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

1. Scope

1.1 This test method covers the laboratory measurement of heat transfer through a specimen under controlled air temperature, air velocity, and thermal radiation conditions established in a metering chamber on one side and in a climatic chamber on the other side.

1.2 This test method generally is used for large homogeneous or nonhomogeneous specimens. This test method may be applied to any building structure or composite assemblies of building elements for which it is possible to build a representative specimen of a size that is appropriate for the apparatus.

NOTE 1—This test method was prepared for the purpose of replacing Test Methods C 236 and C 976. The test method was developed by combining the technical information contained in the two existing hot box methods with some additional information added to improve the test accuracy and reproducibility. Test apparatus, designed and operated under Test Methods C 236 and C 976, should, in most cases, meet the requirements of this test method with only slight modifications to calibration and operational procedures.

1.3 This test method is intended for use at conditions typical of normal building applications. The usual consideration is to duplicate naturally occurring outside conditions that in temperate zones may range from approximately –48 to 85°C and normal inside residential temperatures of approximately 21°C. Building materials used to construct the specimens are generally pre-conditioned to typical laboratory conditions of 23°C and 50 % relative humidity prior to assembly. Practice C 870 may be used as a guide for sample conditioning. Further conditioning prior to testing may be performed to provide moisture conditioned samples, if necessary.

1.4 This test method permits operation under natural or forced convective conditions at the specimen surface. The direction of air flow motion may be either perpendicular or parallel to the surface.

1.5 The hot box apparatus also can be used for measurements of individual building elements that are smaller than the metering area. Special calibration specimens and procedures are required for these tests. The general testing procedures for these cases are described in Annex A4.

1.6 Specific procedures for the thermal testing of window and door systems are described in Test Method C 1199 and Practice E 1423. The hot box also may be used to investigate the effect of non-homogeneous building assemblies such as structural members, piping, electrical outlets, or construction defects such as insulation voids.

1.7 This test method governs steady-state tests 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 **(1)**. Dynamic control strategies have included both periodic or non-periodic temperature cycles, for example, to follow a diurnal cycle.

1.8 This test method does not permit intentional mass transfer of air or moisture through the specimen during measurements of energy transfer. Air infiltration or moisture migration can significantly alter 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 of testing in this test method. ASTM Subcommittee C16.30 has several task groups that are researching this testing need, and will be preparing a separate standard. Further considerations for such testing are given in Appendix X1.

1.9 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 test method 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, calibration, and operation of a hot box apparatus are provided in Refs (1-26).

1.10 This test method does not specify all details necessary for the operation of the apparatus. Decisions on 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 government regulations. If no applicable standard exists, sound engineering judgment that reflects accepted heat transfer principles shall be used and documented.

1.11 In order to ensure the level of precision and accuracy

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

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

1.12 The hot box apparatus, when constructed to measure heat transfer in the horizontal direction, can be used for testing walls and other vertical structures. When constructed to measure heat transfer in the vertical direction, the hot box can be 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 first shall be verified at that orientation with a traceable specimen in place to confirm its ability to accurately obtain results at that orientation.

1.13 *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:*

C 168 Terminology Relating to Thermal Insulating Materials[2]

C 177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus[2]

C 236 Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box[2]

C 518 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus[2]

C 870 Practice for Conditioning of Thermal Insulating Materials[2]

C 976 Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box[2]

C 1045 Practice for Calculating Thermal Transmission Properties from Steady-State Heat Flux Measurements[2]

C 1058 Practice for Selecting Temperatures for Reporting and Evaluating Thermal Properties of Thermal Insulations[2]

C 1114 Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus[2]

C 1132 Practice for Calibration of the Heat Flow Meter Apparatus[2]

C 1130 Practice for Calibrating Thin Heat Flux Transducers[2]

C 1199 Test Method for Measuring the Steady State Thermal Transmittance of Fenestration Systems Using Hot Box Methods[2]

E 230 Standard Temperature-Electromotive Force (EMF) Tables for Thermocouples[3]

E 283 Test Method for Rate of Air Leakage Through Exterior Windows, Curtain Walls and Doors[4]

E 1423 Practice for Determining the Steady State Thermal Transmittance of Fenestration Systems[4]

E 1424 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[4]

2.2 *Other Documents:*

ASHRAE Handbook 1993 Fundamentals Volume, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.[5]

ISO Standard 8990 Thermal Insulation Determination of Steady State Thermal Properties—Calibrated and Guarded Hot Box, ISO 8990-1994(E)[6]

3. Terminology

3.1 *Definitions*—Definitions of terms relating to insulating materials and testing used herein are governed by Terminology C 168. All terms discussed in this test method can be assumed to be those associated with thermal properties of the tested specimen unless otherwise noted.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *metering box energy flow, n*—The time rate of energy loss or gain through the walls of the metering box that must be subtracted from or added to the energy input to the metering chamber as part of the determination of the net energy flow through the test specimen. A more complete discussion of the metering box loss is provided in Annex A1.

3.2.2 *flanking path energy flow, n*—The time rate of energy loss or gain from the metering chamber to the climatic chamber that passes through the sample or sample holder beyond the boundaries of the metering chamber. This energy exchange must also be subtracted from or added to the energy input to the metering chamber as part of the determination of the net energy flow through the test specimen. A more complete discussion of the flanking loss is provided in Annex A3.

3.2.3 *surface resistance, R_i*—the quantity determined by the temperature difference, at steady state, between an isothermal surface and its surroundings that induces a unit heat flow per unit area by the combined effects of conduction, convection, and radiation. Subscripts h and c are used to differentiate between hot side and cold side surface resistances, respectively. Surface resistances are calculated as follows (see Note 5):

$$R_h = \frac{A \bullet (t_{env,h} - t_1)}{Q} \tag{1}$$

$$R_c = \frac{A \bullet (t_2 - t_{env,c})}{Q} \tag{2}$$

3.2.4 Overall thermal resistance, R_u – the quantity determined by the temperature difference, at steady state, between the environments on the two sides of a body or

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

[3] *Annual Book of Standards*, Vol 14.01.

[4] *Annual Book of Standards*, Vol 04.07.

[5] Available from ASHRAE Inc., 1791 Tullie Circle, NE, Atlanta, GA 30329.

[6] Available from ANSI, 105-111 South State St., Hackensack, New Jersey 07601.

assembly that induces a unit heat flow per unit area by the combined effects of conduction, convection and radiation. It is equal to the sum of the resistances of the body or assembly and of the two surface resistances and may be calculated as follows:

$$R_u = \frac{A \bullet (t_{env,h} - t_{env,c})}{Q} \quad (3)$$
$$= R_c + R + R_h$$

3.2.5 Surface Coefficient Determination – An expanded discussion of the interactions between the radiation and convective heat transfer at the surfaces of the test sample is included in Annex A6. The material presented in Annex A6 must be used to determine the magnitude of the environmental temperature which may be required to correct for radiation heat flow from the air curtain baffle.

3.2.6 For very non-uniform specimens where the heat transfer is greatly different from one area to another, and if detailed temperature profiles are not known, only the net heat transfer through the specimen may be meaningful. In these cases, only the overall resistance, R_u, and transmission coefficient, U, are permitted.

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

A = metered area, m^2
λ = thermal conductivity, W/(m•K)
C = thermal conductance, W/(m^2•K)
E = emf output of heat flux transducer or thermocouple, V
h_h = surface heat transfer coefficient, hot side, W/(m^2•K)
h_c = surface heat transfer coefficient, cold side, W/(m^2•K)
h_{conv} = convective surface heat transfer coefficient, W/(m^2•K)
h_{rad} = radiative surface heat transfer coefficient, W/(m^2•K)
L = length of the heat loss path (usually the thickness of the test panel), m
q = heat flux (time rate of heat flow through unit area *A*), W/m^2
Q = time rate of heat flow, total power input to the metering box, W
R = thermal resistance m^2•K/W
R_h = surface resistance, hot side, m^2•K/W
R_c = surface resistance, cold side, m^2•K/W
R_u = overall thermal resistance, m^2•K/W
S = heat flux transducer calibration factor (a function of temperature), W/(m^2•V)
t_a = temperature of ambient air, K or °C
t_{env} = the effective environmental temperature including radiation and convective effects, K or °C (See Annex A6)
t_h = average air temperature 75 mm or more from the hot side surface, K or °C
t_1 = area weighted temperature of specimen hot surface, K or °C
t_2 = area weighted temperature of the specimen cold surface, K or °C
t_c = average air temperature 75 mm or more from the cold side surface, K or °C
t_m = average specimen temperature—average of two opposite surface temperatures, K or °C
Δt = temperature difference between two planes of interest, K or °C
$\Delta t_{s\text{-}s}$ = temperature difference—surface to surface, K or °C
$\Delta t_{a\text{-}a}$ = temperature difference—air to air, K or °C
τ_{eff} = effective thermal time constant of combined apparatus and specimen, *s*
U = thermal transmittance, W/(m^2•K)

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

3.4.1 *apparent thermal conductivity:*

$$\lambda = \frac{Q \bullet L}{A\,(t_1 - t_2)} \quad (4)$$

NOTE 2—Materials are considered homogeneous when the value of the thermal conductivity is not significantly affected by variations in the thickness or area of the sample within the range of those variables normally used.

3.4.2 *thermal resistance, R*:

$$R = \frac{A \bullet (t_1 - t_2)}{Q} \quad (5)$$

3.4.3 *thermal conductance, C*:

$$C = \frac{Q}{A \bullet (t_1 - t_2)} \quad (6)$$

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.

3.4.4 *surface heat transfer coefficient, h,* is often called surface conductance or film coefficient. Subscripts *h* and *c* are used to differentiate between hot side and cold side surface conductances, respectively. These conductances are calculated as follows:

$$h_h = \frac{Q}{A \bullet (t_{env,h} - t_1)} \quad (7)$$

$$h_c = \frac{Q}{A \bullet (t_2 - t_{env,c})} \quad (8)$$

NOTE 4—The surface heat transfer coefficient, h_i, and the corresponding surface resistance, R_i, (see 3.5.1) are reciprocals, that is, their product is unity.

3.4.5 *thermal transmittance, U* (sometimes called overall coefficient of heat transfer). It is calculated as follows:

$$U = \frac{Q}{A \bullet (t_{env,h} - t_{env,c})} \quad (9)$$

The transmittance can be calculated from the thermal conductance and the surface heat transfer coefficients as follows:

$$1/U = (1/h_h) + (1/C) + (/h_c) \quad (10)$$

NOTE 5—Thermal transmittance, *U*, and the corresponding overall thermal resistance, R_u (see 3.5.2), are reciprocals, that is, their product is unity.

4. Summary of Test Method

4.1 The hot box apparatus is designed to determine thermal performance for representative test specimens by establishing and maintaining a desired steady temperature difference across the test specimen for the period of time necessary to ensure constant energy flux 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 energy flow,Q and the temperature differences, ΔT, all of which must be determined under such conditions that the flow of energy is steady.

4.3 The area and temperatures can be measured directly. The energy flow Q, however, cannot be directly measured. To determine the net energy flow through the specimen, a five-sided metering box is placed with its open side against the warm face of the test panel.

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

4.5 Since it is impractical to have the condition described in 4.4, the hot box apparatus must be designed to obtain an accurate measure of the net sample heat flow. The net energy transfer through the specimen is determined from net measured energy input to the metering chamber, corrected for the losses through the chamber walls and flanking loss for the specimen at the perimeter of the metering area.

4.6 The heat loss 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 specimen 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 test panel near the perimeter of the metering area (see Annex A3 and Annex A4).

4.8 Both the metering chamber wall loss and the flanking loss corrections are based upon a series of calibration tests using specimens of known thermal properties that cover the range of anticipated performance levels and test conditions (see Annex A1-Annex A3 for details).

5. Significance and Use

5.1 There is a need for accurate data on heat transfer through insulations and through insulated structures. The data are needed to judge compliance with specifications and regulations and are needed 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 C 177 and C 518 are adequate in providing data on small scale, homogeneous specimens bounded by temperature controlled flat impervious plates. This test method is more suitable for providing such data for large specimens, usually of a built-up or composite nature, that are exposed to temperature-controlled air on both sides.

5.2 For the results to be representative of a building construction, only representative full-scale sections should be tested. The specimens should duplicate framing geometry, material composition and installation practice, and orientation of construction.

5.3 This test method does not establish test conditions, specimen configuration, or data analysis procedures, 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 will be 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 test results must be warned about possible significant differences.

5.4 Detailed heat flow analysis should precede the use of the hot box apparatus for large, complex structures. Structures which contain cavity spaces between adjacent surfaces, that is, 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, baffles at the guard/meter interface, etc. when designing the test arrangement.

5.5 For vertical specimens with air spaces that significantly affect thermal performance, the metering chamber dimension should ideally match the construction height. If this is not possible, horizontal convection barriers shall be installed inside the test specimen air cavities at the metering chamber boundaries to prevent air exchange between the metering and guarding areas.

5.6 Since this test method is used to determine the total energy flow through the test area demarcated by the metering box, it is possible to determine the energy 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 A4 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 test method, the designer should review the discussion on limitations and accuracy in Section 13, discussions of metering box loss inAnnex A1 and Annex A2, and flanking loss, Annex A3. 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 must be designed as a system to provide the desired air temperature, air velocity, and radiation conditions for the test, and to accurately measure the resulting net heat transfer. A diagram of the relative arrangement of those spaces is shown in Fig. 1.

6.2.1 The basic hot box apparatus can be assembled in a wide variety of sizes, orientations, and designs. Two configurations historically have been used for a majority of the designs. The first is the classic guarded 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 known as the calibrated hot box. This configuration can be considered a special case of the guarded hot box in which the surrounding ambient is used as the guard chamber. An additional design consideration for this hot box design is that the metering chamber walls must have sufficient thermal resistance to reduce the metering wall energy flow to an acceptable level. The calibrated design is generally used for testing of large specimens where the cost of a large guard chamber is prohibitive. Fig. 3 shows an example of a calibrated 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 box” and “cold box” apply. In some apparatus, either direction of energy flow may apply.

