it is impossible to create a specimen that has zero specific heat capacity, a specimen can be developed that has a low thermal resistance and low heat capacity. By examination of Eq A10.1, the specimen sample will have a lower time constant if the specific heat capacity ($M_s \cdot C_s$) is kept low, since $A_s$ and $h$ are fixed by the apparatus design. Therefore, to establish a good estimate of the minimum time constant for the apparatus, one shall use a homogeneous, lightweight, low thermal resistance specimen. This specimen design shall produce the shortest test time constant for the testing system.

A10.3.2.3 Therefore, the recommended practice is to measure the apparatus response to a step change in temperature using a low mass specimen, and then use those results to determine the shortest time constant of the system. The time constant of the system would then have to be increased if the time constant of the specimen is determined to be greater than the time constant of the apparatus.

A10.3.3 *Procedure for Experimental Time Constant Determination*—The following experimental procedure is recommended for determining the time constant for a hot box apparatus.

A10.3.3.1 Construct a specimen having the lowest *R*-value and the lightest weight that can be tested within the practical limits of the test apparatus.

A10.3.3.2 Install and seal the specimen in the hot box, close the system, initiate test conditioning. For the initial test conditions, set the air temperatures in the climate and metering chambers 5 to 10°C below the typical set point (see Note A10.1).

A10.3.3.3 Set up the data acquisition system to record all test parameters at a minimum of 5 min intervals and begin recording data.

A10.3.3.4 Continue monitoring the test data until steady state is reached. For this determination use five consecutive 1-h time averages to establish steady state (refer to 10.11.2).

A10.3.3.5 Once steady state conditions have been achieved, quickly change the test conditions in both the climate and metering chamber so that the air temperatures increase and stabilize at higher values. Record the time at which this change occurs, and continue to monitor test data.

A10.3.3.6 Continue monitoring the test data until steady state is reached. For this determination use five consecutive 1-h time averages to establish steady state.

A10.3.3.7 Plot the time versus temperature and net sample heat flow rate (for the usual case of constant temperature control) for the period from shortly before the temperature change to the second time the hot box reaches steady state. (See the example, Fig. A10.1.)

A10.3.3.8 Determine the elapsed time from the temperature change, in which the 5-min averages of temperatures and heat flow was 63.2 % of the final value.

A10.3.3.9 Determine the elapsed time from the temperature change, in which the 5-min averages of temperatures and heat flow was 85.6 % of the final value.

A10.3.3.10 The maximum difference in times for A10.3.3.8 and A10.3.3.9 is equal to the time constant for the test system, $\tau_{eff}$.

NOTE A10.1—For most circumstances, the time constant is independent of the magnitude of the temperature shift or the heat flow of the system. The controlling factor for the time constant will be the heat capacity of the air handling systems and thermal resistance of the thermal chamber walls and specimen. In thermal chambers that only have one mode of temperature control (that is, a metering chamber with electrical heaters, but no active mechanism of cooling), the rate of temperature increase may occur faster than the rate of temperature decrease. In this circumstance, the rate of heat input by the heaters is greater than the rate of heat flow that is lost through the metering chamber walls and specimen. When the air temperature in the metering chamber is increased, the metering chamber is considered to be in active mode in that the temperature controllers are adding heat to metering chamber by activating the heaters. On the other hand, when the air temperature in the metering chamber is decreased, the metering chamber is considered to be in passive mode in that the temperature controllers do not activate the heaters, and the metering chamber loses heat through the metering chamber walls and specimen. The measured time constant of such a hot box is different depending on whether the temperature in the metering chamber is increased or decreased during the time constant test. Since the chiller and heaters are typically activated during a steady state test, the apparatus time constant shall be determined while both the climate and metering chambers have their temperature control in active mode, where the heaters or the chiller system are actively used to change and control the air temperatures. For this reason, it is best to perform time constant tests where the metering chamber air temperature is suddenly increased, not decreased.

