NFRC Test Procedure for Measuring the Steady-State Thermal Transmittance of Fenestration Systems

Adopted:	**March 15, 1991**
Revised:	**April 17, 1997**

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U-value Subcommittee
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Test Document: *NFRC Test Procedure for Measuring the Steady-State Thermal Transmittance of Fenestration Systems*

PREFACE

This NFRC procedure is assembled for use of the NFRC Accredited Testing Laboratories and laboratory inspector(s). It is intended to eliminate the necessity to interpret vague or general statements from all other documents.

This NFRC procedure is a compilation of information from ASTM C1199-91, data from hundreds of thermal performance tests by technicians and engineers, NFRC round robin data, and technical interpretations by NFRC.

The document contains in its entirety incorporates ASTM C1199-91, as well as modifications adopted by NFRC. All new or modified procedures from ASTM C1199-91 have been presented to the ASTM C16 Committee for review and possible inclusion in the next revision of ASTM C1199.

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Section 1
SCOPE

1.1 This standard test method provides requirements and guidelines and specifies calibration procedures required for the measurement of the steady state thermal transmittance of fenestration systems installed vertically. The standard specifies the necessary measurements to be made using measurement systems conforming either to ASTM C 236 or ASTM C 976 for determination of fenestration system thermal transmittance.

1.2 This test method refers to the thermal transmittance, U, and thermal conductance, C of a fenestration system installed vertically in the absence of solar and air leakage effects.

Note 1: This test method does not include procedures to determine the heat flow due to either air movement through the specimen or solar radiation effects. As a consequence, the thermal transmittance results obtained do not reflect performances which may be expected from field installations due to not accounting for solar radiation, air leakage effects, and the thermal bridge effects that may occur due to the specific design and construction of the fenestration system opening. Since there is such a wide variety of fenestration system openings in residential, commercial and industrial buildings, it is not feasible to select a typical surround panel construction to mount the fenestration system test specimen in. This situation allows the selection of a relatively high thermally resistant surround panel which places the focus of the test on the fenestration system thermal performance alone. Therefore, it should be recognized that the thermal transmittance results obtained from this test method are for ideal laboratory conditions in a highly insulative surround panel, and should only be used for fenestration product comparisons and as input to thermal performance analyses which also include solar, air leakage and thermal bridge effects due to the surrounding building structure.

1.3 A discussion of the definitions and underlying assumptions for measuring the thermal transmittance is included.

1.4 This standard may involve hazardous materials, operations and equipment. This standard does not purport to address all of the safety problems 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.

1.5 Projecting Products shall comply with testing requirements as specified by NFRC.

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Section 2

REFERENCED DOCUMENTS

2.1 ASTM Standards

C 168	Definitions of Terms Relating to Thermal Insulating Materials.
C 177	Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot Plate Apparatus.
C 236	Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box.
C 518	Test Method for Steady-State Thermal Heat Flux Measurements and Transmission Properties by Means of the Heat Flow Meter.
C 976	Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box.
C 1045	Practice for Calculated Thermal Transmission Properties from Steady-State Heat Flux Measurements.
C 1199	Standard Test Method for Measuring the Steady State Thermal Transmittance of Fenestration Systems Using Hot Box Methods
E 230	Temperature-Electromotive Force (EMF) Tables for Thermocouples.
E 631	Terminology of Building Constructions.
E 1423	Practice for Determining the Steady-State Thermal Transmittance of Fenestration Systems.

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Section 3
TERMINOLOGY

3.1 Symbols—the symbols, terms, and units used in this document are as follows:

A_{b1} = area of room side baffle, m^2
A_p = Average surface area of inside and outside of product, m^2, = $(A_{int} + A_{ext})/2$
A_s = projected area of test specimen, (same as open area in surround panel), m^2
A_{int} = total exposed interior area of test specimen, m^2
A_{ext} = total exposed exterior area of test specimen, m^2
C_g = Conductance of facing on calibration transfer standard, $W/(m^2 \cdot C)$
C_s = thermal conductance of test specimen (surface to surface), $W/(m^2 \cdot C)$
C_{sp} = thermal conductance of surround panel (surface to surface), $W/(m^2 \cdot C)$
C_{ts} = conductance of calibration transfer standard core, $W/(m^2 \cdot C)$, determined by means of ASTM C 177 or ASTM C 518 and ASTM C 1045
e = emittance of surface
e_1 = emittance of glass
e_{b1} = emittance of the baffle or box wall
f_{1b} = $1.0/[1/e_1 + (A_s/A_{b1}) \cdot ((1/e_{b1})-1)]$ (assuming a view factor of 1.0)
h_{STI} = standardized surface conductance, room side, $W/(m^2 \cdot C)$
h_{STII} = standardized surface conductance, weather side, $W/(m^2 \cdot C)$
h_I = surface conductance, room side, $W/(m^2 \cdot C)$
h_{II} = surface conductance, weather side, $W/(m^2 \cdot C)$
K = convection coefficient, $W/(m^2 \cdot C)^{1.25}$
Q = time rate of heat flow through the total surround panel/test specimen and metering box system, W
Q_{c1} = time rate of convective heat flow from test specimen surface, W
Q_{r1} = time rate of net radiative heat flow from test specimen surface to the surroundings, W
Q_s = time rate of heat flow through the test specimen, W
Q_{sp} = time rate of heat flow through the surround panel, W
Q_{fl} = time rate of flanking loss heat flow around the surround panel, W
Q_{mb} = time rate of heat flow through the meter box (warm room) walls, W
q = heat flux (time rate of heat flow through unit area), W/m^2
q_s = heat flux through the test specimen, W/m^2
q_{r1} = net radiative heat flux to the room side of the test specimen,W/m^2
q_{c1} = convective heat flux to the room side of the test specimen, W/m^2
R = absolute temperature scale called Rankine
t_{b1} = area-weighted baffle surface temperature, room side, ^oC
t_I = area-weighted temperature of room side air, ^oC
t_{II} = area-weighted temperature of weather side air, ^oC
t_1 = area-weighted temperature of test specimen room side surface, ^oC
t_2 = area-weighted temperature of test specimen weather side surface, ^oC
t_1' = area-weighted temperature of room side glass/core interface of calibration transfer standard, ^oC

t_2' = area-weighted temperature of weather side glass/core interface of calibration transfer standard, °C

t_{sp1} = area-weighted room side surround panel surface temperature, °C

t_{sp2} = area-weighted weather side surround panel surface temperature, °C

U_s = thermal transmittance of test specimen (air to air under test conditions), $W/(m^2 \cdot K)$

U_{st} = standardized thermal transmittance of test specimen determined from Calibration Transfer Standard (CTS) surface heat transfer coefficients (air to air), $W/(m^2 \cdot K)$.