6.3 *Apparatus Size*—The overall apparatus shall be sized according to its intended use. For building assemblies, it shall accommodate typical full-scale sections. No one size is considered standard. Generally, the maximum accuracy is obtained when the specimen size is at least that of the metering chamber while the climatic chamber must also match or be larger.

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

6.4 *Construction Materials*—Materials used in the construction of the hot box apparatus require a high thermal resistivity. Polystyrene or other foam materials have been used since they combine both high thermal resistivity, good mechanical properties, and ease of fabrication. One potential problem with some foams is that they exhibit time-dependent thermal properties that would adversely affect the thermal calibration of the apparatus. Most problems associated with the use of these materials can be avoided if material is selected that is initially well along the aging process and by periodic checks of calibration to guarantee that the calibration has not changed significantly over time.

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 of specimen and for maintenance of reasonable test accuracy. For example, for specimens incorporating air spaces or stud spaces, the metering area should exactly span an integral number of spaces (see 5.5). The depth of the metering box should no be greater than that required to accommodate its necessary equipment. Measurement errors in testing with a hot box apparatus are, in part, proportional to the length of the perimeter of the metering area. The relative influence of this diminishes as metering area is increased. Hot Box operators’ experience has demonstrated that for the guarded hot box configuration, the minimum size of the metering area is 3 times the specimen thickness or 1 m^2, whichever is larger **(18)**. From the same experience base, the calibrated box configuration, a minimum specimen size is 1.5 m^2.

6.5.2 The purpose of the metering chamber is to provide for the control and measurement of air temperatures and velocities on one face of the specimen under fixed conditions and for the measurement of the net energy transfer through the specimen. The usual arrangement is a five-sided chamber containing electrical heaters, cooling coils (if desired), and an air circulation system. At steady-state conditions, the energy transfer through the specimen equals the electrical power to the heaters and blowers minus the cooling energy extraction, corrected for the energy passing through the chamber walls and flanking the specimen. Both the metering box wall energy flow

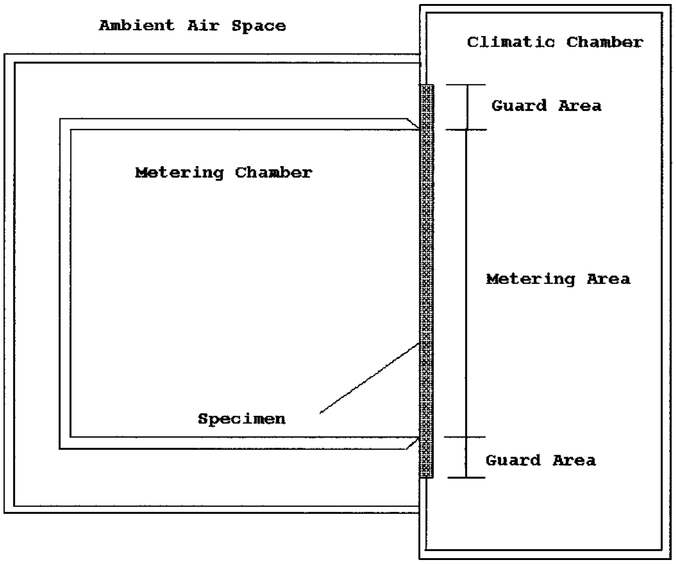

FIG. 1 Typical Hot Box Apparatus Schematic—Definition of Locations / Areas

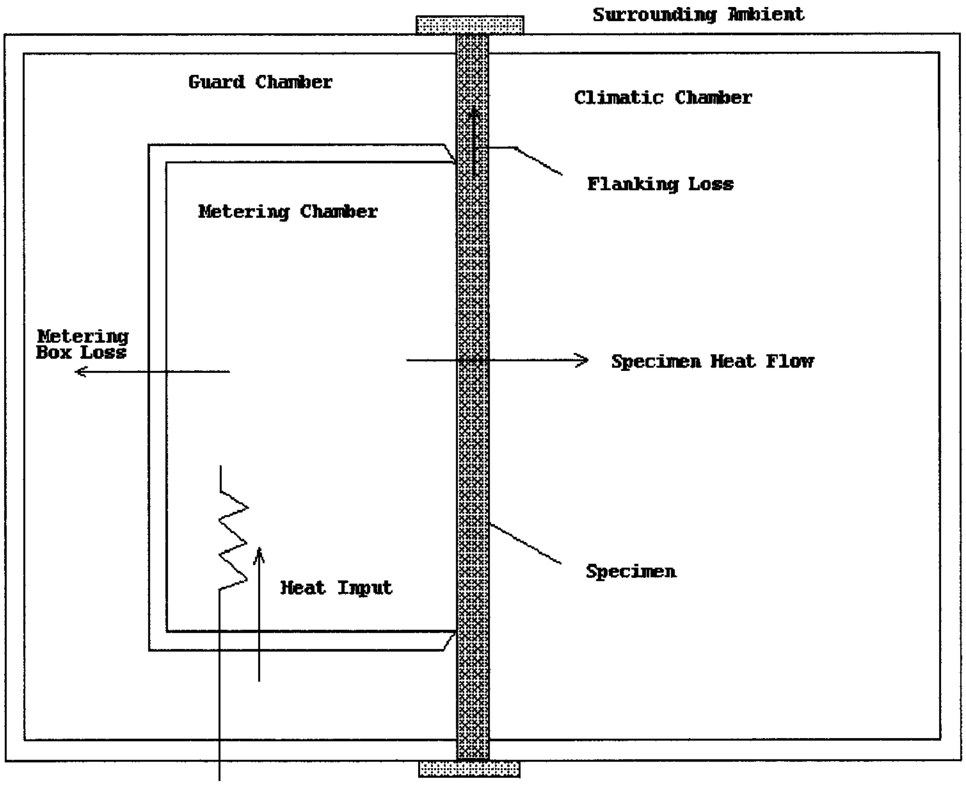

FIG. 2 Schematic Guarded Hot Box

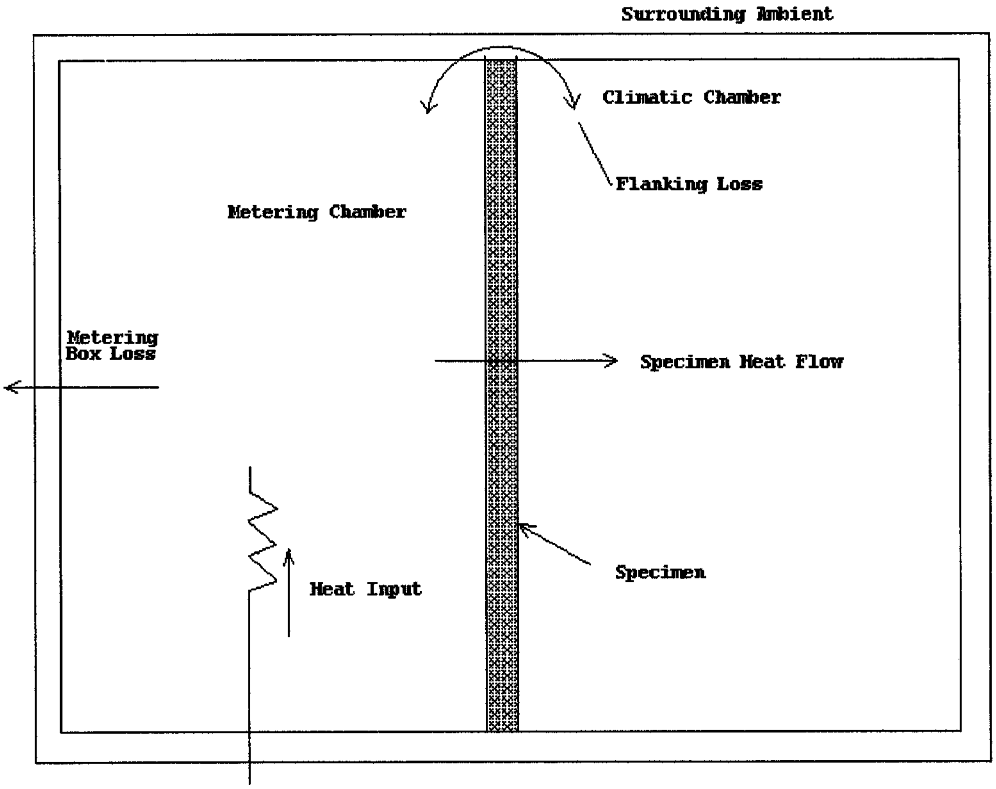

FIG. 3 Typical Calibrated Hot Box Apparatus

and flanking path energy flow are determined from calibration measurements (see Section 8).

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 energy corrections, which may be estimated for design purpose by the equations in Annex A1, Annex A2, and Annex A3, 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). However large the wall losses are, the uncertainty of the resulting corrections to the net energy flow shall not exceed 0.5 % of the net energy flow through the specimen. In some designs, it has been necessary to use a partial guard to minimize metering chamber wall loss.

6.5.3.2 The metering chamber wall losses should be as low as 1 or 2 % of the heat transfer through the specimen and should never be greater than 10 % of the specimen heat transfer if the highest accuracy is to be achieved. 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 recommended as an extreme and is based upon operator experience and potential errors analysis. The choice of construction of the metering chamber can be made only after review of the expected test conditions in which chamber wall losses and their uncertainties are considered in relation to the anticipated heat transfer through the test specimen and its desired maximum uncertainty. The influence of the guarding temperature upon the ability to maintain steady temperatures within the metering chamber also must be considered in choosing between highly insulated walls and a tightly controlled guard space conditioning.

6.5.3.3 For best results, the heat transfer through the metering chamber walls should be uniform so that a limited number of heat flux transducers or differential thermocouples can be used to characterize the energy 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. Any structural members shall not 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 should be avoided as much as possible.

NOTE 9—One method of constructing satisfactory chamber walls is by gluing together large blocks of an aged, uniform low conductivity cellular plastic insulation such as extruded polystyrene foam. A thin covering of a reinforced plastic or coated plywood is recommended to provide durability, moisture, and air infiltration control.

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

6.5.3.5 In applications where the metering chamber contacts the specimen at locations within its edge boundaries, an air-tight 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 inspections of the sealing system are 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 characterize the energy flow through the metering box walls, adequate controls and temperature-monitoring capabilities are essential. Small temperature gradients through the walls can occur due to the limitations of controllers. Since the total wall area of the metering box is often more than twice the metering area of the panel, these small temperature gradients through the walls may cause energy flows totaling a significant fraction of the energy input to the metering box. For this reason, the metering box walls shall be instrumented to serve as a heat flow transducer so that energy flow through them can be minimized and measured and a heat flow correction for metering chamber wall energy flow shall be applied in calculating test results. The use of one of the following methods is recommended for monitoring metering box wall heat loss.

NOTE 10—The choice of transducer types and mounting methods used to measure the heat flow through the metering chamber walls is arbitrary. However, they must provide adequate coverage and output signal to properly quantify the metering chamber wall heat loss during testing.

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. Caution should 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 environmental air velocities and temperatures. Precautions shall also be taken when determining the number of differential thermocouples. Based upon a survey of hot box operators **(18)**, five differential thermocouple pairs per m^2 of metering box wall area are recommended as a minimum. At no time shall there be less than one pair of differential thermocouples on each of the five sides of the metering chamber. 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 may be connected in series to form a thermopile in which the individual emf's are summed to give a single output or readout individually in cases where significant differences may occur or be expected in the local heat flow levels.

6.5.4.2 Separate heat flux transducers may be placed on the metering chamber walls. Precautions shall 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 should initially be 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 may be measured separately or as a group. If measured separately, the transducers should be demountable from the surface so their calibrations, at heat flux levels typical of use, may be checked periodically (see Practice C 1130). If the measurement procedure is to calibrate the chamber with the heat flux transducers in place, the transducer outputs may be connected in series to provide a single reading.

6.5.4.3 Regardless of the method of hot box metering wall instrumentation used, the metering box wall losses shall be correlated with the signal outputs during the calibration process. See Section 8 and Annex A2 for this process.

6.6 *Climatic Chamber*:

6.6.1 The purpose of the climatic chamber is to provide for the control and measurement of the air temperature and velocity under fixed conditions on the side of the specimen opposite the metering chamber. In the usual arrangement, it consists of a five-sided insulated chamber with internal dimensions matching or greater than the test specimen 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 specimen size. This arrangement is specially 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 also should be well insulated to reduce the refrigeration capacity required.

6.6.3 Heaters, fans, and cooling coils should be placed such that the internal surface temperatures as seen by the specimen are not greatly different from the air temperatures. 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 energy flow, the frame shall be at least as thick as the thickest specimen to be tested. In the outward direction perpendicular to the normal heat 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. Thus the thermal resistance of flanking paths that would allow heat to bypass the specimen must be kept high. Conductive plates, fasteners, or structural members shall not be used in the flanking paths and the thickness and conductance of skins must be kept to a minimum.

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 upon the velocity, temperature uniformity, and distribution patterns of the air circulated past the sample surface.

6.8.2 Circulation air temperature differences of several degrees can exist from air curtain entrance to exit due to heating or cooling of the air curtain as it passes over the sample surface. The magnitude of this difference is a function of the energy 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.

6.8.3 Natural convection tests may be required for a wall test apparatus or in a floor/ceiling test apparatus without forced ventilation. When desired, tests may be run under these natural convection conditions. The air velocity shall be below 0.5 m/s if natural convective air conditions are to be approximated with some forced air flow to maintain temperature control.

6.8.4 When more uniform air temperatures are desired, it is necessary to provide curtains of forced air moving past the specimen surfaces.

6.8.5 The design of the air circulation system will have an impact on this difference, and trade-offs 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 insulated wall systems.

6.8.6 For the most uniform test results, the maximum temperature change for the circulating air exposed to the test panels shall be less than 2 % of the overall air-to-air temperature difference. The gradient along the direction of flow should be held to less than 1 K/m.

6.8.7 The direction of air flow in a hot box apparatus is arbitrary and may be parallel, that is, up, down, 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, however, the specification requirements may dictate that a specific direction is necessary to evaluate the system performance.

6.8.8 Higher air velocities 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 3.4 m/s for summer conditions and 6.7 m/s for winder conditions.