A10.3.4 *An Example for a Typical Hot Box Apparatus*—An example of an actual time constant test is provided in Fig. A10.1 and Table A10.1. The determination of time constant of the climate side baffle temperature is graphically shown. Table A10.1 presents the results of analysis for all the critical parameters. In this example, the climate side air temperature was suddenly increased 22.2°C (from −12.2 to 10°C), and the metering side air temperature was simultaneously increased 11.1°C (from 26.6 to 37.7°C). The specimen used for this experiment was a surround panel constructed of 127 mm thick polystyrene foam faced on both sides with 3 mm high-density polystyrene sheet. The time constant for the chamber with this specimen was finally considered to be 1 hour. However, the test operators have chosen to use 6 time constants of steady state data since the time constant for power was 1 h and 10 min ($5\tau$ = 5 h and 50 min ~ 6 h).

A10.4 *Calculation of Specimen Time Constants*:

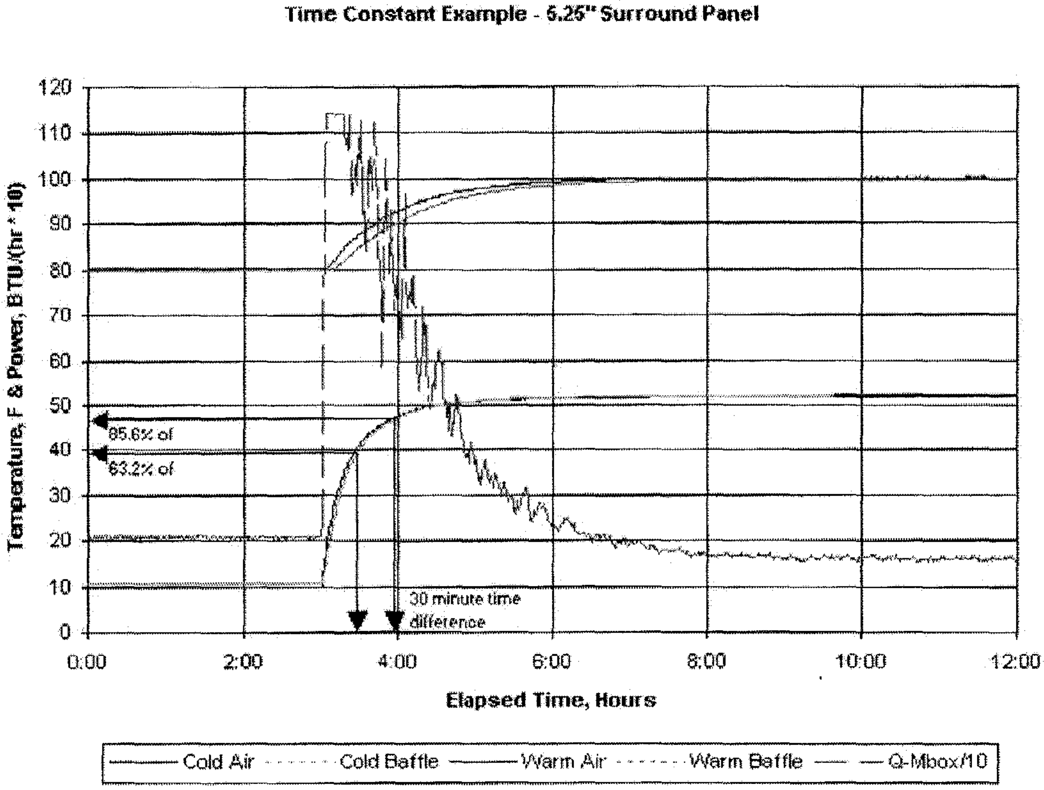


FIG. A10.1 Example Data Time Constant Determination

TABLE A10.1 Time Constant Example—133 mm Surround Panel

| Description | Symbol | 63.2 % Time | 85.6 % Time | Difference |
|---|---|---|---|---|
| Cold Air Temperature | $T_c$ | 3:24:00 | 3:54:00 | 0:30:00 |
| Cold Baffle Temperature | $T_{b2}$ | 3:29:00 | 3:59:00 | 0:30:00 |
| Cold Surround Panel Temperature | $T_{sp2}$ | 3:29:00 | 4:04:00 | 0:35:00 |
| Cold Surround Panel Guard Temperature | | 3:29:00 | 4:09:00 | 0:40:00 |
| Warm Air Temperature | $T_h$ | 4:04:00 | 4:59:00 | 0:55:00 |
| Warm Baffle Temperature | $T_{b1}$ | 4:19:00 | 5:14:00 | 0:55:00 |
| Warm Surround Panel Temperature | $T_{sp1}$ | 4:24:00 | 5:24:00 | 1:00:00 |
| Guard Surround Panel Temperature | | 4:24:00 | 5:19:00 | 0:55:00 |
| Guard Air Temperature | | 3:59:00 | 4:24:00 | 0:25:00 |
| Total Heat Flow into Metering Chamber | $Q_s$ | 7:44:00 | 8:54:00 | 1:10:00 |

A10.4.1 Since the value of the overall time constant, $\tau_{eff}$, determined in the previous section is for the low thermal resistance, low heat capacity specimen, it is necessary to evaluate the magnitude of the time constants for other specimen constructions. Of course, one could repeat the experimental procedure of A10.3.3 for every specimen. This approach, however, is expensive.

A10.4.2 One alternative is to calculate the time constant of the specimen based upon the simple formula shown in Eq A10.1. Fortunately, the time constant of a homogeneous system, such as a simple specimen, can be approximated by a first order equation, Eq A10.1:

$$\tau_s = \frac{M_s \cdot HC_s}{h' \cdot A_s} \quad (A10.1)$$

where:

$\tau_s$ = specimen effective time constant, h,
$M_s$ = mass of the composite specimen, kg,
$HC_s$ = equivalent composite specific heat, W h/kg K; equal to the sum, for the test specimen, of the product of the individual component's heat capacity and weight, divided by the total weight of the specimen,
$A_s$ = heat transfer area, m$^2$,
$h'$ = the composite surface coefficient which includes an estimate of the internal heat flow resistance, W/m$^2$ K,

and:

$$1/h' = (1/h_s) + (R) \quad (A10.2)$$

where:

$h_s$ = the surface coefficient, W/m$^2$ K, and
$R$ = the estimated specimen resistance, m$^2$ K/W.

A10.4.3 This procedure still may be too complex for a typical building construction that has many structural members with significantly different heat flow rates. A further simplification for our purpose is to estimate the time constant for each of the simple heat flow paths and then combine them into an "averaged" time constant for the complex structure. Review of the ASHRAE Fundamentals volume and other resource books on transient heat transfer, shows that the common method for combining the heat transfer parameters for a complex structure is to add the system path effects together using a parallel path technique. Applying this principle to the calculation of the time constant yields the following:

$$A_s / \tau_s = A_1 / \tau_{s1} + A_2 / \tau_{s2} + ... + A_i / \tau_{si} \quad \text{(A10.3)}$$

where:
$A_s$ = overall specimen area, m$^2$,
$A_i$ = component heat path area, m$^2$,
$\tau_s$ = specimen composite time constant, h, and
$\tau_{si}$ = specimen path component time constant, h.

A10.5 *Overall Test Time Constant:*

A10.5.1 The effective overall time constant is used to fix the time periods required for data acquisition and determination of final system stability. Above, we have established estimates for the apparatus time constant, $\tau_{ap}$, and the composite specimen time constant, $\tau_s$, for our test setup. As outlined in A10.2, the remaining step is to choose the effective overall time constant that controls our process. This choice is made as follows:

A10.5.1.1 If $\tau_s >> \tau_{ap}$, then use $\tau_{eff} = \tau_s$, or

A10.5.1.2 If $\tau_{ap} >> \tau_s$, then use $\tau_{eff} = \tau_{ap}$, or

A10.5.1.3 If $\tau_{ap} >> \tau_s$, then use the larger of $\tau_{ap}$ or $\tau_s$.

A10.5.2 To simplify the calculations and data logging, round the scan period time down to the nearest simple fraction of 1 h for the test. For example, if the time constant is determined to be 33.5 min, use 30 min; or, if the time constant is 12.5 min, use 10 min. Remember this estimate is a guide for testing and an exact determination is not required.