ó = Stefan-Boltzmann constant = 5.6703×10^{-8} $W/(m^2\$K^4)$

3.2 Definitions

Definitions and terms are in accordance with definitions in ASTM E 631 and ASTM C 168, from which the following have been selected and modified to apply to fenestration systems. See Figure 1 for temperature locations used in the following definitions:

3.2.1 Test specimen thermal conductance, CCThe time rate of heat flow through a unit area of a test specimen (fenestration system), induced by a unit temperature difference between the test specimen surfaces. It is calculated as follows:

$$C_s = 1 / (1/U_s - 1/h_I - 1/h_{II}) \qquad \text{or} \qquad C_s = Q_s/[A_s(t_1 - t_2)] \tag{1}$$

3.2.2 Surface conductance, h (often called surface or film coefficient)CThe time rate of heat flow from a unit area of a surface to its surroundings, induced by a unit temperature difference between the surface and the environment. Subscripts are used to differentiate between room side (**I**) and weather side (**II**) surface conditions (See Figure 1). It should be recognized that due to radiation effects, the room side air temperature (t_I) , may differ from the respective room side baffle temperature (t_{b1}). If there is a difference of more than " 1.0C, (" 2.0F) or "2.0C, (" 4.0F) for single glazed products, on the room side, the radiation effects must be accounted for to maintain accuracy in the calculated surface conductances. The room side and weather side surface conductances are calculated as follows:

when: $t_I = t_{b1}$" 1.0C, (" 2.0F),
except for single glazed products, then $t_I = t_{b1}$" 2.0C, (" 4.0F):

$$h_I = q_s/(t_I - t_1) \qquad \text{or} \qquad h_I = (q_{r1} + q_{c1})/(t_I - t_1) \tag{2}$$

For the weather side, then:

$$h_{II} = q_s/(t_2 - t_{II}) \tag{3}$$

3.2.3 Test specimen thermal transmittance, U_s (sometimes called overall coefficient of heat transfer)CThe heat transmission in unit time through unit area of a test specimen and its boundary air films, induced by unit temperature difference between the environments on each side. It is determined as follows:

$$U_s = Q_s/A_s\$(t_I - t_{II}) \tag{4}$$

3.2.4 Standardized Thermal Transmittance, U_{st} C The heat transmission in unit time through unit area of a test specimen and standardized boundary air films, induced by unit temperature difference between the environments on each side. It is calculated as follows:

$$U_{ST} = 1/[(1/h_{STI}) + (1/C_s) + (1/h_{STII})] \qquad (5)$$

Where h_{STI} and h_{STII} are the standardized surface conductances on the room side and weather side, respectively. Their numerical values are specified in section 7.1.10.

3.2.5 Surround panel (sometimes called the mask, mask wall, or homogeneous wall)**C**A homogeneous panel in which the test specimen is mounted. (See Section 5.1.2 for a description of a surround panel.)

3.2.6 Test specimenC The fenestration system or product being tested.

3.2.7 Calibration transfer standardC An insulation board of known stable thermal conductivity (i.e. expanded polystyrene) traceable to primary standards that is faced on both sides with glass or polycarbonate, instrumented with temperature sensors and is used to calibrate the surface conductances. (See APPENDIX A.1 for the design of a calibration transfer standard.)

3.2.8 View Factor - The portion of the metering box "viewed" by the test specimen that is exchanging radiation with the interior test specimen surface. This area of the metering box would be comprised of the baffle surface and any portion of any perimeter metering box wall that the test specimen is exchanging radiation with at a 90° incident angle. For most test specimens using this method, the metering box baffle would be the only surface exchanging radiation with the test specimen.

3.2.9 Projecting Products - Any product that has a test specimen projected area to wetted area ratio less than or equal to 0.8.

Section 4

SIGNIFICANCE AND USE

4.1 This test method details the calibration and testing procedures, and necessary additional temperature instrumentation required in order to apply ASTM C 236 or ASTM C 976, or most current applicable ASTM Test Method, to measure the thermal transmittance of vertical fenestration systems.

4.2 Since both temperature and surface air film conditions affect results, use of recommended conditions will assist in reducing confusion caused by comparing results of tests performed under dissimilar conditions. Standardized test conditions for determining the thermal transmittance of fenestration systems are specified below.

NFRC Test Conditions:

1. Interior ambient temperature of 21.1 C ("0.25 C), 70F (" 0.5F).
2. Exterior ambient temperature of -17.8 C ("0.25 C), 0F (" 0.5F).
3. The interior relative humidity shall be maintained at or below 15 %.
4. An interior measured film coefficient during CTS panel calibration testing of 8.29 W/m^{2}C (1.35 Btu/hr-ft^2-F) (" 5%).
5. An exterior measured film coefficient during CTS panel calibration testing of 28.97 W/m^{2}C (5.1 Btu/hr-ft^2-F) (" 10%) .

4.3 This test method does not include procedures to measure the heat flow due to either air movement through the test specimen or solar radiation effects.

4.4 The thermal transmittance of a test specimen is affected by its size and three-dimensional geometry. Therefore, it is mandatory that fenestration systems be tested at the sizes specified in the NFRC 100.

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Section 5
CALIBRATION

5.1 General

Prior to performing the surround panel calibration testing, the surround panel thermal characteristics shall be determined using either ASTM C518 or ASTM C177 (See Note 2). The thermal test facility shall install a continuous and homogeneous surround panel in the metering box opening for calibration purposes. The thermal resistance of the surround panel shall be determined at the standard NFRC test conditions identified in Section 4 of this document. The test laboratory shall compare the ASTM C518 or ASTM C177 results to the tested surround panel values.

After the surround panel has been tested, a calibration transfer standard shall be mounted in the surround panel opening. As explained in ***Note 1*** and ***Note 2***, there may be a strong interaction between the heat flow in an actual surrounding wall and the frame of the fenestration system. If the surrounding wall construction contains highly conductive materials, the heat flow through the fenestration system frame could be significantly changed. Since it is not feasible to select a typical wall to use as a surround panel, it is desirable to have a relatively high thermally resistive surround panel to minimize this "shorting" interaction so that the heat flow through the fenestration system itself can be measured as accurately as possible.