NOTE 11—Distinction should be 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 should be adequate to shield the test panel surface from any heat sources located behind it. A baffle thermal resistance of 1 (K m^2/W) is recommended for this purpose.

6.8.9.2 The baffle-to-specimen spacing may be adjustable to serve as one means of adjusting the air flow velocity. For the purpose of maintaining a well-mixed and characterized air curtain, a spacing of 150 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

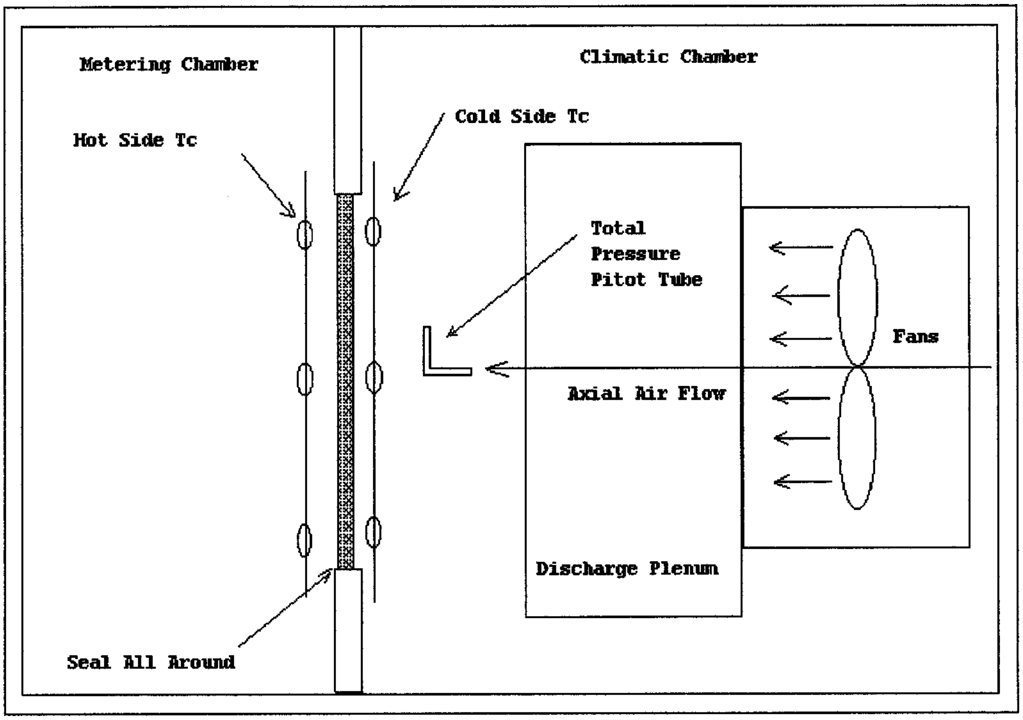

FIG. 4 Hot Box Arrangement for Perpendicular Air Flow

have an emittance greater than 0.8.

6.8.10 *Air curtain velocity uniformity*—Uniform air flow across the specimen width may be 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 should incorporate adjustable slots or louvers to air in obtaining uniform distribution.

6.8.10.1 After construction of an air circulation system, an air velocity profile shall be made across the area perpendicular to the direction of air flow in the proximity of the specimen. 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. 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 its width. 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 calibration checks.

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

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 meter the volumetric air flow 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 (assuming the baffle to be well-sealed).

6.8.11.2 Another method, which should be used only as a check of the previous methods, is to calculate the velocity from a heat balance between the rate of loss or gain of heat by the air as it moves through the baffle space, as indicated by its temperature change, and the rate of heat transfer through the test panel, average values of which can be determined from the test data.

6.8.11.3 The recommended 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 recommended. 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 6.8.9 should be used to determine the optimum sensor location.

6.9 *Air Temperature Control*:

6.9.1 Air entering the air curtains shall be uniform in temperature across its width and for steady-state tests it 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 may be switched on to provide fixed levels of heat. Fine tuning is provided by an additional heater that is 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 operating 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 may be pulsed on-off 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 should be small and efficient, since without cooling, they determine the least possible net heat 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 may be 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 energy 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 energy extraction is controlled by the inlet-to-chamber air temperature difference, the flow rate, the liquid properties, and the heat exchanger efficiency. The amount of cooling used should be limited to that necessary to overcome any excess blower or other heating loads or to that necessary to achieve desired dynamic cool-down rates since test accuracy will be lost if excessive heating must be used to compensate for large cooling. For example, if both the heating and cooling energies are known to within 1 %, but the difference of these two energy levels is 10 % of the net heating or cooling, then the net energy exchange is known only to ±10 %.

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 dew point temperature on the warm side must be kept below the temperature of the cold side when the warm surface is susceptible to ingress of moisture vapor. In general, tests in the hot box apparatus are conducted on substantially dry test specimens, with no effort made to impose or account for the effect of the vapor flow through or into the specimen during the test.

6.10 *Temperature Measurement*:

6.10.1 When surface temperatures are required, specimen surface temperature sensors shall be located opposite each other on the two faces of the specimen. These sensors shall be chosen and applied to the surface in a manner such that the indicated temperature is within ± 0.2K 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) they meet or are calibrated to the special limits of error as specified in Tables E 230; (3) if the junctions are twisted and welded or soldered; and (4) if at least 100mm 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. Application of alternate temperature sensor systems may be used if comparative measurements or calculations show that the basic requirements are met.

6.10.2 If the specimen construction, and therefore its thermal resistance, is uniform over its entire area, a minimum number of sensors spaced uniformly and symmetrically over the surface is sufficient. The required minimum number of sensors per side shall be at least 2 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 greatly nonuniform, additional sensors (often a great number such as two or three times the normal amount, as determined by trial and error) must be used to adequately sample the different temperature areas so that a reliable area weighted mean surface temperature may be obtained.

6.10.2.3 If an accurate determination of the average surface temperatures cannot be obtained, measure the transmission coefficient, U, or the overall resistance, R_u, and calculate the average panel resistance, R, of the specimen by subtracting off the previously determined surface thermal resistances established using a transfer standard of similar 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 and test panel for this technique to have reasonable accuracy (see Practice C 1199).

NOTE 15—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 heat 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 Temperatures of the air on each side of the specimen may be measured by thermocouples or temperature-sensitive resistance wires or other 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 16—A suitable radiation shield may be made by using 12 mm diameter, 75 mm long pieces of thin walled plastic tubing covered on the inside and 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 10) a minimum spacing from the specimen surface of 75 mm is suggested. At higher velocities, the required minimum spacing may be higher. 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 air flow bulk temperature.

6.10.3.3 Thermocouple sensors used for measurement of air temperatures shall be made of wire not larger than 0.25 mm (No. 30 AWG) that meet or are calibrated to the special limits of error specified in Tables E 230 for Type T thermocouples. 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 shall be measured by placing sensors on all surfaces seen by the specimen. A minimum area density of five sensors per meter squared of baffle area, but not less than one sensor per baffle surface, is recommended. Although not a specific requirement for some tests, this measurement is highly recommended for all tests since this 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 conductances due to differences in these temperatures; and **(3)** is a necessary component of the data analysis for specimens such as windows that have a high thermal conductance (see discussion on mean radiant temperature determination in Annex A6).

6.11 *Specimen Pressure Difference*:

6.11.1 For some tests, it will be 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 air flow resistance between the specimen surfaces is low. When this measurement is required, the specimen test pressure difference is defined as the difference, side to side, in local pressure measured in the direction perpendicular to the specimen surface, at a location at the geographic center of the metered area at a distance 75 mm from the surfaces of the sample. For a discussion of balancing pressure difference in a hot box apparatus, see Practice C 1199.

6.12 *Instruments*:

6.12.1 All signal conditioning and data logging instruments should be located outside of the apparatus, and shall meet the following requirements:

6.12.1.1 All instrumentation shall have adequate speed of sensor and readout response, time constants, so that the scanning speed will not adversely affect 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 heat transfer to less than ±0.5 % of the specimen heat transfer. This requires a heat flux transducer calibration accuracy of 5 % or better.

6.12.1.4 The types of acceptable air velocity sensors are not specified here as many are possible depending on the box design and test conditions. However, an accuracy of ±5 % of the reading is required and 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.

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 by balancing cooling against measured heating.

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

7. Sampling and Test Specimens

7.1 Test specimens shall be representative of typical product (field) applications. As such, tests on apparatus requiring smaller than representative specimens should be avoided. The construction details of the specimen to be investigated may be modified but only as necessary for test purposes. It must be recognized that modifications to the construction may result in conditions that do not represent true field conditions. In many cases, conduction and convection paths have considerable effect on the performance of the specimen and must be left intact. During specimen design the following must be considered:

7.1.1 *Size*—The specimen shall be size for the apparatus. Normally, the outside dimensions of the specimen must match the inside dimensions of the specimen frame. If smaller elements must be tested, a surround panel may be used to fill out the required size. The surround panel aperture for test purpose must be sufficiently small relative to the metering area such that the minimum distance between the metering area boundary and the aperture boundary is greater than or equal to 100 mm or the thickness of the mask, whichever is greater. The minimum distance from the test specimen edge to the outer perimeter of the surround panel shall be at least twice the surround panel thickness (see Annex A4 for other surround panel construction recommendations). Limitations on the use of convection barriers at the meeting boundary must be considered when designing the test specimen. Three dimensional structures may be tested, if the apparatus size permits.

NOTE 17—Scaled down 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.

7.1.2 *Sensors*—Temperature sensors for the measurement of surface temperatures shall be installed as directed in 6.10. When desired, additional temperature and other types of sensors may be installed throughout the interior of the specimen for special investigations.

7.1.3 *Mounting*—Specimens shall be located in the same position in test frames as the calibration specimens were during calibration tests so that flanking geometry is duplicated.

7.1.4 *Sealing*—The specimen must be gasketed, caulked, taped, or otherwise sealed in place to prevent air movement around its perimeter. The procedures and material for sealing must be chosen to minimize flanking heat loss. If specimens are suspected of being porous so that a significant heat transfer may result from air infiltration through the specimen, then tests should be run before and after sealing both faces. If the overall resistance changes significantly, then the specimen does not possess unique properties independent of the imposed conditions. Results from all tests shall be reported. Thin, air-impervious sheets of paper or plastic may be glued on to seal surfaces without significantly affecting thermal conduction. Some specimens may be sealed with suitable paint. In all cases, the surface emittance shall be 0.8 or greater.

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

7.1.6 *Internal Air Barriers*—When testing a specimen that has air cavities that extend beyond the boundaries of the metering section, it is necessary to install internal convection barriers at 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 that are insulated with reflective insulations having no internal air barriers.

7.1.7 *High lateral conductance specimens*—For all specimens, it is necessary to maintain a near zero lateral heat flow between any guard and the metering areas of the specimen. This can be achieved by maintaining a near zero temperature difference on the specimen surface between the metering and guard areas. However, in specimens incorporating an element of high lateral conductance (such as a metal sheet), it may be necessary to separate the metered and the guard areas of the highly conductive element with a thermal break such as a narrow gap caused by a saw cut.

8. Calibration and Standardization

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 calibration is necessary since the measured heat input to the metering chamber includes not only the heat transfer through the specimen, but also metering box loss, flanking loss, and other such losses as through gaskets, penetrations for wires or pipes, mechanical fasteners, or other less obvious heat loss paths. Thus, the net specimen heat transfer must be determined from the measured heat input by applying a correction for these losses. This correction, which is determined by calibration procedures, may be different for each set of operating conditions and for test specimens of different thickness or thermal resistance. The accuracy of the test results depend upon the accuracy of this correction. In a properly designed apparatus, however, the losses are a relatively small fraction of the 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 18—A discussion of the calibration for the metering chamber walls is presented in Annex A2. A discussion of flanking loss calibration for one apparatus is given by Lavine et al (*12*) and in Annex A3).

8.3 In principle, if all details of construction and all material thermal properties are known, it should be possible to calculate all extraneous losses 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 correction procedure must 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 may be used as a check to indicate any changes in wall material properties. Calculations may be useful in estimating the magnitude of the major losses so that experimental procedures may be better directed. Indeed, the most practical calibration technique may use 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 calibration procedure of 8.5, using a correction dependent upon test variables developed statistically from tests on known calibration standards, shall be used. The choice of the calibration procedure details should 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 *Calibration specimens*—The accuracy of the calibration 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 calibration 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, be free of internal air spaces that would affect the thermal resistance or allow internal convection, and be stable over the time period of use. Additionally, such specimens should 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 must be designed to minimize deviations in thermal resistance (as verified by small scale tests of specimens with and without joints). Calibration specimens must 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 interlaboratory comparison tests (round robins). The thermal resistance of calibration specimens shall be determined by measurements in proven apparatus such as Test Method C 177 Guarded Hot Plate, Test Method C 518 Heat Flow Meter, or another hot box that has been verified or calibrated by specimens traceable to a national standards laboratory. Generally, the hot box calibration specimen will be larger than the apparatus used in these measurements; thus, it will be necessary to measure smaller representative pieces. Such pieces may be cut from the calibration specimen if they can be replaced without change in the average thermal properties, or they can be selected from companion pieces of the same lot of material used to fabricate the specimen.

NOTE 19—Suitable calibration specimens have been constructed from molded glass fiber board of approximately 100 to 125 kg/m^3 density or aged cellular polystyrene board blown with a fugitive agent. During the calibration tests, both surfaces of the calibration panel shall be faced with air-impervious skins having an emittance greater than 0.8.

8.5 Since significant losses may exist that are not directly related to heat flow through the chamber walls and therefore not related to the emf output of the wall heat flow meters or thermopiles, a full experimental calibration is necessary. This procedure involves running a series of tests over the expected operating range using a calibration 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 calibration specimen, calculated from the measured temperature drop across it and its known resistance. Since it is impractical to run a sufficient number of tests to cover all possible sets of operating conditions, and since some of the extraneous heat losses included in the measured 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 validity of the regression relation and the choice of variables. For greatest accuracy, it is necessary to run calibration specimens covering the expected range of specimen thickness and thermal resistance and to include these variables in the regression analysis. The need for such tests may also be investigated by mathematical analysis. In some cases, such analysis may be sufficient to derive a satisfactory specimen thickness/resistance correction to be applied to the regression relation.