A10.6 *Alternative Methods*—Often a laboratory tests only one type of specimen. In these cases, a simplified method of determining the system time constant can be utilized. The following paragraphs list two possible alternate methods.

A10.6.1 One alternate approach utilizes a high thermal resistance, high heat capacity system to determine the system time constant. By a line of analysis similar to that illustrated above, a well insulated concrete wall, for example, would yield a very long specimen time constant. This time constant would significantly exceed the time constant of the apparatus. Therefore, this alternate method is to measure the time constant of the apparatus with the highest-mass specimen installed, and use that time constant for all specimens that are less massive. While this would eliminate the need to calculate the time constant of massive systems, it also would increase the time of testing required for less massive specimens.

A10.6.2 A second alternative approach has been used for fenestration testing. Fenestration test specimens are typically mounted in homogeneous surround panels, which have an aperture cut in them for installation of window products. Since the calculation of the time constant of most fenestration products would be time consuming, if not impractical, the results from measuring the time constant of the thickest continuous surround panel is often used as the time constant of most fenestration specimens. Using this approach, the time constant of the fenestration specimen only needs to be calculated if the thermal resistance is higher than the equivalent area of surround panel (that was used to measure the time constant), or if the fenestration specimen is excessively massive.

## A11. DESIGN AND CONSTRUCTION OF THE HOT BOX CHARACTERIZATION AND SURROUND PANELS

A11.1 The procedures outlined in Annex A4-Annex A6 specify the steps required to quantify the relationships for metering box wall loss and flanking loss. For the experimental analysis of these parameters, a characterization panel that fits the metering box opening is required. The surround panels required for measurement of specimens smaller than the opening of the metering chamber are identical in construction to the characterization panels. The exception is that the characterization panel is continuous and the surround panel has a hole, at its center, large enough to hold the specimen. Since the construction, but not necessarily the thickness, is identical for both panels, this section presents instructions on the fabrication and instrumentation of both characterization and surround panels. For purposes of this discussion, the word "panel" shall apply to both types.

A11.2 The need to determine the panel heat flow, $Q$, accurately requires that the panel be designed to act as a heat flux transducer with an transducer output proportional to the temperature difference, $\Delta t$, which is in turn proportional to the total heat flow through it. This consideration is the basis for the specific recommendations, which follow.

A11.3 *Construction and Instrumentation of the Panels*:

A11.3.1 The panels shall be constructed from a uniform thickness of a homogeneous and stable material of low thermal conductivity. Suitable materials are high-density glass fiber or polystyrene boards laminated together as necessary. The assembled panel shall be non-hygroscopic to minimize changes in its thermal resistance with ambient humidity conditions.

A11.3.2 Surround panels have also been fabricated by sandwiching layers of homogeneous insulation between layers of rigid materials such as plywood or plastic. Such surround panels, though non-homogeneous, are uniform in the direction perpendicular to the direction of heat flow and are characterized in the same manner as homogeneous panels. Surround panels shall have adequate strength to support the weight of the specimens to be tested.

A11.3.3 If the panel is assembled from multiple pieces of identical material, thickness and thermal conductivity, then the joints between the pieces shall be sealed with tape or caulk that is at the same emittance (± 0.1) as the panel surface to which it is attached. Tape shall not be placed more than 50 mm (2.0 in.) from the edge of the joint. If rigid insulation is used as the core material, there is an opportunity to use a "tongue and grove" or a lapped joints to help minimize the air infiltration through the joint.

NOTE A11.1—A recommended surround panel core material is expanded polystyrene (bead board) having a density in excess of 20 kg/m$^3$, which has been aged unfaced in the laboratory for a minimum of 90 days. Polyisocyanurate or other fluorocarbon-expanded cellular foam insulations are not recommended as their thermal conductivity has been shown to significantly change over time. Suitable facing materials are approximately 3 mm thick heat-resistant rigid ABS thermoplastic sheets with smooth or matte finish faces or similar thickness high-impact polystyrene plastic sheets. The surround panel needs to have some horizontal and vertical saw cuts made in the cold side facing material to minimize the effects of differential thermal expansion between the cold and hot side faces. The thin cuts should be covered with similar emittance tape strips to provide a smooth surface to the weather and room side air streams.