5.1.1 The test configuration for fenestration products shall be calibrated using a heat flux transducer calibration transfer standard (CTS Panel) constructed as described in Appendix A.1 and illustrated in Figure 2. The calibration transfer standard has a core material of known characteristics traceable to primary standards such as the guarded hot plate of a national standard laboratory. The projected area of the calibration transfer standards used shall cover the same range as the test specimen model size and tolerances as specified in the NFRC 100-91, Section 5.2.

Two calibration transfer standards shall be used; one approximately the largest model size to be tested and one approximately the smallest fenestration size to be tested.

It is also recommended that the smallest CTS Panel be constructed in such a manner as to permit the rotation of the panel to be installed in the surround panel in a horizontal orientation (e.g.: a 1219 mm x 1829 mm (48" x 72") size could also be tested in a 1829 mm x 1219 mm (72" x 48") orientation). Extreme care should be taken when handling CTS Panels with glass facing.

5.1.2 A surround panel, consisting of a stable homogeneous thermal insulation material with a thermal conductivity at 24C (75F) not in excess of 0.04 W/(m·K) [0.28 Btu-in/hr-ft^2-F] and having a very low gas permeance, shall be provided for mounting the test specimen (see Figure 3). For structural integrity, the homogeneous insulation board core may be sandwiched between two sheets of a support material having a very low gas permeance and stable thermal and dimensional properties. The opening in the central homogeneous insulation board core may be covered with a non-reflecting tape to minimize surface damage. The width of the homogeneous insulation board core of the surround panel (see Figure 3) shall be at least the maximum thickness of the test specimen and in no circumstances be less than 100 mm (4 in). The maximum thickness of the homogeneous insulation board core of the surround panel should be no more than 25 mm (1 in) greater than the maximum thickness of the test specimen (i.e., 100 mm (4 in) $\leq$ core thickness $\leq$ test specimen thickness + 25 mm (1 in) and the core thickness $\geq$ window thickness). Unless specifically required for test specimen mounting purposes, no thermal bridges should exist in the surround panel. In these specific situations where the surround panel is not homogeneous, a detailed drawing describing the surround panel and the thermal bridge materials and the modified surround panel construction, along with the measured thermal conductivities (using ASTM C 177 or ASTM C 518) of all materials used, shall be included with the test report.

Note 2: A recommended surround panel core material is expanded polystyrene (beadboard) having a density in excess of 20 kg/m^3 (1.25 lbf/ft^3) which has been aged unfaced in the laboratory for a minimum of 90 days. A suitable facing material is 12 mm (0.5 in) thick type AB (no knots) fir plywood that is taped at all joints and painted with two coats of a non-reflecting, low air and moisture permeance paint having a known or measured emittance. Another facing material found suitable is 3 mm (0.118") to 4 mm (0.157") Hi-impact polystyrene (ABS Plastic). An alternative means to eliminate or minimize air permeance is to introduce suitable air/moisture retarders between the core and facers. It is a requirement that the thermal conductivity of the materials used for the surround panel be measured in a guarded hot plate (ASTM C 177) and/or a heat flow meter (ASTM C 518) at a 1.6C (35F) mean (moderate winter @ 21C/-18C (70F/0F). It is also recommended that thermal conductivity be measured at two additional temperatures; extreme winter 21C/-30C (70F/-22F) and summer 24C/52C (75F/126F) temperature (room side/weather side) conditions. For added confidence in establishing the heat flow through the actual surround panel used in a test, it is a requirement that it be installed in the hot box before the test specimen mounting hole(s) are cut and ASTM C 236 or ASTM C 976 tests at the NFRC 100-91 temperature conditions be made to determine the flanking loss around the homogeneous panel and verify the thermal resistance previously determined for the surround panel as described in Section 5.1.

5.1.3 The following equation shall be used to determine flanking loss as described in Note 2:

$$Qfl = Q - Qsp - Qmb \tag{6}$$

5.1.4 In addition to the air temperature measurements specified in ASTM C 236 and ASTM C 976, the following temperature measurements are required.

5.1.4.1 **Radiating surface temperatures—**The temperature of all interior surfaces, including the baffle, of the metering chamber exchanging radiation heat transfer with the test specimen using the same area weighting criteria as specified in ASTM C 236 or ASTM C 976.

5.1.4.2 Air temperatures C The air temperature sensors shall be located 3" from the surface of the surround panel. The air temperature sensors shall be arranged in a vertical grid network, with a minimum thermocouple density as determined by the relationship

$$N = A/(0.07 + 0.08 * / A)$$

where A is the metering area in m^2. If the number of thermocouples is within 10% of the number determined by this relationship, then the requirements of this section are judged to be met. The rows and columns closest to the metering box walls shall be located at a minimum distance of 6" from each meter box wall. Parallel averaging of air temperatures shall be allowed on vertical elevations (horizontal rows) only.

5.1.5 Air leakageC All potential air leakage sites on the surround panel and at the interface between the surround panel and the test specimen shall be sealed on the interior and exterior with non-metallic tape or caulk to minimize or eliminate air leakage between the room side and weather side chambers. The thermal performance can be affected by the method and placement of the test specimen air seal. Therefore, the test specimen is to be sealed with tape of similar surface emittance to that of the adhering surface. For vertical and horizontal sliding products, the test specimen shall be sealed at the interior or exterior location nearest to the primary air seal. For all other fenestration product types, the test specimen shall be sealed at the interior. Perimeter joints between the test specimen and the surround panel shall be sealed on both sides of the wall. In no case shall the tape or caulk cover more than 12 mm (0.5 in.) of the test specimen frame or edge. As an additional precaution to minimize the potential for leakage of air through and around the sealed test specimen, means shall be provided to measure and equalize the pressure difference across the test specimen, or an air leakage test shall be performed in accordance with ASTM E283 at 75 Pa (1.57 lbf/ft^2), equivalent to approximately 11.1 m/s (40 kmh or 25 mph) wind, to validate air leakage rates before and after the thermal performance test. For hot boxes which have a perpendicular or parallel wind flow (to the test specimen weather side surface) wind direction , this shall be accomplished by balancing the weather side total pressure with the room side static pressure to within 0 " 10 Pa (0 " 0.21 lbf/ft^2). The pressure sensors used shall be located outside the boundary layer on the glazing surface. The exterior pressure sensor shall be oriented perpendicular to the center of the test specimen weather side surfaces. The interior pressure sensor shall be located in such a location as to not be influenced by any forced convection.

Note 3: Sealing techniques should be governed by two primary criteria:

(1) The sealant applied should be of similar (" 0.2) emittance as the surface to which it is being applied; and
(2) The sealant is applied in as minimal amount possible to achieve the reduction in air leakage.