NOTE 20—Examples of calibration procedures are given by Rucker and Mumaw **(9)**, by Lavine et al **(12)** and in Annex A2-Annex A4.

8.6 In addition to the initial calibration sequence, it is necessary to repeat selected calibration 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 calibration shall be 1 year.

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

9. Conditioning

9.1 Normally, pre-test conditioning shall be in ambient air, for a period long enough to come to practical equilibrium. One recommended condition is in air at 24°C with 50 % relative humidity. Where specifics are not provided by the requester, uses Practice C 870 as a guide conditioning. 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 buildup. Conditioning requirements specified by code or construction specifications shall govern for the test, where available. To avoid abnormally long conditioning periods, building materials may be preconditioned at laboratory conditions prior to test panel assembly.

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, should be chosen to meet requirements of the specimen investigation, usually to match use conditions.

10.2.3 When not otherwise directed, it is suggested that air velocities be the minimum required to achieve the desired temperature uniformity under the requirements of 6.8.2 and be in the direction of natural convection, and that the sample pressure differential be essentially zero.

10.2.4 Whenever the temperature conditions are not otherwise specified, Practice C 1058 should be used as a guide for selecting the appropriate test temperature conditions.

10.3 Construct the test specimen in the sample frame opening as specified in 7, including installation of all required sensors.

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

10.4 Place the test frame, with the sample 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. Leak check sample, if possible, (see 7.1.4).

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 10.9 are obtained.

10.9 *Stabilization and Test Times*:

10.9.1 *Thermal steady-state*—For purpose is of this test method, the definition of thermal steady-state is identical to that described in Terminology C 168.

10.9.2 The required time to reach stability for a steady-state test depends upon the properties of both the 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 cannot be provided. A combined apparatus and specimen time constant, τ_{eff}, calculated from dimensions and estimated physical properties, can be helpful in estimating stabilization times.

NOTE 21—The thermal time constant, τ_{eff}, of the system is the time required to come to within 1/e (37 %) of the fixed value after a step thermal 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 temperature. 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 system can be approximated from a knowledge of the thermal diffusivities of the components of the system, but it is more readily determined experimentally.

10.9.3 Annex A5 contains a suggested procedure for estimating the thermal time constant of a test system.

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

10.10 *Test Data Acquisition and Completion*:

10.10.1 *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, τ_{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.

10.10.2 *Test completion criteria*—This combination of five data acquisition runs shall constitute a valid test if each datum obtained for each measured variable differs from its mean by no more than the uncertainty of that variable as estimated to establish the values given in the report. If the data obtained during this period is changing monotonically with time, the test shall also be considered suspect and further repeated runs shall be conducted until the steady drift is no longer observed. Such a drift, even at low levels, may indicate that the specimen characteristics are changing or that the system is not steady-state within its test capabilities. In either event, serious errors may result.

10.10.3 *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 should be tested. Upon acquisition of each additional data set, an analysis of the last five sets should be performed to see if the criteria of 10.10.2 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 22——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. For example, a modified procedure developed for windows testing is presented below:

The term steady-state refers to the 8-h time period during which all essential parameters involved in determining the tested thermal transmittance of a fenestration product meet the criteria stated below:

1. The average interior and exterior test specimen individual temperatures do not change by more than ±0.25 K over the entire test period.
2. The average ambient air temperature do not vary by more than ±0.25 K over the test period.
3. The average metering box wall heat flow does not vary more than ±1 % and does not change monotonically over the entire test period.
4. The net heat input to the metering box shall be recorded by computer at 5-min intervals or less and shall not deviate more than ±1 % from the average power readings at any time during the entire test period. The average power into the metering box also shall not change monotonically during the test period.
5. The thermal transmittance of the sample shall not vary more than± 1 % when comparing any one-hour inclusive time period with any other one-hour period within the entire test period. The two one-hour time periods shall not overlap.
6. In order for the test result to be valid, the final calculated test result shall be the average result calculated for the last five time constant periods of the stabilized test period.

10.11 *Recorded Test Data*:

10.11.1 The data acquired during the testing period shall include but not be restricted to the following:

10.11.1.1 The total net energy or average power transferred through the 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 heat transfer and flanking loss, any other extraneous loss, and corrections for the enthalpy of infiltration air entering the metering chamber (see Annex A1),

10.11.1.2 All air and surface temperatures specified in 6.10,

10.11.1.3 The average air velocity on each side of the specimen (see 6.8.10),

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

NOTE 23—For either parallel or perpendicular forced-air velocity conditions, care should be taken to quantify the amount of air leakage between the climatic and metering chambers. This may be done by several techniques. These are: (1) tracer gas methods, or (2) calibration of the air flow rate as a function of the pressure difference using Test Method E 1424.

10.11.1.5 The effective specimen dimensions and metered area (the projected area perpendicular to the direction of heat 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 can have surface areas as much as 50 % greater than the projected areas,

10.11.1.6 The metering of the hot box, that is, the area between the centerline of the metering box gaskets for the guarded box and the area between the inside edges of the specimen frame for the calibrated hot box, and

10.11.1.7 Any other conditions specific to this test such as modifications to the normal specimen design required to construct a specimen for test purpose.

11. Calculation

11.1 For steady-state tests, the average thermal transmission properties appropriate for the specimen are calculated by the equations given in 3.1 and 3.2, using the average data obtained in 10.10 and 10.11. Practice C 1045 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 may be expressed as either thermal resistance, R, thermal conductance, C, overall thermal resistance, R_u, or thermal transmittance, U. This method allows two procedures which are to be used in 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 they can be measured by temperature sensors and a representative average obtained. For some specimens, the choice may be arbitrary and must be made by the user of the method or by the sponsor of the test, or it may be specified in applicable regulations or specifications. In all cases the procedures used must be fully reported. The two procedures are:

11.2.1.1 For uniform and nearly uniform specimens, the average surface temperatures may 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 heat transfer and the difference in the average temperatures of the two surfaces.

11.2.1.2 For very nonuniform specimens (see 6.10.2.3), meaningful average surface temperatures will not exist. In this case the thermal resistance, R, is calculated by subtracting 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 (Note 21), but using a uniform test specimen of approximately the same overall thermal resistance.

NOTE 24—Surface resistances have been found to depend significantly on the magnitude of the heat flux as well as the ambient conditions affecting the surface. When using the procedure of 11.2.1.2, it is important that the heat flux for the uniform specimen be similar to that through the nonuniform specimen and that air temperature, air velocity, and the temperature of surfaces that exchange radiation with the specimen also be similar.

11.3 *Calculation of Thermal Properties*:

11.3.1 For homogenous specimens of insulation material, the thermal conductivity, λ, may be calculated if the specimen meets the requirements of Terminology C 168. Available test data must demonstrate that the thermal resistance of the material under test is linearly proportional to thickness within the range of temperatures and thickness under consideration. An expected error of these assumptions must be assigned to the thermal conductivity result as part of the report.

11.3.2 For a relatively uniform but nonhomogeneous specimen such as normal walls, floors, ceilings, etc., the thermal properties that may be calculated are the resistance, R, conductance, C, overall resistance R_u, transmittance, U, surface resistance, R_c and R_h, and surface conductances, h_c and h_h.

11.3.3 For very nonuniform specimens where the heat transfer is greatly different from one area to another, and if detailed temperature profiles are not known, only the net transfer through the specimen (see 10.11), may be meaningful.

In these cases, only the overall resistance, R_u, and transmission coefficient, U, are permitted.

11.3.4 For a specimen smaller than the metering chamber opening, the properties that apply to that specimen, as per the distinctions of 11.3.1-11.3.3, may be calculated if surround panel calibration tests have been run that permit the specimen heat transfer to be determined. Annex A2 presents considerations for these calculations.

11.3.5 Generally the overall thermal resistance, R_u, or the thermal transmittance, U, should be determined under the conditions of interest. When this is not possible or when directed by applicable agreements or regulations, the overall resistance, R_u, may be determined from the thermal resistance, R, obtained as directed in 11.1 or 11.2, by adding standardized surface resistances. One source of standardized resistances is the ASHRAE Handbook Fundamental Volume.

NOTE 25—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 nonuniform specimens with high conductance surface elements connected to thermal bridges when measured resistances, R, are obtained under still air conditions and the standardized surface resistances are typical of high wind velocities. The user is cautioned to be aware of such possible discrepancies.

12. Report

12.1 Report the following information:

NOTE 26—The primary units used in this test method are SI, but either SI or U.S. customary (USCS) units may be used in the report, unless otherwise specified. Table 1 provides conversion factors between USCS and SI units.

12.1.1 Identification of the test laboratory with address and telephone number, responsible scientist 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 differ 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 material, such as some concretes and woods, the moisture content should also be given). If the thermal conductivities of these materials, at the test conditions, have been measured, these values should also be included.

NOTE 27—A generic description in addition to the brand name also should be reported where possible. The following is an example of a generic description: preformed, cellular polystyrene, Type II with a density of 22 kg/m^3; spruce-pine-fir with a moisture content of 12 % and a dry density of 486 kg/m^3.

12.1.3 Pertinent information regarding the specimen preconditioning for the test panel.

12.1.4 The dimensions of the metered area and its relationship to the overall specimen dimensions and to principal elements of the specimen.

12.1.5 Specimen orientation and the direction of heat transfer during the test.

12.1.6 Average air velocity and direction on both sides of the specimen and air velocity distribution if nonuniform.

12.1.7 Latest calibration check date and procedure used. References for the calibration report(s) shall also be included.

12.1.8 Average pressure differential across the specimen and the average air flow volume rate, if applicable.

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

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

12.1.9.2 For nonuniform specimens including test elements, separate measured temperature averages for each different area

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.

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

or element must be given. Areas for each elements shall also be reported.

12.1.10 Net heat transfer through the specimens, steady-state average rate or the average amount per cycle or other stated time interval for dynamic tests. Include values for metering box loss, flanking loss, and other losses included in the net energy calculation.

12.1.11 Any thermal transmission properties calculated in 11.3, and their estimated error (see 13.1 and Note 27).

12.1.12 A full description of test procedure 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 the following provisions of Test Method C 1363" (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 test method depends upon test equipment and operating procedures, and upon the test conditions and specimen properties. 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 reference specimens from appropriate standards laboratories. In general, the best overall accuracy will be obtained in apparatus with low box wall loss and with low flanking loss. Low box wall loss can be achieved by using highly insulated walls subjected to low temperature differences. Low flanking loss, in relation to metering box heat input, can be achieved by using large boxes where the ratio of perimeter to area is less, and by minimizing any highly conductive layers of 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. Thus the highest accuracy will be obtained for low-resistance specimens subjected to high temperature differences.

NOTE 28—As an example, an outline of the procedure for an uncertainty analysis for thermal resistance, R, is as follows:

From 3.1.2, $R = (t_1 - t_2)A/Q$ where the power through the specimen, Q, is the sum of the electrical power input to the metering box, Q_h; the heat into the metering box through its walls, Q_b; and the flanking loss power, Q_{fl}; such that $Q = Q_h + Q_b + Q_{fl}$ (other terms such as blower input or cooling may be added as needed).

Combining these equations, the relation for resistance is $R = (t_1 - t_2)\,A / (Q_h + Q_b + Q_{fl})$. The individual uncertainty for each item in this equation must be estimated. Such estimates may be made from a knowledge of individual instrument and transducer uncertainty or from the results of calibration experiments designed to investigate such uncertainties. Then, following the propagation of errors theory which assumes the errors to be independent, 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 29—Uncertainty estimates for existing apparatus range from 1 to 10 % or more depending upon the variable mentioned. 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 m^2/W) specimen.

13.2 *Interlaboratory Comparison Results*:

13.2.1 *Background*—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 m^2/W. The regression equation for each data set was:

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

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

over a mean temperature range of 4 to 43°C. The mean specimen density ranged from 20.2 to 23.9 kg/m^3. The report of this round robin was prepared by Bales **(19)**.

13.2.2 *Precision*—At a specimen thermal resistance of R = 2.81 K m^2/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 C 177), from the National Institute of Standards and Technology and supported by measurements from other

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

Mean Temperature (°C)	Reproducibility Interval (%)		Difference in Resistance (m^2K/W)
	Calibrated	Guarded	
4	13.6	14.6	± 0.22
24	14.4	15.6	± 0.22
43	15.4	17.2	± 0.22

laboratories, the average value for the round robin specimen is a thermal resistance of 2.81 K m^2/W at an average density of 20.8 kg/m^3. The mean value as measured by the composite of the calibrated hot boxes was 2.88 (K m^2/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 m^2/W) or 1.1 % less than the expected value.

NOTE 30—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.

13.3 No interlaboratory comparison exists for this latest version of the generic hot box method. Improvements to this test method based upon experiences of the hot box operators would suggest that this test method has improved precision and bias over the two previous standards. 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; hot box; test method; thermal properties; thermal resistance

ANNEXES

(Mandatory Information)

A1. CALCULATIONS OF METERING BOX HEAT LOSS

A1.1 The following equations may be used to estimate the heat loss through the walls of a five-sided rectangular metering box made of homogeneous material. They are based upon Langmuir's equations **(15)** by considering the loss to be half that of a closed six-sided box form by placing two of the open-sided boxes together. The heat loss in watts for the five-sided box is given by:

$$q = \frac{\lambda \bullet A_{\text{eff}} \bullet (t_i - t_o)}{L} \tag{A1.1}$$

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

$$A_{\text{eff}} = A_i + 0.54\, L\, \Sigma e_i + 0.60\, L^2 \tag{A1.2}$$

where:

A_i = box inside surface area, m^2,
L = wall thickness, m,
λ = effective wall thermal conductivity, W/m•K,
t_i = inside wall temperature, K,
t_o = outside wall temperature, K, and
Σe_i = sum of all (total of 8) interior edge lengths formed where two walls meet, m.

A2. METERING WALL TRANSDUCER OUTPUT AND HEAT FLOW RELATIONSHIP

A2.1 The procedure given in Annex A2 outlines the steps required to obtain the relationship between metering chamber wall heat flow and its measurement transducer output. This method addresses the technique that will yield the heat flow relationship as a function of the transducer output including a zero offset, if present.