A11.3.4 *Surround Panels*:

A11.3.4.1 Surround panels are required for testing specimens smaller than the metering area.

A11.3.4.2 The surround panel aperture, in which the specimen is installed, shall fit the specimen snugly. Cracks, greater than 3.2 mm width, shall be filled with insulation and caulked or taped at the surround panel surfaces to prevent air leakage. It is desirable that the insulation used to fill cracks has the same thermal conductivity and thickness as the surround panel assembly. The edge of the opening in the surround panel shall be covered with non-metallic tape to minimize surface damage of the exposed core insulation. Surround panels used for characterization testing shall have the specimen aperture filled with the same material, thickness, thermal conductivity and assembly as the adjacent surround panel during the characterization tests. The joint between the perimeter surround panel and the panel filling the aperture shall be flush and sealed with tape or caulk as described above.

A11.3.4.3 The thickness of the surround panel shall be at least the maximum thickness of the specimen, and shall be in no circumstances less than 100 mm. Also, the maximum thickness of the surround panel shall be no more than 25 mm greater than the maximum thickness of the test specimen. That is, for test specimen maximum thickness less than or equal to 100 mm, the surround panel thickness shall be 100 mm. For test specimen maximum thickness greater than 100 mm, the surround panel thickness should be equal to the specimen thickness rounded to the next higher 25 mm.

A11.3.4.4 The restriction of surround panel thickness is to limit the flanking loss through the surround panel at the uncovered areas of its aperture. Other special instances, for example, a building element designed to be set a few centimeters outward from the plane of the inner surface of a wall, requires special characterization of the surround panel. In this case, a panel of known thermal conductance shall be in the same position at the juncture with the surround panel aperture as the window.

A11.3.4.5 Unless specifically required for test specimen mounting purposes (very high mass test specimens), no thermal anomalies (that is, thermal bridges like wood or metal) shall exist in the surround panel. It may be necessary, in some cases, to incorporate framing in the surround panel to support heavy specimens such as heavy-duty metal frame windows or masonry sections. Framing members shall be kept away from the specimen aperture and away from the point of contact of the metering walls so as not to contribute excessively to lateral heat transfer at these locations. Such non-uniform surround panels shall be characterized after the hole is cut using calibration blanks of the same thickness and thermal conductance as the insulated part of the surround panel. In those specific situations where the surround panel is not homogeneous, detailed drawings and description of the surround panel construction, along with the measured results shall be included with the test report.

A11.4 *Instrumentation of Characterization and Surround Panels*:

A11.4.1 The surface temperature sensors used to measure the temperature difference across the panel shall be permanently installed uniformly flush with or just under its surfaces. When thermocouples are used, they shall be connected; *(1)* as a differential thermopile for determination of the surround panel temperature difference, or, *(2)* as individual thermocouples for exploring temperature distributions on the faces of the panel. At a minimum density, there shall be five temperature sensors per square meter installed on each panel surface. The temperature sensors shall be placed in the center of equal sized areas, or their output shall be area weighted to determine the average temperature of the surround panel surface. As a minimum, there shall be eight temperature sensors on each face of the surround panel. Four located at positions bisecting the four lines from the corners of the specimen aperture to the corresponding corners of the metering area and an additional four at positions bisecting the sides of the rectangle having the first four thermocouples at its corners. A suitable temperature sensor arrangement shall be chosen for non-uniform surround panels that provide representative average surface temperatures. This is particularly important when natural convection is used and air temperatures and film coefficients vary over the metering surface. If framing members are used, an area-weighted average of temperatures measured over the members and away from them is necessary. The panel, which acts as a heat flow meter, shall be calibrated so that the heat flow is known as a function of the average temperature difference (or thermopile output voltage) across it or as indicated by the permanently installed thermocouples.