5.2 Calibration Tests

5.2.1 Procedure

5.2.1.1 Install the calibration transfer standard 25 mm (1") from the exterior (cold side) surface of the surround panel. Seal the cracks around the perimeter of the calibration transfer standard with non-metallic tape and/or caulking to prevent air leakage.

5.2.1.2 Establish steady state temperature conditions for which the surround panel is to be calibrated and record measurements of power, temperatures, velocity and pressure.

5.2.1.A Criteria for NFRC Steady State

1. Determining steady-state involves two separate evaluations. First, a series of four hourly sets of data are compared to the group mean to determine if steady state has been achieved. Second, two additional consecutive two-hour test periods are individually compared to the average initial four-hour period and each other to verify steady-state conditions are maintained. The following tests are applied to both assessments.

2. The average room and weather side air temperatures and all other non-specimen surface temperatures shall not vary by more than " 0.25C (" 0.5F) over the entire eight (8) hour steady state period.

3. The total heat input into the metering box, Q (including Q_{mb} and warm room circulating fan power) shall be used to determine steady state. The mean of the four one-hour steady state periods shall agree within " 1% of the mean of each of the two hour test periods and each of the two (2) two-hour test periods must be within " 1% of one another.

5.2.2 Data Analysis

5.2.2.1 **Total heat flowC**The time rate of heat flow through the test assembly (surround panel, calibration transfer standard, and metering box system), Q, is determined by the procedures specified in Section 7.1.3, equation 21.

5.2.2.2 Surround panel heat flow, Q_{sp}, is then:

$$Q_{sp} = C_{sp} * A_{sp}(t_{sp1} - t_{sp2}) \tag{7}$$

where:
A_{sp} = surround panel area, m^2
C_{sp} = results of ASTM C518 or C177 tests

t_{sp1} = area weighted room side surround panel surface temperature, ^{o}C
t_{sp2} = area weighted weather side surround panel surface temperature, ^{o}C

Note: The surround panel heat flow is determined as defined in Section 5.2.2.2. Any difference in heat flow in these equations may be attributable to flanking loss occurring at the perimeter interface of the CTS Panel and the surround panel opening.

Note 4: If a mean temperature correction for the surround panel is required, conduct a calibration test at a 1.7C (35F) mean. Additional calibration tests may be performed at two other different mean temperature conditions as recommended in ***Note*** 2.

If t_{b1} = t_{I} (" 1.0C["2.0F]) and t_{b2} = t_{II} (" 1.0C["2.0F]) go to section 5.2.2.4 to determine the surface conductances.

If t_{b1} t_{I} and t_{b2} t_{II} go to section 5.2.2.7 to determine the surface conductances.

5.2.2.3 Calibration transfer standard heat flow, Q_s, is calculated from:

$$Q_s = Q - Q_{sp} - Q_{fl} - Q_{mb}$$

where Q_{fl} is defined in Section 5.1.3

As a secondary check on Q_s, the following equation is suggested:

$$Q_s = C_{ts}\$A_s\,(t_1' - t_2') \tag{8}$$

where: C_{ts} = conductance of calibration transfer standard core, W/(m^{2}$K), as determined by either ASTM C 177 or ASTM C 518 and ASTM C 1045
A_s = area of calibration transfer standard, m^2
$t_{1'}$ = average temperature of room side glass/core interface of calibration standard, ^{o}C (See Figure 1)
$t_{2'}$ = average temperature of weather side glass/core interface of calibration standard, ^{o}C (See Figure 1)

5.2.2.4 Surface conductances, h_I and h_{II}, when t_{b1} = t_I (" 1.0C["2.0F]) and t_{b2} = t_{II} (" 1.0C["2.0F]):

$$h_I = Q_s/[A_s(\,t_I - t_1)] \tag{9}$$

where: t_I = average room side air temperature, C

t_1 = average room side calibration transfer standard surface temperature, C, which is calculated from the following:

$$t_1 = t_1' + C_{ts}\$(t_1' - t_2')/C_g \tag{10}$$

where: C_g = Conductance of glass facing material on calibration transfer standard, $W/(m^2\$K)$

Note 5: The conductance of the glazing layer is the thermal conductivity of the glazing material divided by the glazing layer thickness. A value of 1.0 $W/(m\$C)$ [6.94 $Btu\$in/(hr\$ft^2\$F)$] for the thermal conductivity of float glass is recommended if the actual value is not provided by the manufacturer. For soda lime glass, a value of 0.92 $W/(m\$C)$ [6.39 $Btu\$in/(hr\$ft^2\$F)$] may be more appropriate, however the manufacturer should be consulted before using this value. In other cases, such as laminated or plastic glazing, the glazing manufacturer shall provide the measured thermal conductivity of the glazing material. If no documentation is provided, it will be the responsibility of the test laboratory to acquire the thermal conductivity of the facing material using primary standard traceable methods.

$$h_{II} = Q_s/[A_s\$(t_2 - t_{II})] \tag{11}$$

where: t_{II} = average weather side air temperature, ^oC
t_2 = weighted average weather side calibration transfer standard surface temperature, ^oC, which is calculated from:

$$t_2 = t_2' - [C_{ts}\$(t_1' - t_2')]/C_g \tag{12}$$

5.2.2.5 Room side radiative heat transfer, Q_{r1}C When the room side baffle or box wall is close to the test specimen, parallel plate radiative heat transfer can be assumed. Then:

$$q_{r1} = Q_{r1}/A_s = F_{1b}\$\text{ó}\$[(t_{b1}+273.16)^4-(t_1+273.16)^4] \tag{13}$$

where: F_{1b} = $1.0/[1/e_1 + (A_s/A_{b1})\$((1/e_{b1})-1)]$ (assuming a view factor of 1.0)
e_1 = emittance of glass
e_{b1} = emittance of the baffle or box wall
A_{b1} = area of baffle, m^2
t_{b1} = area weighted baffle temperature,

^oC
ó = Stefan-Boltzmann constant = $5.6703x10^{-8}$ $W/(m^2\$C^4)$

5.2.2.5.1 The test specimen and the surfaces the test specimen is exchanging radiation with must meet two criteria: a view factor of 1, and each individual baffle surface temperature must be within "1.0C ("2.0F) of the mean of all the surface temperatures. If either of these conditions is not met, the radiative heat transfer in the Appendices, Section 11, is required.