A2.2 It is essential that the air velocity and power input in the metering, guard, and environmental boxes be held constant along with all temperatures throughout each calibration phase. By holding the air velocity and input along with the surface temperatures constant, the operator ensures a constant heat transfer film coefficient to the specimen during the test. The E_o value associated with negligible net heat flow across the meter box walls is then obtained form the relationship between Q_m and E. The equation that describes the total heat flow drawn schematically in Fig. A2.1 is:

$$Q_f + Q_h + Q_m + Q_{fl} = Q_s = A\, \Delta T / R \tag{A2.1}$$

where:

Q_f = heat flow due to the fan, W,
Q_h = heat flow due to the heater, W,
Q_m = metering box wall heat flow, W,
Q_{fl} = heat flow by the flanking path, W,
Q_s = heat flow through the specimen, W,
R = thermal resistance of the specimen, m^2•K/W,
A = metered area of heat flow, m^2,
ΔT = temperature difference across the specimen, K,
E_o = thermopile emf when net heat through the metering box walls is negligible, and
E = thermopile emf, V.

From an operational standpoint, the objective of proper metering box operation is to make Q_m equal to or neatly zero. Q_m is a function of the transducer output, E, which can be described by:

$$Q_m = F\, n\, (E) = \mathrm{mE} + \mathrm{b} \tag{A2.2}$$

A2.3 To quantify m, at least three test runs must be

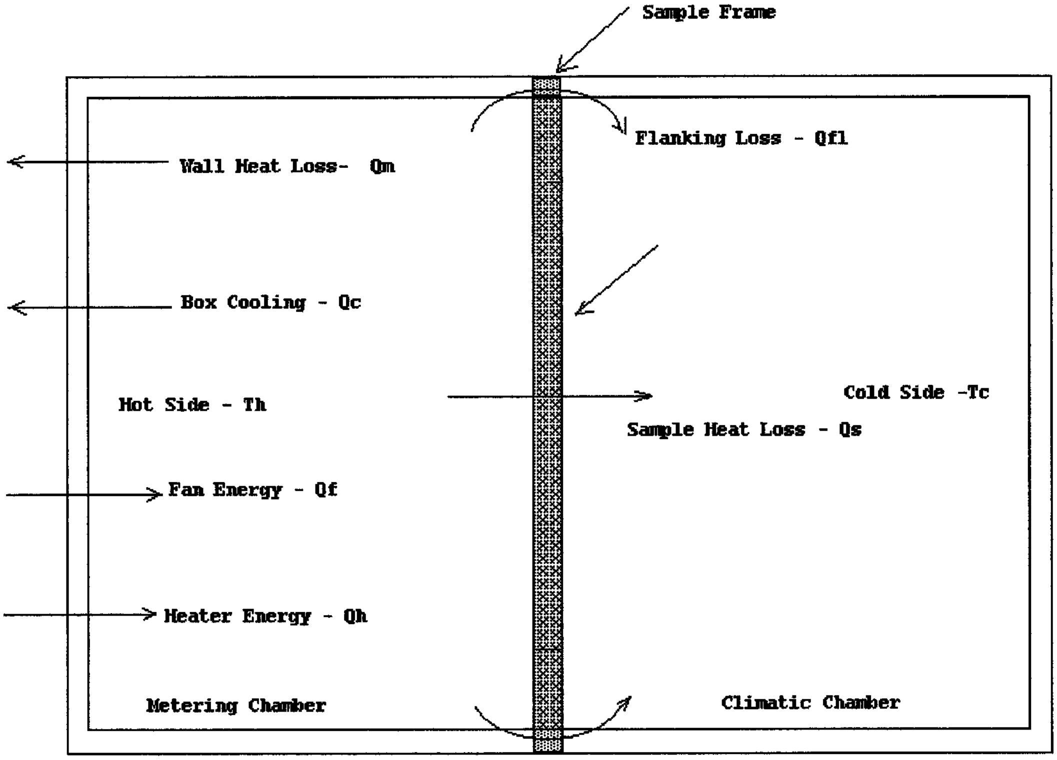

FIG. A2.1 Hot Box Metering Chamber Heat Balance Schematic

performed with differing levels of E. Adjustment of the value of E can be accomplished by adjusting the guarding temperature while holding the other temperatures constant. The level of change required to establish a good relationship will depend upon the transducer sensitivity and the metering wall thermal resistance. E must be held constant within each test. The specimen surface-to-surface temperature difference and mean temperature must be constant and at the same value of Q_s, for all of the calibration tests can be approximated by assuming the design R. It is not necessary to know the true R of the specimen. Plot Q_m as calculated from Eq A2.1 versus the transducer output E. The slope of the line is m in Eq A2.2.

A2.4 The next step is to quantify the zero offset, b, for Eq A2.2. Set the temperature difference across the specimen surface equal to zero ($Q_s = 0$). Substituting Eq A2.2 into Eq A2.1 and setting $Q_s = 0$ reduces Eq A2.1 to:

$$Q_f + Q_h = -(\mathrm{m\,E} + b) \qquad \text{(A2.3)}$$

Notice that setting the temperature difference across the specimen to zero also forces the flanking loss, Q_{fl}, to also be equal to zero.

$$b = Q_f + Q_h + \mathrm{m\,E} \qquad \text{(A2.4)}$$

This test is accomplished by adjusting the box controls such that the fan wattage is at operational conditions and the heater wattage is at the minimum value that maintains temperature control. Adjust the climatic chamber temperature to match the metering chamber temperature. In this configuration, no energy is flowing through the specimen. During this test, lateral heat flow must still be negligible. Using m that was determined previously, use Eq A2.4 to determine b. The thermopile emf value that pertains to negligible net flow through the meter box walls E_o can then be calculated using Eq A2.5:

$$E_o = -(b/m) \qquad \text{(A2.5)}$$

A3. FLANKING LOSS CALIBRATION

A3.1 General Discussion

A3.1.1 This annex describes the flanking loss calibration procedure that must be used in determining the flanking loss correction for the hot box apparatus. Depending upon the design and control of the test facility, the flanking loss may be insignificant for a guarded box. The error statement for each facility shall include a discussion of the flanking loss.

NOTE A3.1—The example provided herein to clarify the procedure is based upon the 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 specimen area of 2.7 m × 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 should be useful as a guide for other hot box users.

A3.1.2 The flanking loss is defined as the quantity of heat that flows between the metering and climatic chambers through the frame that holds the specimen. Flanking loss may also be the flow of heat from the metering chamber to the guard chamber that passes through the specimen. Finally, the flanking loss may also be the additional passage of heat through the surround panel wall surrounding the test specimen when the surround panel calibration panel thickness is different from the test panel thickness. Fig. A3.1 shows three examples of potential flanking loss location. The flanking loss is expected to be a function of the construction through the flanking loss passes, the temperature difference the two chambers, the mean temperature of the construction, and the thickness of the specimen.

NOTE A3.2—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_s). 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_s would be 0.6 %.

A3.1.3 The magnitudes of Q_{fl} and Q_s are strongly related, since both are proportional to the Δt across the specimen. For the example above, the value of 6 % is typical for Q_{fl} relative to Q_s. This magnitude could be significantly different for another frame construction or different specimen area. In contrast to the example above, if a plywood skin were used as the skin for the frame, it would 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.

A3.2 Preliminary Analysis

A3.2.1 A preliminary analysis must be made to predict the form of the flanking loss calibration equation as a function of the appropriate variables, that is, air-to-air temperature difference between the chambers, associated mean temperature, and the specimen thickness. Refer to Fig. A3.1, which shows a cross section of the joint between the frame and the specimen. The primary direction of heat flow is parallel to the surface skin. Since the skin normally has a fairly high conductivity compared to the internal materials, it cannot be ignored as a heat flow path. The flanking loss can occur through both the skin and the insulation beneath. For this analysis the use of a finite element model is recommended.

A3.2.2 For ease of calculation of the flanking of loss correction, the heat loss along two paths may be lumped together and described as a single path with an effective conductivity, length, and area. The exact form of this equation will be determined from the modeling results. However, the flanking loss has been successfully predicted using the following equation form:

$$Q_{fl} = \lambda_{\mathrm{eff}} \cdot (A/L)_{\mathrm{eff}} \cdot \Delta t_{a-a} \tag{A3.1}$$

where:

Q_{fl} = flanking loss,

λ_{eff} = effective conductivity of base insulation and the skin material,

$(A/L)_{\mathrm{eff}}$ = effective area/path length of entire frame around its perimeter, and

t_{a-a} = air-to-air temperature difference.

A3.2.3 Strictly speaking, the effective conductivity is a function of temperature, since the thermal conductivities 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 increases, the path length for flanking loss will increase. Therefore, the function $(A/L)_{\mathrm{eff}}$ will decrease with increasing specimen thickness.

A3.2.4 Once the basic form of the model is determined, a sensitivity analysis should be conducted on the flanking loss model. This sensitivity study will fix the significant variables controlling the flanking loss, determine the form of the resulting correction equation, and be used as a guide for the experimental verification of the model.

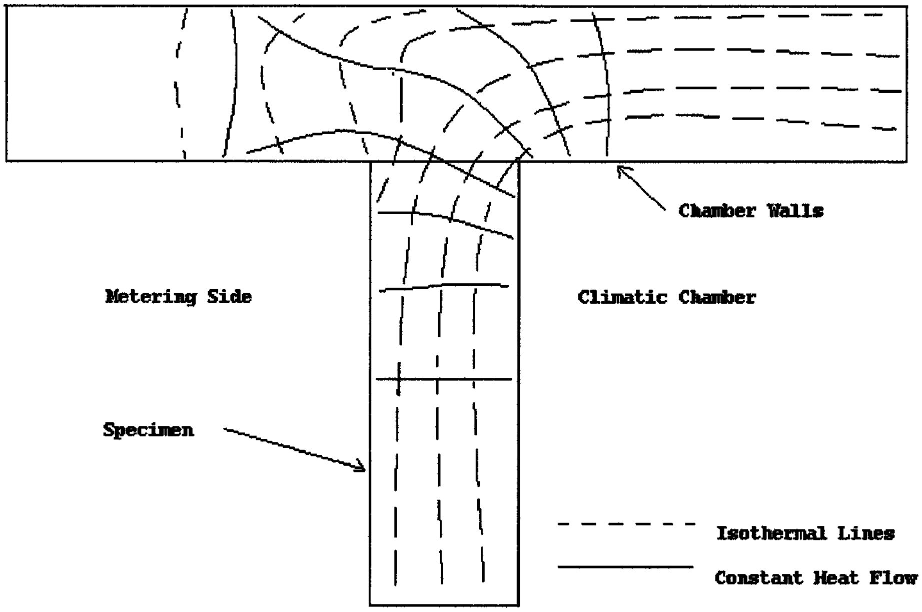

FIG. A3.1 Typical Flanking Loss Geometries

NOTE A3.3—For the example hot box, the thickness dependence of the flanking loss was investigated theoretically using HEATING5, 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 chamber 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.

Modeling runs were made on the example facility to determine the thickness effect. The thickness of the specimen ranged from 19 to 300 mm, and the specimen conductivity was held constant. (A few runs were made that determined that varying the specimen conductivity did not strongly affect the flanking loss.) Fig. A3.2 illustrates the shape of flanking loss as a function of specimen thickness, as predicted by the HEATINGS model. Since $\Delta t_{a\text{-}a}$ 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 $(A/L)_{eff}$ 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.

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 conductivity has only a minor influence on the specimen heat flow. It was, however, included in the final calibration equations.

A3.3 Experimental Model Verification

A3.3.1 Once the model has been used to develop the relationship between the various factors controlling the level of flanking loss, it is necessary to conduct a series of experimental tests on known specimens in order to develop the magnitude of the equation coefficients for the various factors. The factors of the investigation probably will be the same as those discussed in A3.2. Each variable should be tested at its range of expected values. This would include, as a minimum, tests several thicknesses, mean temperatures, and temperature differences.

NOTE A3.4—In the example calibration procedure, a series of hot box tests was run on homogeneous calibration specimens with known thermal characteristics. Single thickness (35 mm) and triple thickness (105 mm) specimens were constructed for characterizing flanking loss as a function of specimen thickness. To investigate the temperature dependence of the flanking loss, a series of tests was performed on each calibration specimen. Temperature differences across the specimen ranged from 28 to 58 K, and mean temperatures varied from -13 to 49 °C.