A11.4.2 Surround panels being used as characterization panels (that is, the specimen aperture is filled with a known specimen) shall have a uniform layout of temperature sensors across the surround panel surfaces and the surfaces of the material filling the specimen aperture. It is sometimes more difficult to uniformly instrument the surround panel when the specimen aperture is filled with an actual specimen, which often has its own instrumentation scheme (that is, as specified in Practice E1423). As a general practice, the hot side surface temperature sensors are place directly opposite the cold side sensors. The array of surface temperature sensors are arranged to produce the area weighted average surface temperature for each surface of interest. See 6.10 for details.

A11.4.3 To protect the panel and the permanently installed thermocouples, the surfaces must be impervious to air. A permanent coating or thin facing on each face of the panel is desirable. However, the coating or facing shall be of low lateral conductance so that it does not contribute excessively to lateral heat transfer at the juncture with the specimen or at the boundary of the metering area. The emittance of the panel surfaces shall be uniform and unchanged after testing. In all cases, the emittance of the panel surfaces shall be high ($\varepsilon > 0.8$). The adhesive, caulk or tape used to mount the temperature sensor instrumentation shall have the same emittance as the surrounding surface ($\varepsilon \pm 0.1$).

A11.4.4 It is probable that many specimens to be tested are inhomogeneous or non-uniform in construction for structural reasons, and in consequence that the local thermal conductance differs considerably at different frontal areas of the element. The variations are inherent, and the result of the test is an average conductance or transmittance value for the total construction, provided that the conductance variations at edges do not seriously impair the validity of using the surround panel as an adequate heat flow meter. This matter varies with each case and therefore must rest on the judgment and technical experience of those conducting the test measurement. A useful guiding principle is that nothing shall be incorporated in, or omitted from, a specimen being tested that would make it not representative of the assembly that would be found in actual installation in service. For example, if a metal window ordinarily is installed with inset wood framing, the test specimen shall include just so much of the wood framing as is properly chargeable to it.

A11.5 *Characterization of the Panel as a Heat flow Transducer:*

A11.5.1 Characterization of any panel material, whether used for characterization, surround panel, or as a transfer standard for windows testing (see Test Method C1199) shall be made by means of thermal tests on a representative sample of the assembled panel, their individual components, or tests on the entire panel. For this reason, it is required that the thermal resistance of a sample assembly of the characterization or surround panel be measured in an apparatus conforming to Test Methods C177 or C518 at a minimum of three temperatures over the range of conditions at which the panel will be used. An alternative is to measure the thermal resistance of a larger panel in a hot box apparatus and then subsequently reducing the panel to the size required to fit the surround panel aperture.

A11.5.2 The characterization tests should cover the range of mean temperatures at which the panel will be operated during the testing. At any one surround panel mean temperature, there should be little variation of $Q_{sp}/\Delta t$ with $\Delta t$, but $Q_{sp}/\Delta t$ may vary slightly with mean temperature due to the change of thermal conductivity to the surround panel material.

NOTE A11.2—Additional uncertainty may arise due to the possible influences of the specimen in causing two or three-dimensional heat flow at its boundary with the surround panel and thus affecting the surround panel heat flow in regions adjacent to the element. Surround panel heat flow, determined under a given set of conditions with a transfer standard in place, may change when the specimen is installed, even though the test conditions remain unchanged. If the specimen is expected to have this influence, an attempt shall be made to evaluate its impact on the desired accuracy of the test.

# APPENDIX

(Nonmandatory Information)

## X1. AIR AND MOISTURE MASS TRANSFER

### X1.1 General

X1.1.1 Heat transfer through an insulation or insulated structure is significantly increased by air infiltration or moisture migration into or through the specimen. Since such phenomena can occur in field applications, it is desirable to duplicate the conditions in the laboratory hot box and to test for heat transfer due to air and moisture transfer combined with that due to the imposed temperature difference. In principle, such testing is possible and indeed some hot boxes have been designed for these tests. Such tests are not included in the scope of this method because of the limited experience with them and because of the uncertainties of relating the results to the performance that occurs in field applications. While this method does not recommend such tests, the following guidance is given for those researchers who might attempt such tests.