Note 6: To avoid the need to do a radiative calculation, a large baffle parallel to the surround panel may be installed close enough to the surround panel so that the test specimen (or CTS Panel) only "sees" the baffle. The baffle is required to meet the view factor and the isothermal requirements.

5.2.2.6 Room Side Convective Heat Transfer, Q_{c1}

$$Q_{c1} = Q_s - Q_{r1} \tag{14}$$

and

$$q_{c1} = Q_{c1}/A_s \tag{15}$$

Using equation (15), the convection constant K in the following equation for the convective heat transfer to the test specimen can be determined.

$$K = q_{c1}/(t_I - t_1)^{1.25} \tag{16}$$

Note 7: The convective heat transfer calculation assumes natural convection on the room side of the calibration transfer standard. To ensure that a single convection coefficient, K, can be used for fenestration system tests, its behavior should be investigated, using the calibration transfer standard, over the range of heat flows expected. The hot box operator may use a convective correlation different from equation (16) if it is more appropriate for the convective heat transfer situation which exists for that operators hot box. However, the test report should include the alternative form of equation (16) used and the alternative value of the convection constant K obtained.

5.2.2.7 Surface conductances, h_I and h_{II} when t_{b1} t_I and t_{b2} t_{II}

5.2.2.7.1 Room side surface conductance, h_I

From equations (13) and (15):

$$h_I = (q_{r1} + q_{c1})/(t_I - t_1) \tag{17}$$

where t_1 is calculated according to equation (10).

5.2.2.7.2 Weather side surface conductance, h_{II}

where:

$$h_{II} = Q/[A_s(t_2-t_{II})] \tag{18}$$

where t_2 is calculated according to equation (12).

Section 6
TEST PROCEDURE

6.1 Installation of Fenestration System

The fenestration system to be tested shall be installed in the surround panel with a configuration that simulates the actual installation as closely as possible. That is, the complete assembly, including all frame elements and operating hardware, should be in place during the test. The sealing requirements specified in Section 5.1.4, Air Leakage for the calibration transfer standard also apply here.

Products which are not designed to be mounted to the exterior surface of a rough opening shall be mounted flush with the exterior surface of the surround panel, and no greater than 1-1/2" from the interior surface of the surround panel, with the exception of the requirements as stipulated in Section 5.1.2.

6.2 Determination of Total Exposed Surface Area

The fenestration system installed in the surround panel for testing shall have the surface areas determined for both the interior and exterior of the product. Each surface applied thermocouple, either on the interior or the exterior, shall have a surface area determined to be used in calculating an area-weighted surface temperature. This shall be accomplished by taking two linear measurements for each frame and/or sash component, height plus depth. The measurements shall be taken in a perpendicular direction from the point of contact of the edge-of-glass to frame/sash member interface to the interior or exterior most point of the frame, and conclude at the point of contact of the perimeter framing member to surround panel interface. In certain instances, judgement of the laboratory may have to be relied upon to determine the exact locations to begin and end the total surface area measurements. These areas shall then be used for the determination of surface area-weighted temperature measurements to be used in equations 26 and 27 which are found in Sections 7.1.7 and 7.1.8 respectively. (See Figure 6 in Appendices for illustrations)

6.3 Temperature Measurements

After establishing steady state conditions as described in Section 5.2.1.A the following measurements should be made:

6.3.1 All measurements specified in ASTM C 236 or ASTM C 976.

6.3.2 Additional temperature measurements shall be made on the surround panel wall. The surround panel sensors shall have a minimum thermocouple density as determined by the relationship:

$$N = A/(0.07 + 0.08* / A)$$

where A is the metering area in m^2. If the number of thermocouples is within 10% of the number determined by this relationship, then the requirements of this section are judged to be met.

6.3.3 It is a requirement to make temperature measurements on the fenestration system frame, glazing (center and near edges) and on any other test specimen surfaces (sills, muntins, etc.), in order to provide a representative area weighted value of the fenestration system surface to surface temperature difference. It must be recognized that there is such a wide range of fenestration system designs, therefore it is not possible to specify the locations of the test specimen temperature sensors to provide a correct area weighted determination of the various surface temperatures for all configurations. Specified interior and exterior specimen surface temperature locations are to be placed in accordance with ASTM E1423, Section 7.2. Each glazing corner edge thermocouple shall be placed at a point 12.5 mm (1/2") from the adjacent framing member(s). Also see AAMA 1503.1-88, Figure 5 for additional guidance on the location of test specimen surface temperature sensors. This technique of area weighted temperature measurements may be applicable when the frame and glazing conductances are similar and the surface geometry is not too complicated. If this is not the case, excessive use of temperature sensors may cause the surface conductances h_I and h_{II} to differ from calibration tests introducing further uncertainty in the results.

6.3.3.a. The attachment of thermocouples shall be performed by using a nominal 1" wide by 4" long adhesive-backed flat-white or equal emittance aluminum foil tape with the 4" dimension parallel to the thermocouple wire.

6.3.4 Radiation effectsC To minimize the effect of radiation induced error on the temperature sensors, the temperatures of the following surfaces exchanging radiation heat transfer with the fenestration system must be measured; 1) room side baffle, hot box walls and portions of the surround panel which the test specimen can see. The temperature sensors must be applied to these surfaces with tape or adhesive which has an emissivity similar to that of the surface. Any heating and cooling devices located on the interior side of the surround panel must be shielded from the surround panel/fenestration system. The air temperature sensors should either be shielded or be as small as possible so that they are not significantly effected by surfaces that they are exchanging radiation with (See ASTM C 236 Section 6.5.2 or ASTM C 976 Section 5.7.).

6.4 Wind Speed Measurements

The exterior applied dynamic wind (perpendicular or parallel) shall produce an exterior film coefficient of 28.97 W/m^2C (5.10 Btu/hr-ft^2-F) " 10% during calibration testing of a CTS Panel. The weather side wind speed shall be measured in the free stream condition. One such method for perpendicular weather side wind would be to have the exterior wind speed measured at the mid-point area of the exit aperture of the discharge plenum. The sensor shall be located a maximum distance of 150 mm (6") toward the wind generator from the vertical plane of the exit aperture. Note that the center of the exit aperture and the center of the test specimen should be in the same plane as noted in Section 5.1.4. For parallel flow patterns, it is recommended that this location 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 minimum distance of 75 mm (3") out from the test specimen center point is recommended. Periodic traversing of the air flow field to determine the air velocity distribution is advisable. On the room side, where natural convection conditions are used, it is advisable to also have a sensor on that side so that natural convection conditions can be verified.