A3.4 Data Analysis and Final Equation Coefficients

A3.4.1 The "required" flanking loss was defined as the flanking loss required to balance the other energy gains and losses on the metering chamber. That is, from the energy balance on the metering chamber:

$$Q_{fl,req} = Q_{in} - Q_{ch} - Q_s \quad (A3.2)$$

where:

$Q_{fl,req}$ = required flanking loss,

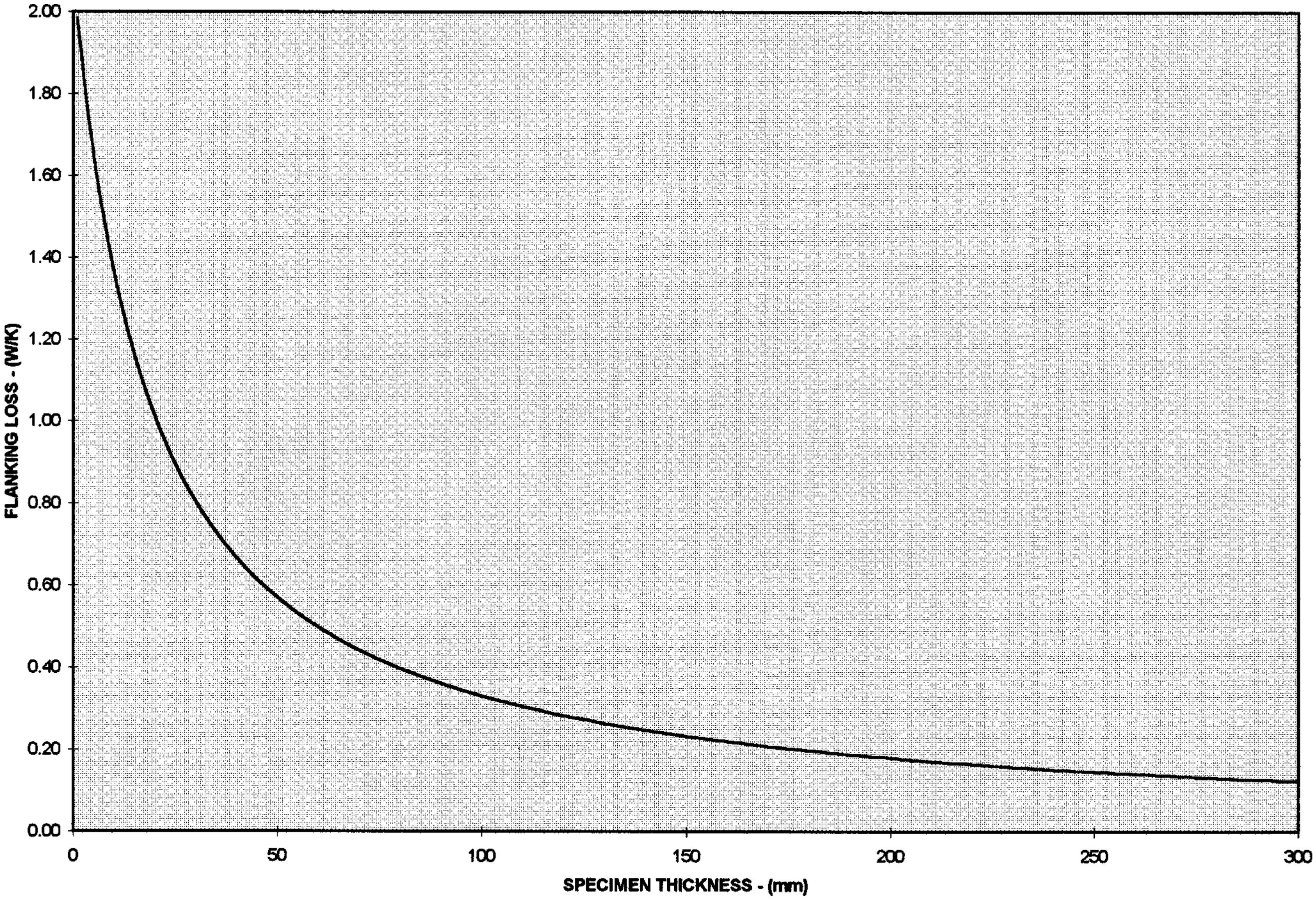

FIG. A3.2 Relationship Between Thickness and Flanking Loss

Q_{in} = heat input from resistance heaters, fans, minus heat extracted by the coiling coil,
Q_{ch} = chamber wall loss, known from previous calibration,
Q_s = specimen heat flow,
= $C_s * A_s * \Delta t_{s\text{-}s}$
C_s = specimen conductance, a known function of temperature,
A_s = specimen area, and
$\Delta t_{s\text{-}s}$ = surface-to-surface temperature difference across the specimen.

A3.4.2 In order to check the validity of the predicted temperature dependence of flanking loss from the test results, the flanking heat loss required, $Q_{fl,req}$, shall be calculated for each of the tests. The results are then plotted versus $\lambda_{eff}\Delta t_{a\text{-}a}$ as in Fig. A3.3.

NOTE A3.5—For our example, a strong linear trend 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 our example, 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.

A3.4.3 Notice that the regressions of Q_{fl} vs. $\lambda_{eff}\ \Delta t_{a\text{-}a}$ also provide an experimental estimate of the function $(A/L)_{eff}$. As in the example of Fig. A3.4, 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 are in agreement, then the appropriate coefficients can be determined by regression.

NOTE A3.6—For our example, the theoretical model results and the two experimental estimates of $(A/L)_{eff}$ are plotted in Fig. A3.4. It can be observed that the experimental points 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 more steep.

A3.4.4 From the modeling results, it is probable that the flanking loss dependence on thickness has the general equation form of Eq A3.3:

$$(A/L)_{\text{eff,th}} = \frac{a}{(b + th)} \tag{A3.3}$$

where a and b are model constants and th is the specimen thickness. The two constants were solved for using the two experimental estimates of $(A/L)_{eff}$.

NOTE A3.7—The resultant curve is also plotted in Fig. A3.4, and gives a reasonable representation of flanking loss as a function of thickness.

A3.4.5 Combining the results of the regressions on the individual effects from our experiments will yield the equation for correction of the flanking loss as a function of the experimental variables.

NOTE A3.8—Thus, for the example hot box, the flanking loss can be described by an equation of the form:

$$Q_{fl} = \lambda_{eff} \bullet (a / (b + th)) \bullet \Delta t_{a-a} \tag{A3.4}$$

where λ_{eff} is a function of mean temperature.

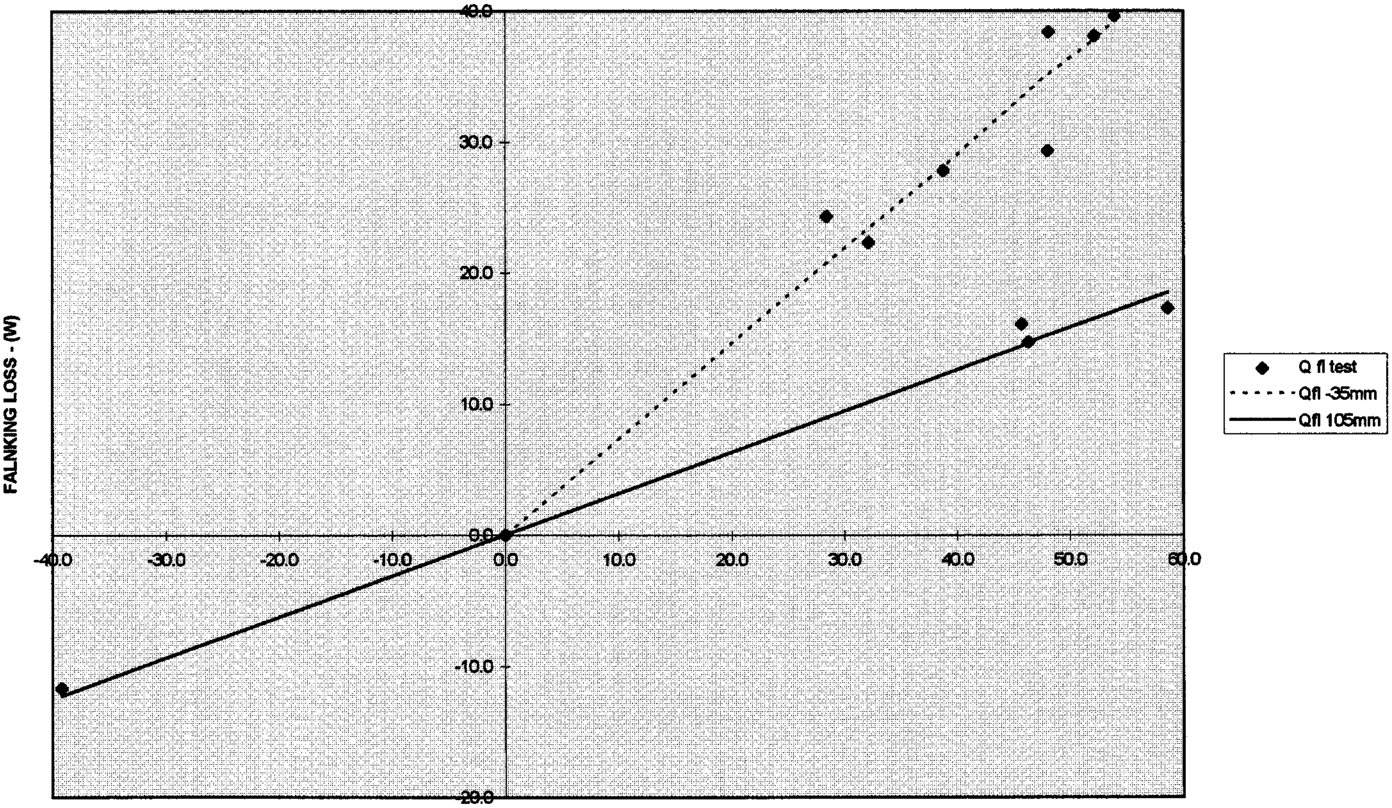

FIG. A3.3 Flanking Loss Versus Conductivity Times Temperature Difference

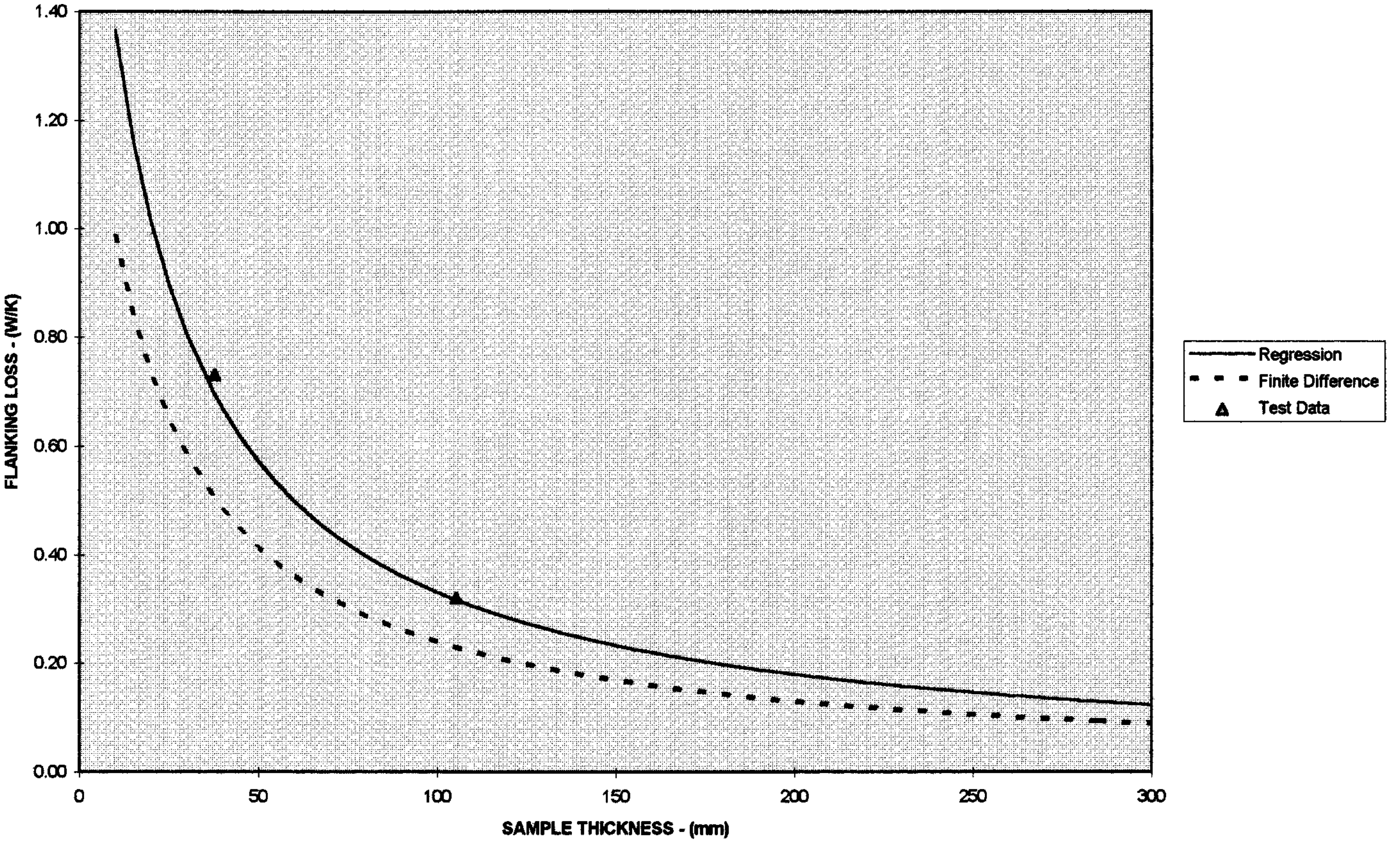

FIG. A3.4 Flanking Loss Results Versus Data and Modeling Predictions

A3.4.6 Consideration must be given to various possible sources of errors in the flanking loss calibration procedure. The three listed below are highlighted for consideration.

A3.4.6.1 The flanking loss equation developed from tests using one particular frame may differ slightly for other frames of the same general construction.

A3.4.6.2 The data analysis assumed that the specimen heat flow could be calculated as $Q_s = C_s \bullet A_s \bullet \Delta t_{s\text{-}s}$. This presupposes one-dimensional heat flow through the specimen. In actuality, the heat flow will be two-dimensional to some extent near the frame.

A3.4.6.3 Finally, the testing and analysis are generally performed on homogenous 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 conductivity would behave differently. The model used in this calibration can be used to investigate these concerns for the particular box construction.

A3.5 Final Evaluation of Flanking Loss Calibration

A3.5.1 As a final check of the accuracy of the flanking loss calibration equation, the net specimen heat flow should be calculated from the energy balance on the metering chamber for each of the calibration tests. The calculation used the flanking loss equations described above and the chamber wall loss equations from previous calibration experiments. The net values of the conductance for the calibration specimens are then found from:

$$C_s = Q_s / (A_s \bullet \Delta t_{s-s}) \quad \text{(A3.5)}$$

NOTE A3.9—The results of this analysis for the example hot box are plotted versus mean specimen temperature in Fig. A3.5. 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 %.