### X1.2 Air Infiltration

X1.2.1 Provisions have been made in some hot box apparatus for the measurement of both heat transfer and air flow under simultaneous temperature and air pressure differentials imposed across the specimen. In such cases, the apparatus was constructed to meet all requirements of Test Method E1424 with recommended capabilities, in either direction, of flow rates up to 0.005 $m^3/s$ for each square meter of specimen area and pressure differentials to 125 Pa. Pressure taps were installed at mid height of the metering chamber and at the same height in the climatic chamber.

X1.2.1.1 **Caution:** Pressure differentials across the specimen and across box walls shall be limited to values which will not cause physical damage to the apparatus. Adequate precautions shall be taken to prevent excessive pressures and to protect personnel against possible injury in case of accidental failure.

X1.2.1.2 The air supply equipment shall maintain the dew point of air entering the hot side below that of the cold side temperature in order to prevent condensation within or on specimen. Air entering the cold chamber shall be dried sufficiently to prevent undue frosting of evaporator coils.

X1.2.2 The apparatus and specimen perimeter shall be gasketed or otherwise sealed to limit leakage both to the environment and around the specimen. Checks using an impervious specimen shall show negligible leakage for the metering chamber. A small leakage for the climatic chamber is allowable but shall be calibrated and corrections made if the flow to or from the climatic chamber is being metered.

X1.2.3 Corrections to the test heat balance for the enthalpy of the infiltration air are necessary. The magnitude of the correction will depend upon the temperature of the incoming air and the direction of its movement. If the direction is from the metering chamber to the climatic chamber, the heat carried with the air entering the metering chamber will directly add to (or subtract from) the metered heat and a correction must be made which equals the product of the air mass flow rate, its specific heat, and the temperature difference between the incoming air and that in the metering chamber. If the direction is from the climatic chamber to the metering chamber, no correction is necessary since the heat balance for the climatic chamber is not determined. In either case, the air shall be so introduced that it is thoroughly mixed to achieve the chamber air temperature before impinging upon the specimen.

X1.2.4 Measurements of heat flow made while a pressure differential is imposed can, in some respects, simulate the effect on thermal performance due to air infiltration caused by wind impingement. It is difficult, however, to relate such data to field conditions of actual wind impingement upon buildings or specimens because of the variable effects due to size, shape, and orientation and the interaction with surrounding surfaces. It must also be recognized that a wind will not necessarily impose a pressure differential across a wall equal to its velocity pressure. Thus, it is only possible to conduct tests under specified air pressure differentials and to report the results without direct relation to wind velocities. Surface thermal resistance, $R_s$, as a function of wind velocity may be found in the literature (see, for example, **(16)**. Such values, when used for the added outside surface resistance as directed in 11.3 along with the thermal resistance measured under the pressure differential and an appropriate inside surface resistance, can give an estimate of the overall thermal resistance, $R_u$, and transmittance, $U$, under wind impingement.

### X1.3 Moisture Migration

X1.3.1 Modifications to the hot box apparatus have been attempted for the measurement of heat transfer due to the combined effects of moisture migration and to the imposed temperature differential (and to an imposed pressure differential, if desired). Moisture driven behavior is complicated to measure. It seems reasonable to expect that strict steady-state thermal conditions will be established only if the specimen and the air on the hot side are completely dry or if a constant rate of moisture is introduced on the hot side under conditions that it flows through the specimen at that same rate without change in state.

X1.3.2 Non-steady state phenomena may also be of interest. If moisture is introduced on the hot side at an excessive rate and if flow to the cold side is prevented or restricted by vapor barriers or other impervious or semi-permeable layers, an accumulation of moisture will occur, either by condensation or by freezing, depending upon conditions. These effects are of interest and have been studied in the calibrated hot box. Other moisture effects are also of interest such as heat transfer during the drying of a moist specimen under the influence of a temperature gradient or during the evaporation of moisture or the melting of ice in a specimen. In all these cases, changes occur slowly enough that quasi-equilibrium is established for a period sufficiently long enough to obtain the required thermal test information.

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