6.5 Glazing Deflection

Variations in the pressure in the space between the sheets of glass in sealed glazing units may cause deflections in the glass. In extreme cold weather cases, the glass surfaces may bow and come into contact with each other at their centerpoints. This change in the enclosed space dimensions can significantly effect the thermal conductance, C_s, and the thermal transmittance, U_s, of the test specimen. Factors which can cause a pressure unbalance between the glazing unit enclosed air space and the surrounding environment are:

(1) Differences in the barometric pressure due to a difference in the elevations of the fenestration system manufacturing facility and the testing facility.
(2) Changes in barometric pressure at the testing facility due to local weather variations.
(3) Changes in the mean temperature of the glazing unit enclosed airspace during testing.

Recognizing that glass deflection can cause a change in the thermal conductance, C, and the thermal transmittance, U, an estimation of the gap spacing between the glass sheets is required immediately before and after the test. The initial gap thickness can be estimated by either measuring the overall glazing thickness at the center or measuring the the deflection profile of each glass plate and then subtracting the thickness of the individual plates. Gap thickness during the test can be estimated from the initial thickness measurements minus the change in glass deflections which occur during the test. The glazing deflection measurements shall be performed on both sides of the fenestration system and must be included in the test report. The glazing deflection measurements should be performed:

(1) After the fenestration system has been delivered to the testing laboratory and has come to equilibrium in the laboratory.
(2) Just before the test commences, and
(3) Immediately after the test is completed and the test specimen enclosed air space mean temperature is close to that which existed during the test.

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Section 7
CALCULATION PROCEDURE

7.1 General Calculations

The following sections offer two methods of calculating the standardized thermal transmittance. The following criteria shall be used to determine which method is to be used in calculating the standardized thermal transmittance:

The area-weighted method shall only be used if the measured thermal transmittance, U_s, is equal to or greater than 3.4 W/m^2C (0.60 $Btu/hr\text{-}ft^2\text{-}F$) or the ratio of the test specimen projected area to wetted area on either side of the test specimen is less than or equal to 0.8. In all other cases, the CTS Method shall be used to determine the standardized thermal transmittance, U_{st}.

The following shall be calculated for each test:

7.1.1 The time rate of heat flow through the test assembly, Q, as determined using procedures outlined in ASTM C 236 or ASTM C 976.

7.1.2 Surround panel heat flow, Q_{sp}

$$Q_{sp} = C_{sp} \cdot A_{sp} \cdot (t_{sp1} - t_{sp2}) \quad \text{(surface to surface)} \tag{19}$$

Where:

C_{sp} = the thermal conductance of the surround panel, is determined by ASTM C 177 or ASTM C 518 measurements. The calibration of the surround panel shall verify the values determined by ASTM C177 or ASTM C518 measurements.

7.1.3 Test specimen heat flow, Q_s

$$Q_s = Q - Q_{sp} - Q_{fl} - Q_{mb} \tag{20}$$

where Q_{fl} was determined during calibration testing of the surround panel as described in Section 5.1.

7.1.4 Test specimen thermal transmittance, U_s

$$U_s = Q_s/[A_s \cdot (t_I - t_{II})] \tag{21}$$

where A_s is equal to the interior projected area of the test specimen.

7.1.5 Equivalent room side surface temperature, t_1

Equivalent room side surface temperature of test specimen, t_1, is calculated by solving the following three equations for Q_{r1}, Q_{c1} and t_1:

$$Q_s = Q_{r1} + Q_{c1} \tag{22}$$

$$Q_{r1} = A_s \cdot F_{1b} \cdot \sigma \cdot [(t_{b1} + 273.16)^4 - (t_1 + 273.16)^4] \tag{23}$$

$$Q_{c1} = A_s \cdot K \cdot (t_I - t_1)^{1.25} \tag{24}$$

where K and F_{1b} are determined from the calibration tests and As is equal to the interior projected area of the test specimen. The values for K and F_{1b} are to be derived from the CTS Panel calibration test which has a projected area closest to the test specimen projected area.

Note 8: One way to solve these equations is by iteration. Assume a value for t_1 in equation (23), calculate Q_r, determine Q_c from equation (22), then calculate a new t_1 from equation (24). If this new value is different from the assumed value, then use the average of the two t_1 values in equation (20) and repeat the calculation until the t_1 values agree to within 0.1C (0.18F).

7.1.6 Equivalent weather side surface temperature, t_2

$$t_2 = Q_s/(h_{II} \cdot A_s) + t_{II} \tag{25}$$

where h_{II} is determined from the calibration tests.

7.1.7 Room side surface conductance, h_I

$$h_I = Q_s/[A_s \cdot (t_I - t_1)] \tag{26}$$

where the room side surface temperature, t_1, used is either the measured weighted average value or the calculated equivalent value as determined in Section 7.1.5.

7.1.8 Weather side surface conductance, h_{II}

$$h_{II} = Q_s/[A_s \cdot (t_2 - t_{II})] \tag{27}$$

where the weather side surface temperature, t_2, used is either the measured weighted average value or the calculated equivalent value as determined in Section 7.1.6.

Note 9: It should be noted that the surface heat conductances, h_I and h_{II}, determined from the appropriately sized calibration transfer standard may differ from the surface conductances that exist during a hot box test on a specific test specimen. Actual fenestration systems usually have frame and sash surfaces which introduce three-dimensional convective heat transfer effects in the surface heat conductances. As a result of this, the test specimen surface conductances will differ from those obtained with the non-framed, essentially 2-dimensional calibration transfer standard tested under the same conditions. In this standard test method, it is assumed that the differences are small enough so that the calibration surface conductances can be used to calculate equivalent test specimen average surfaces temperatures, t_1 and t_2, and the test specimen thermal conductance, C_s.