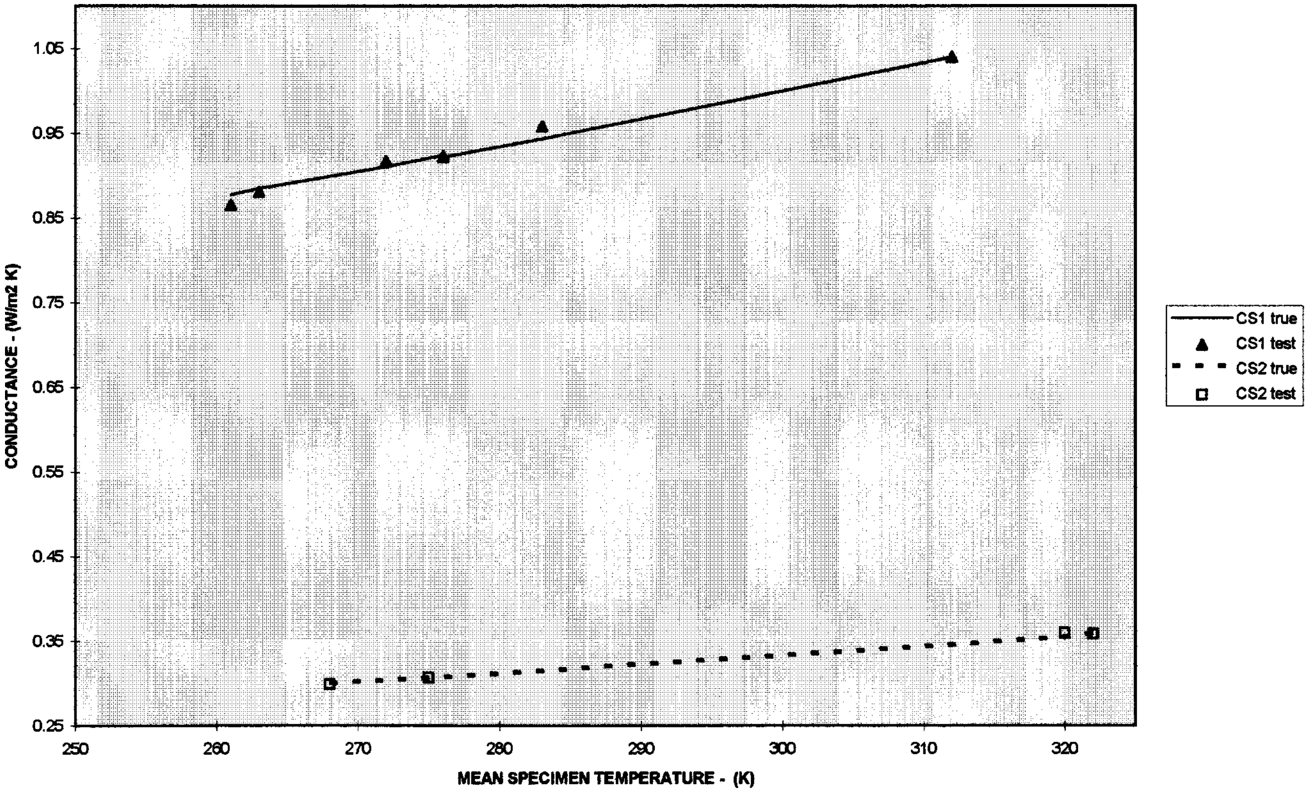

FIG. A3.5 Specimen Conductance Versus Mean Temperature Comparison of Test and Known Values

A4. USING THE CALIBRATION HOT BOX TO DETERMINE HEAT TRANSFER THROUGH BUILDING ELEMENTS SMALLER THAN THE METERING AREA

A4.1 General Considerations

A4.1.1 In this use, the building element of area A_e is located centrally in the metering area A_t, and is surrounded by a homogeneous surround panel of area $A_m = A_t - A_e$. The total heat flow rate, Q_t, determined by the hot box measurement assuming no interaction consists of two heat flow rates in parallel, in accordance with the equation:

$$Q_t = Q_e + Q_m \tag{A4.1}$$

where Q_e is the total through the building element area A_e, and Q_m is that through the surround panel area A_m. To determine Q_e, measurement is made of Q_t and Q_m is inferred from calibration measurements made by means of hot box tests of the surround panel either before the aperture for the building element is cut out or with a blank of known thermal conductance installed in place of the building element.

A4.1.2 The uncertainty in Q_e is evidently equal to the difference of the algebraic uncertainty in Q_t and Q_m. The fractional uncertainty is given by:

$$\Delta Q_e/Q_e = (\Delta Q_t - \Delta Q_m)/(Q_t - Q_m) \tag{A4.2}$$

$$= [(\Delta Q_t/Q_t) - (\Delta Q_m/Q_t)]/(1 - Q_m/Q_t)$$

where ΔQ_e is the algebraic uncertainty in Q_e, etc. An estimate of the fractional uncertainty $\Delta Q_m/Q_t$ is dependent upon the method used to calibrate the surround panel. If the calibration is made before the aperture for the building element is cut out, then:

$$\Delta Q_m/Q_t = (\Delta Q_t'/Q_{t1}) \times (A_m/A_t) \tag{A4.3}$$

where $\Delta Q_t'$ is the uncertainty in heat flow measured during the calibration test. If a blank of known thermal conductance is used to calibrate the surround panel, then:

$$\Delta Q_m/Q_t = (\Delta Q_t' - \Delta Q_{ti})/Q_t \tag{A4.4}$$

where ΔQ_{t1} is the algebraic uncertainty in determination of heat flow through the blank. Little can be said in general about the magnitudes of the algebraic fractional uncertainties $\Delta Q_t/Q_t$ and $\Delta Q_m/Q_t$, 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 $\Delta Q_e/Q_e$ is reduced as $\Delta Q_m/Q_t$ is made small. Also, as Q_m is made small, the term $\Delta Q_m/Q_t$ is presumably also made less significant. Thus, the fractional systematic uncertainty possible in the determination of Q_e is reduced by increasing either the area of the building element (if feasible) or the total thermal resistance of the surround panel.

A4.1.3 The need to determine the surround panel heat flow, Q_m, accurately requires that the surround panel be designed to act as a heat flux transducer with an emf output and temperature difference, Δt, proportional to the total heat flow through it. This consideration is the basis for the specific recommendations that follow.

NOTE A4.1—Additional uncertainty may arise due to the possible influences of the building element in causing two- or three-dimensional heat flow at the 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 calibration standard in place, may change when the building element is installed, even though the test conditions remain unchanged. The user of this procedure should attempt to evaluate their magnitude in relation to the desired accuracy of the test.

A4.2 Recommendations

A4.2.1 It is recommended that the surround panel be made of a suitable uniform thickness of a homogeneous and stable material of low thermal conductivity having adequate strength to support the weight of the building elements to be tested. Suitable materials are faced high-density glass fiber or polystyrene boards laminated together as necessary. Stronger surround panels can be fabricated by sandwiching layers of insulation between layers of rigid materials such as plywood. Such surround panels, though non-homogeneous, are uniform in the direction perpendicular to the direction of heat flow and are calibrated in the same manner as homogeneous surround panels. It may be necessary in some cases to incorporate framing in the surround panel to support heavy building elements such as heavy-duty metal frame windows or masonry sections. Such nonuniform surround panels are necessarily calibrated using blanks of known thermal conductance. Framing members must be kept away from the juncture with the building element and with the boundary of the metering area so as not to contribute excessively to lateral heat transfer at these points. It is important that the surround panel be low in hygroscopicity to minimize changes in its thermal resistance with ambient humidity conditions, and that it be impervious to air flow through it.

A4.2.2 Thermocouples for measuring the temperature difference across the surround panel should be permanently installed uniformly flush with or just under its surfaces. These may be connected in series differential for determination of the surround panel temperature difference, or as individual thermocouples for exploring temperature distributions on the faces of the surround panel. It is recommended that there be at least eight thermocouple junctions on each face of uniform surround panels, four at positions bisecting the four lines from the corners of the building element aperture to the corresponding corners of the metering area, and four at position bisecting the sides of the rectangle having the first four thermocouples at its corners. A suitable thermocouple arrangement would have to be chosen for nonuniform surround panels that would 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 surround panel, as a heat flow meter, should be calibrated and used in terms of the average temperature (or thermocouple emf) difference across it indicated by the permanently installed thermocouples.

A4.2.3 To protect the surface of the surround panel and the permanently installed thermocouples, it is necessary to render the surfaces impervious to air. A permanent coating or thin facing on each face of the surround panel is desirable. However, the coating or facing must be of low lateral conductance so that it does not contribute excessively to lateral heat transfer at the juncture with the building element or at the boundary of the metering area. The emittance of the surround panel surfaces should be uniform, and unchanged after calibration. In cases where the transmittance (rather than the conductance) of the building element is of particular interest, it is preferable that the emittance of the surround panel surfaces be high ($\epsilon > 0.8$).

A4.2.4 In view of the desirability of high thermal resistance of the surround panel relative to that of the building element, the uniform thickness of the surround panel should, in general, not be less than that of the building elements to be tested, and may be greater than that of the thinner elements. Surround panel thickness greatly exceeding that of the building element is to be avoided if possible because of lateral heat flow in the surround panel due to its exposure at uncovered areas of its aperture. (In special instances, for example, a window designed to be set a few inches outward from the plane of the inner surface of a wall, a special calibration of the surround panel as a heat flow meter may be necessary using a blank of known thermal conductance in the precise position of the window at the juncture with the surround panel aperture.)

A4.2.5 The surround panel aperture in which the building element is installed for test should set the element specimen snugly. Cracks between them should be minimal in width, and should be filled completely with a good flexible insulation and caulked or otherwise sealed at the surround panel surfaces to prevent air leakage. It is desirable that the insulation used to fill cracks have approximately the same conductivity as the surround panel material; it would then be possible, if the cracks aggregate an area significant in relation to the surround panel area, to compensate for the increased virtual surround panel area by increasing the surround panel heat flow indicated by its temperature drop in proportion to the increase in area.

A4.2.6 It is probable that many building elements to be tested are inhomogeneous or nonuniform in construction for structural reasons, and in consequence that the local thermal conductances differ 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 is a matter that varies with the case, and therefore must rest on the judgment and technical experience of those conducting the test measurement. A useful guiding principle is that nothing should be incorporated in, or omitted from, a building element 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 should include just so much of the wood framing as is properly chargeable to it.

A4.3 Calibration of the Surround Panel As a Heat Flux Transducer

A4.3.1 The calibration of the surround panel is made by means of hot box tests either before the aperture for the building elements is cut out or with a blank of known thermal conductance installed in place of the building element. The surround panel must be fully prepared with the permanent differential thermocouples installed and any final facings or coatings applied. Several tests are made, adequately covering the range of surround panel mean temperatures (and perhaps surround panel temperature drops and box air velocities) at which the surround panel will be operated in tests of building elements. In each test, under steady-state conditions, the metering box heat flow Q_t', the corresponding surround panel temperature drop Δt, and the emf indicated by its permanently installed thermocouples are determined. The net surround panel heat flow Q_m' corresponding to Δt is calculated as $Q_t' \times (A_m/A_t)$ when the calibration is made before the aperture is cut, where A_m and A_t are as defined earlier, and as $(Q_t' - Q_{t1})$ for the calibrated-blank method where Q_{t1} is the calculated heat flow through the blank. In the latter method of calibration, a suitable blank must first be prepared and calibrated. The recommendations with regard to the construction of uniform masks and installation of surface thermocouples should also be followed for the blank. It is recommended the blank be the same thickness as the building element and be positioned in the precise position of the building element at the juncture with the surround panel aperture. Surface temperatures on both sides of the blank should be measured by at least one surface thermocouple for each 0.5 m^2 of area, but no less than four, distributed uniformly over the area. The blank is calibrated by either measuring the thermal conductance of representative samples of the blank material in a Test Method C177 guarded hot plate or Test Method C518 heat meter apparatus or by measuring the thermal conductance of a large specimen of blank material in the hot box and subsequently reducing it to the size required to fit the surround panel aperture. The calibration should cover the range of mean temperatures at which the blank will be operated during the calibration tests on the mask. At any one surround panel mean temperature there should be little variation of $Q_m'/\Delta t$ with Δt, but $Q_m'/\Delta t$ may vary slightly with mean temperature due to the change of thermal conductivity to the surround panel material.

A4.4 Specific Instructions—An Example

A4.4.1 An example of specific instructions for construction and calibration of a surround panel system for elements smaller than the metering chamber area is presented in Test Method C 1199, Section 5.

A5. RECOMMENDED PRACTICE FOR ESTIMATION OF THE TESTING SYSTEM TIME CONSTANT

A5.1 General Considerations

A5.1.1 The time required to perform a hot box test is determined in part by the speed of response of the testing apparatus and the test sample's response to changes in its environment. One measure of this response to change is the time constant, τ, of the system. As described in Note 21, the time constant, τ, 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.

A5.1.2 For the hot box apparatus, the response is controlled by either the apparatus design or the assembled properties of the test sample. For test purposes, if the apparatus time constant, τ_a, is greater than the sample time constant, τ_s, the test will be controlled by the value of τ_a. If, however, $\tau_a < \tau_s$, then the sample response will be the controlling factor in the test completion.

A5.1.3 Since the operation of the hot box apparatus is a heat transfer problem, it appears logical that the controlling factors for the hot box test would include: (1) the heating or cooling capacities for the apparatus; (2) the air circulation patterns and velocities; (3) the internal heat capacity of the test chambers; (4) the thermal diffusivities of the material used to construct the apparatus; (5) the specimen geometry; (6) the specimen thermal diffusivity; and (7) the specimen heat capacity.

A5.2 Approach

A5.2.1 The controlling testing system time constant is determined by the following procedure: (1) estimate the time constants for the apparatus, (2) estimate the time constant for the test specimen and then (3) pick the larger which is the time constant which controls the test. This effective time constant, τ_{eff}, is then used to fix the time periods for data acquisition and determination of final system stability.

A5.3 Response of the Apparatus

A5.3.1 The design of the apparatus should include consideration of the speed of response of the test chambers to changing test conditions. The speed of response of the apparatus, or time constant, τ_a, is fixed by the design and for a properly designed system should be less than the specimen time constant in most situations. Since the test apparatus is generally complex compared to the sample, and since it does not change with test sample, it is recommended that the apparatus time constant, τ_a, be determined by experimental means. The recommended procedure for this determination is illustrated in A5.4.