7.1.9 Test specimen thermal conductance, C_s

$$C_s = 1 / (1/U_s - 1/h_I - 1/h_{II}) \tag{28}$$

7.1.10 Test specimen standardized thermal transmittance, U_{st}

$$U_{st} = 1.0/[(1/h_{STI}) + (1/C_s) + (1/h_{STII})] \tag{29}$$

Where h_{STI} and h_{STII} are the standardized surface conductances on the room side and weather side, as defined below.

$$h_{STI}(W/m^2\cdot K) = 1.77(t_I-t_1)^{0.25} + \sigma\cdot e_1[(t_I+273.16)^4-(t_1+273.16)^4]/(t_I-t_1)$$

or (30)

$$h_{STI}(Btu/h\cdot ft^2\cdot F) = 0.27(t_I-t_1)^{0.25} + \sigma\cdot e_1[(t_I+459.67)^4-(t_1+459.67)^4]/(t_I-t_1)$$

where: σ = Stefan-Boltzmann constant = 5.6703×10^{-8} W/m$^2\cdot$K^4
or
= (0.1712×10^{-8} Btu/h$\cdot$ft$^2\cdot$R^4)

e_1 = emittance of glass surface on warm side

h_{STII} = 30.0 W/(m$^2\cdot$C)
or
[5.1 Btu/(h$\cdot$ft$^2\cdot$F)]

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Section 8

PRECISION AND BIAS

8.1 The precision and bias for this test procedure is being determined.

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Section 9

REPORT

9.1 The report shall include all of the information specified in ASTM C 976 Section 11 or ASTM C 236 Section 10, and NFRC LAP and subsequent NFRC LAP Bulletins. The test specimen size and design shall also be reported. Any non-standard test specimen size and non-standard test conditions used shall also be reported. If the test specimen size is non-standard (" 1/2" in width and/or height of the Model size referenced in Table 1 of NFRC 100), then the text "non-standard size" shall be inserted immediately following the size everywhere the size is listed, both in the full report and in any summary. If the test conditions are non-standard, then the text "non-standard test conditions" shall be inserted immediately following the name of the procedure, such as NFRC 100, everywhere the test procedure is listed, both in the full report and in any summary.

9.2 In addition, if applicable, the time rate of heat flow through the total surround panel/test specimen, Q; the surround panel calculated time rate of heat flow, Q_{sp}; the time rate of flanking loss heat flow for the surround panel, Q_{fl}; the time rate of heat flow through the metering box(warm room) walls, Q_{mb}; the net test specimen heat flow rate, Q_s; the weather side and warm room side average baffle temperatures, t_{b1} and t_{b2}; the surround panel area, A_{sp}; the room side and weather side baffle areas, A_{b1} and A_{b2}; the calculated thermal conductance, C_s; the measured thermal transmittance, U_s; the calculated room and weather side surface conductances, h_I and h_{II}; the values of t_1 and t_2; the projected area, A_s, the total exposed interior area, A_{int}, and the total exposed exterior area, A_{ext}, of the specimen; of the fenestration system shall be reported and each of their estimated uncertainty specified. The procedures used to estimate the uncertainties should also be documented as an Appendix to the report. The criteria used to establish steady state conditions and the test period duration should also be documented. The following statement from Section 3.5 must be included in the test report directly after the above results are reported. "This test method does not include procedures to determine the heat flow due to either air movement through the specimen or solar radiation effects. As a consequence, the thermal transmittance results obtained do not reflect performances which may be expected from field installations due to not accounting for solar radiation, air leakage effects, and the thermal bridge effects that may occur due to the specific design and construction of the fenestration system opening. Therefore, it should be recognized that the thermal transmittance results obtained from this test method are for controlled laboratory conditions and should only be used for fenestration product comparisons and as input to thermal performance analyses which also include solar, air leakage and thermal bridge effects".

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Section 10
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Section 11

APPENDICES (Mandatory Information)

A1. Calibration Transfer Standard Design (Mandatory Information)

This large heat flux transducer is used in the calibration of the surface conductances and for checking the surround panel conductance. Figure 2 is a schematic diagram of a calibration transfer standard which consists of a homogeneous, well characterized, core calibration material made from an insulation board that has a known thermal conductivity measured by ASTM C 177 or ASTM C 518.

Note 17: A recommended calibration transfer standard core material is expanded polystyrene (beadboard) having a density in excess of 20 kg/m^3 (1.25 lbf/ft^3)which has been aged unfaced in the laboratory for a minimum of 90 days. A suitable facing material is 3 or 6 mm (0.12 or 0.24 in) float glass. It is required, prior to assembly of the calibration transfer standard, that the thermal conductivity of the material used for the core of the calibration transfer standard be measured in a guarded hot plate (ASTM C 177) or a heat flow meter (ASTM C 518) at, at a minimum, the following three sets of temperature conditions:

(1) cold side = -30°C (-22°F); warm side = 21°C (70°F)
(2) cold side = -18°C (0°F); warm side = 21°C (70°F)
(3) cold side = 24°C (75°F); warm side = 52°C (125°F)

For detailed information on the design see the publication by Goss, Elmahdy, and Bowen listed in Section 10, Bibliography.

The temperature sensors are area weighted and located in the manner shown in Figure 2. The 49 temperature sensors shown are for a 1 m by 1 m (3.3 ft by 3.3 ft) square calibration transfer standard. For other sizes, similar temperature sensor densities should be used. The purpose of the temperature sensors is to be able to measure accurately the temperature difference across the core material of the calibration transfer standard. It has been found satisfactory to use 30 gage thermocouple wire that is wired as a thermopile to obtain an accurate core temperature difference. The small diameter twisted wire pair should be hammered as flat as possible and then soldered to a thin copper shim material approximately 20 mm X 20 mm (0.8 in X 0.8 in) in size. The reverse smooth side of the shim material is then adhered with contact cement to the glazing facing inner surfaces. The glazing facing inner surfaces are then adhered to the core material with a polystyrene compatible contact cement. Since the thermal conductivity of the core material is known, and it is possible to accurately measure its thickness, the conductance of the core material can be calculated. This allows the heat flux through the calibration transfer standard to be determined from measurement of the temperature difference across the core material.

A2. Radiation Heat Transfer Calculation Procedure (Mandatory Information)

This calculation procedure is to be used when the assumption that the fenestration system and baffle surfaces are parallel surfaces and the fenestration system only exchanges radiation heat transfer with the isothermal baffles is not true. In many situations, the fenestration system also exchanges radiation heat transfer with the surround panel opening surfaces and with nonisothermal baffle and other surfaces. In those situations, the radiation calculation procedure described in this Appendix is required. Before using the calculation procedure described in this Appendix, it is recommended the section on radiation heat transfer found in Chapter 3 of the 1989 (or the most recent version in print) ASHRAE Handbook of Fundamentals be studied. The material in the following sections of this Appendix closely follows the radiation heat transfer material given in the 1989 ASHRAE Handbook of Fundamentals.

A2.1. Radiation Heat Transfer in an Enclosure

In addition to heat transfer by convection (mass motion plus conduction), there is radiation heat transfer between different surfaces in enclosures. In an enclosure, such as the six sided one shown in Figure 4, there are multiple reflections between the different surfaces and there may be partial absorption at each surface of the enclosure.