A5.4 Experimental Determination of the Effective System Time Constant

A5.4.1 As discussed in A5.3.1, for any experimental setup, the measured response is the sum of the responses of the individual parts. Therefore, with an experimental approach to the time constant determination, the measured time constant, τ_{eff}, will be the combined response of the apparatus constant, τ_a, and the sample time constant, τ_s. If the time constant of the sample is significantly less than the time constant of the apparatus, the apparatus time constant, τ_a, can be determined from the measured effective time constant, τ_{eff}, using a simple experiment.

A5.4.2 The challenge now is to design a test specimen with a short time constant. Fortunately, the time constant of a homogeneous, low internal thermal resistance system can be approximated by the following first order equation:

$$\tau_s = \frac{M \bullet C}{h \bullet A_s} \quad \text{(A5.1)}$$

where:

τ_s = system time constant, hr,
M = mass of the sample, lb,
C = equivalent heat capacity, Btu / lbm F,
A_s = heat transfer area, ft^2, and
h = average surface coefficient, Btu/ hr ft^2 F.

By examination of Eq A5.1, the test sample will have a lower time constant if the specific heat capacity ($M \bullet C$) is kept low, since A_s and h are fixed by the apparatus design.

A5.4.3 It is impossible to create a test sample that has zero internal resistance; however, a specimen can be developed that has a low internal resistance and low heat capacity. To accomplish this requires a light weight, low *R* specimen. Ideally, since the time constant of the test system does not change, the test sample for this purpose could be the same as that used to establish the low *R* end of the calibration range. In general, this will establish a good estimate of the time constant for the apparatus. This result should be the shortest test time constant for the testing system.

A5.4.3.1 By similar path of reasoning, one could reason that a high R, high heat capacity system, for example, a well insulated, concrete wall, would yield the longest sample test time constant.

A5.4.4 *Procedure for experimental time constant determination:* The following experimental procedure is recommended for determining the time constant for a hot box system.

A5.4.4.1 Construct a sample having the lowest *R* value and the lighest weight that can be tested within the practical limits of the test apparatus. (Heating capacity is the critical issue here.)

A5.4.4.2 Close the system and let the test sample and apparatus come to equilibrium at the test laboratory temperature.

A5.4.4.3 Set up the data acquisition system to record all test parameters at five-minute intervals.

A5.4.4.4 Initiate test conditioning and record the test data from time zero at five-minute intervals.

A5.4.4.5 Continue monitoring the test data until steady-state is reached. For this determination, use four consecutive one hour time averages to establish steady-state.

A5.4.4.6 Plot the time versus net sample heat flow rate (for the usual case of constant temperature control) for the period from start to steady-state (see Fig. A5.1).

A5.4.4.7 Determine the elapsed time from startup, in which the five minute heat flow was 63.2 % of the final value.

A5.4.4.8 Determine the elapsed time from startup, in which the five minute heat flow was 86.5 % of the final value.

A5.4.4.9 The difference in times for Step A5.4.4.7 and 5.2.4.8 is equal to the time constant for the test system, τ_{eff}.

NOTE A5.1—For this determination, the time constant will be independent of the magnitude of the temperature shift or the heat loss of the system. The controlling factor for the time constant will be the heat capacity of the air handling system and the ability of the data system to accurately measure the correct temperature and heat flows.

A5.5 Sample Test Time Constants

A5.5.1 Since the value of the time constant, τ_{eff}, determined

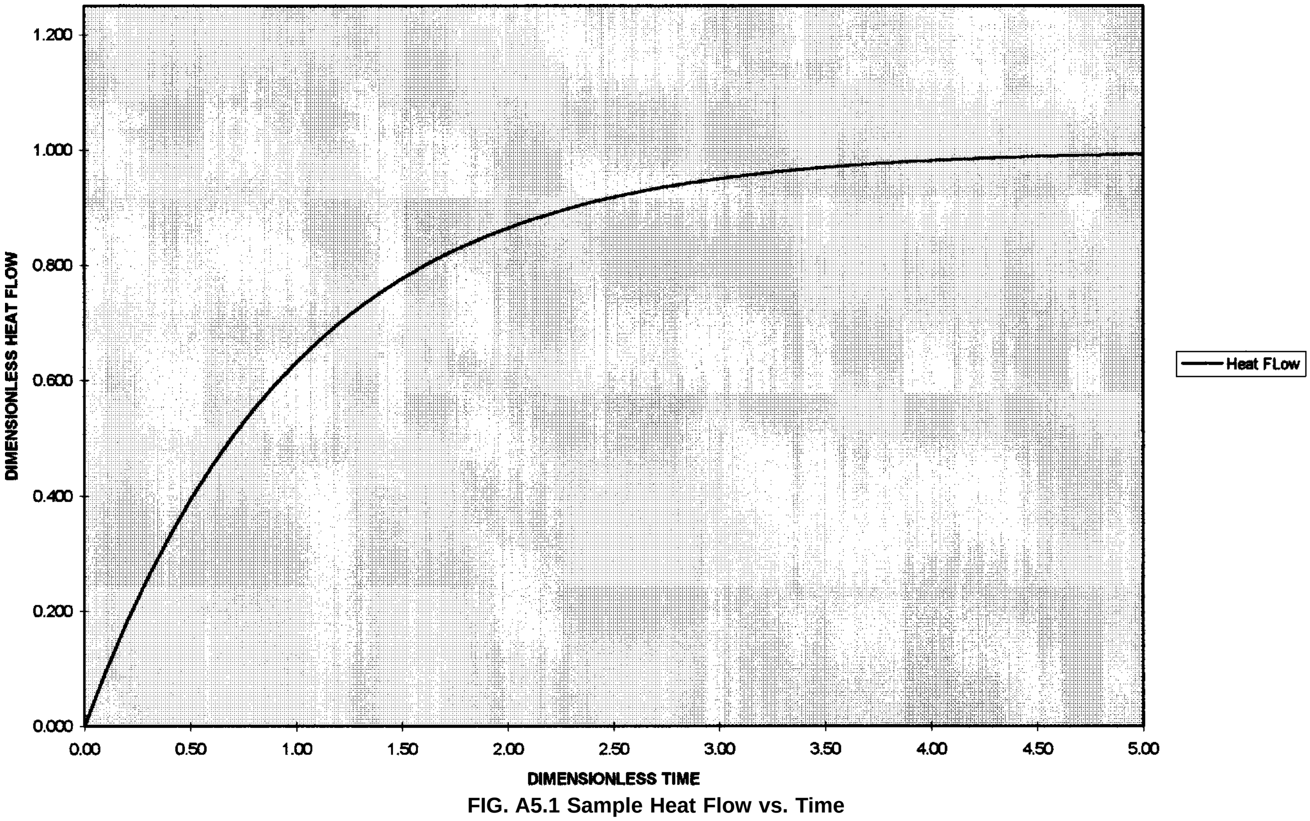

FIG. A5.1 Sample Heat Flow vs. Time

in the previous section is for the low *R*, low heat capacity specimen, it is still necessary to determine the time constants for the rest of the potential test sample constructions. Of course, one could repeat the experimental procedure of A5.4 for all test specimens. However correct, this approach would be expensive. An alternative is to estimate the time constant for the sample based upon the simple formula similar to Eq A5.1 as shown in Eq A5.2:

$$\tau_{se} = \frac{M \bullet C}{h' \bullet A_s} \qquad \text{(A5.2)}$$

where:
τ_{se} = effective sample time constant, hr,
M = mass of the composite sample, lb,
C = equivalent composite specific heat, Btu/lbm F,
A = heat transfer area, ft^2, and
h' = the composite surface coefficient which includes an estimate of the internal heat flow resistance, Btu/ hr ft^2 F.

and:

$$1/h' = (1/h_s) + (R_{we}) \qquad \text{(A5.3)}$$

h = the surface coefficient, Btu/ hr ft^2 F, and
R_{we} = the estimated sample resistance, hr ft^2 F/Btu.

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 “average” 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:

$$A_o/\tau_s = A_1/\tau_{s1} + A_2/\tau_{s2} + \ldots\ldots + A_i/\tau_{si} \qquad \text{(A5.4)}$$

where:
A_o = overall sample area, ft^2,
A_i = component heat path area, ft^2,
τ_o = sample composite time constant, hr, and
τ_{si} = sample path component time constant, hr.

A5.6 Overall Test Time Constant

A5.6.1 We have now established estimates for the apparatus time constant, τ_a, and the composite sample time constant, τ_s, for our test setup. As outlined A5.2, the remaining step is to choose the time constant that controls our process. This choice is made as follows:

A5.6.1.1 If $\tau_s >> \tau_a$, then use $\tau_{\text{eff}} = \tau_s$, or

A5.6.1.2 If $\tau_a >> \tau_s$, then use $\tau_{\text{eff}} = \tau_a$, or

A5.6.1.3 It $\tau_a \approx \tau_s$, then use the larger of τ_a or τ_s.

A5.6.2 For purpose of ease of calculation and data logging, the period of the scan time used for the test may be approximated by rounding down to the nearest simple fraction of one hour. For example, if the time constant is determined to be 33.5 minutes, use 30 minutes. Or, if the time constant is 12.5 minutes, use 10 minutes. Remember, this is a guide for testing and an exact determination is not required.

A6. DETERMINATION OF ENVIRONMENTAL TEMPERATURE WITHIN THE HOT BOX ENVIRONMENT

A6.1 General Considerations

A6.1.1 The heat transfer environment seen by the test specimen surfaces within a hot box apparatus are generally controlled by two types of heat transfer. The first is the convective heat transfer, which exchanges heat from the surface to the surrounding air by convective means. This heat flow, a function of the system geometry, air curtain properties, and air flow velocity, is generally expressed by Eq A6.1.

$$Q_{\text{conv}} = h_{\text{conv}} * \text{Area} * \Delta T_{s-a} \qquad \text{(A6.1)}$$

where:
Q_{conv} = heat loss by convection from the test specimen surface,
h_{conv} = convective heat loss coefficient, and
$\Delta T_{s\text{-}a}$ = temperature difference between the test specimen surface (*s*) and air curtain (*a*).

A6.1.2 The second mode of heat flow is from radiative heat transfer, which exchanges heat between the test specimen surface and the surrounding enclosure by radiation exchange. This heat flow, also a function of system geometry, and surrounding surface temperatures, is generally expressed by Eq A6.2.

$$Q_{\text{rad}} = \epsilon_{\text{eff}} * h_{\text{rad}} * \text{Area} * \Delta T_{s-b} \qquad \text{(A6.2)}$$

where:
Q_{rad} = heat loss by radiation from the test specimen surface (*s*) to that of the surrounding enclosure (*b*), and
ϵ_{eff} = effective emittance of the test specimen and surrounding enclosure surfaces. The effective emittance is defined in Eq A6.3:

$$\epsilon_{\text{eff}} = \frac{1}{[\,1/\epsilon_s + 1/\epsilon_b - 1\,]} \qquad \text{(A6.3)}$$

where:
ϵ_b = area weighted emittance of the surroundings as seen by the test specimen,
ϵ_s = emittance of the test specimen surface, and
h_{rad} = radiation heat transfer coefficient for the system. This coefficient is defined in Eq A6.4:

$$h_r = 4 \bullet \sigma \bullet T_{\text{mean}}^{\;3} \qquad \text{(A6.4)}$$

where:

σ = Stefan-Boltzmann constant = 5.673e-08 (W/m^2 K^4)

$$T_{mean}^3 = 1/4 \bullet [t_s^2 + t_b^2]\,[t_s + t_b] \quad (A6.5)$$

where:

$\Delta T_{s\text{-}b}$ = temperature difference between the test specimen surface and the surrounding enclosure surfaces.

A6.1.3 For Eq A6.4 and Eq A6.5, the temperatures used shall be in degrees absolute.

A6.1.4 The total energy exchange from the sample surface is then the sum of the two modes of heat flow from the surfaces defined in Eq A6.6:

$$Q_{total} = Q_{conv} + Q_{rad} \quad (A6.6)$$

A6.1.5 The development of the equations above is general for both test specimen surfaces in the hot box. The remaining concept to be defined is that of effective environmental temperature for the test environment. Eq A6.7 defines the effective environmental temperature as that effective temperature that yields that same net energy exchange in the simple convective mode as the combination of convection and radiation seen in the test situation.

$$Q_{total} = (h_{rad} + h_{conv}) \cdot Area \cdot (T_s - T_{env}) \quad (A6.7)$$

NOTE A6.1—Further discussion of environmental temperature is found in ISO Standard 8990.

APPENDIX

(Nonmandatory Information)

X1. AIR AND MOISTURE MASS TRANSFER

X1.1 General

X1.1.1 Heat transfer through an insulation or insulated structure may be significantly increased by air infiltration or moisture migration into or through the specimen. Since such phenomena can occur in field applications, it would be 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 may occur in field applications. This method, however, does not allow such test and, to those attempting them, the following considerations may be useful.

X1.2 Air Infiltration

X1.2.1 Provisions may be made in the calibrated hot box 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 should be constructed to meet all requirements of Test Method E 1424 with recommended capabilities, in either direction, of flow rates to 0.005 m^3/s for each square meter of specimen area and pressure differentials to 125 Pa. Pressure taps should be 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 must be limited to values which will not cause physical damage. Adequate precautions must be taken to ptevent excessive pressures and to protect personnel against possible injury in case of accidental failure.

X1.2.1.2 The air supply equipment should 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 the specimen. Air entering the cold chamber should be dried sufficiently to prevent undue frosting of evaporator coils.

X1.2.2 The apparatus and specimen perimeter should be gasketed or otherwise sealed to limit leakage both to the environment and around the specimen. Checks using an impervious specimen should show neglibible leakage for the metering chamber. A small leakage for the climatic chamber is allowable but must 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 may or may not be necessary, depending upon the temperature of the air and the direction of 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 that 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 must 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 building elements 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 Provisions may also be made in the calibrated hot box 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 effects may be complicated. 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 may occur, either by condensation or by freezing, depending upon conditions. These effects may be of interest and may be studied in the calibrated hot box. Other moisture effects may also be 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 may occur slowly enough that a quasi-equilibrium is established for a period sufficiently long to obtain the required information, or dynamic effects may be studied.

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