In order to determine the net radiative heat transfer per unit surface area, q_r, from each surface the following assumptions are made. It is assumed that each surface of the enclosure is at a uniform (or isothermal) temperature. Although the temperature of each surface is not exactly uniform, the temperature variation is usually not significant. Therefore, a uniform temperature (the average temperature of the surface) can be assumed in the analysis of the radiative heat transfer. Assuming isothermal surfaces also makes it possible to assume a uniform radiosity and irradiation of each surface of the enclosure. Any surface where the assumption of a uniform temperature is not valid shall be divided into smaller uniform temperature area elements and the radiosity and irradiation of each area element should be considered in analyzing radiative heat transfer between different surfaces. This will make the analysis substantially more complex so it is advantageous to design an enclosure with uniform temperature surfaces.

Radiosity, J, is the radiation heat transfer energy that leaves a surface. Irradiation, G, accounts for all of the radiation heat transfer energy received by a surface. In order to determine the net radiative heat transfer per unit surface area, q_{ri}, from each surface i, it is assumed that the surfaces are diffuse-gray, and opaque (no transmission of radiation through the surface); and that the medium inside the enclosure is nonparticipating (i.e. non-absorbing and non-emitting).

The net rate at which radiation leaves surface i, q_{ri}, is equal to the difference between the radiosity and irradiation of surface i:

$$q_{ri} = A_i \boldsymbol{\$}(J_i - G_i) \qquad \text{(A2.1)}$$

where J_i is the radiosity and G_i is the irradiation of surface i. By definition, radiosity is a combination of the energy emitted form the surface, and the portion of the irradiation energy that is reflected from the surface. Mathematically this can be written as:

$$J_i = E_i + p_i \$ G_i \qquad (A2.2)$$

where E_i is the emissive power and p_i is the reflectance of surface i. Substituting equation (A2.2) into equation (A2.1), the net radiative heat transfer can also be expressed as:

$$q_{ri} = A_i \$ (E_i - a_i \$ G_i) \qquad (A2.3)$$

where $a_i = 1 - p_i$ is the absorptance. If the irradiation has a similar wavelength distribution as the emitted energy (i.e., the surfaces are made of the same material and are at similar temperatures), we can assume that the absorptance is equal to the emittance of the surface.

$$e_i = a_i \qquad (A2.4)$$

where the emittance is defined as the ratio of the actual radiant heat transfer energy emitted to the radiant heat transfer energy emitted from a perfect radiator:

$$e_i = E_i/E_{bi} \qquad (A2.5)$$

where

$$E_{bi} = ó \$ T_i^4 \qquad (A2.6)$$

For an opaque surface, the radiosity, using equations (A2.4), (A2.5) and (A2.6) can be written as:

$$J_i = e_i \$ E_{bi} + (1 - e_i) \$ G_i \qquad (A2.7)$$

solving for G_i in equation (A2.7) and substituting into equation (A2.1), it follows that:

$$q_{ri} = (E_{bi} - J_i)/[(1 - e_i)/(e_i \$ A_i)] \qquad \text{(A2.8)}$$

The surface radiosity J_i must be known in order to evaluate the radiation heat transfer q_{ri}, in equation (A2.8). The irradiation of surface i is evaluated from the radiosities of all of the surfaces in the enclosure. Using the definition of the view factor (see the definition of the angle or view factor in Chapter 3 of the 1989 ASHRAE Handbook of Fundamentals and the figure of angle factors for surfaces that make up a rectangular enclosure), the total rate at which radiation reaches surface i from all surfaces is:

$$A_i \$ G_i = \text{Ó}\ F_{ji} \$ A_j \$ J_j \qquad \text{(A2.9)}$$

where Ó is the summation over $j = 1$ to ns.

Using the reciprocity relation for view factors ($A_i \$ F_{ij} = A_j \$ F_{ji}$) and substituting equation (A2.9) into equation (A2.1) we can obtain an alternative expression for the net radiation heat flux from surface i:

$$q_{ri} = \text{Ó}\ A_i \$ F_{ij} \$ (J_i - J_j) \qquad \text{(A2.10)}$$

where ns is the total number of surfaces in the enclosure. Combining equations (A2.8) and (A2.10):

$$(E_{bi} - J_i)/[(1 - e_i)/(e_i \$ A_i)] = \text{Ó}\ (J_i - J_j) \$ (A_i \$ F_{ij}) \qquad \text{(A2.11)}$$

Using an electric analog network representation to help solve radiation problems is an effective tool for visualizing radiation exchange in an enclosure (see Figure 5).

For any number of surfaces ns (ns = 6 for the rectangular enclosure shown in Figures 4 and 5), the radiosities can be determined by solving a system of ns simultaneous equations. Rearranging equation (A2.11), it can be written in the matrix form as:

$$[\,K\,]\cdot\{\,J\,\} = \{\,E\,\} \qquad \text{(A2.12)}$$

Section A2.2 shows the full details of the matrix [K] and the vector {E} for a six sided rectangular enclosure.

The radiosities, J, can be found by solving the following equations in matrix form:

$$\{\,J\,\} = [\,K\,]^{-1}\cdot\{\,E\,\} \qquad \text{(A2.13)}$$

Once the values of the radiosity, J_i, are known, the net radiation heat transfer from any surface i can be obtained from equation (A2.8).

A2.2 Evaluation of Radiation Heat Transfer

In order to calculate the radiation heat transfer between different surfaces of an enclosure, it is necessary to obtain the radiosity corresponding to different surfaces of the enclosure. In Section A2.1 equation (A2.11) was obtained as the following:

$$(E_{bi} - J_i)/[(1 - e_i)/(e_i\cdot A_i)] = \Sigma\,(J_i - J_j)\,(A_i\cdot F_{ij}) \qquad \text{(A2.11)}$$

Defining the following variables to simplify the notation:

$$c_i = (1 - e_i)/(e_i\cdot A_i) \qquad \text{(A2.14)}$$

$$b_{ij} = A_i\cdot F_{ij} \qquad \text{(A2.15)}$$

Note that $A_i\cdot F_{ij} = A_j\cdot F_{ji}$. Therefore,

$$b_{ij} = b_{ji} \qquad \text{(A2.16)}$$

We also have:

$$E_{bi} = \sigma\cdot T_i^4 \qquad \text{(A2.6)}$$

Substituting the above relationships into equation (A2.11), we obtain the following equation:

$$(E_{bi} - J_i)/c_i = \Sigma (J_i - J_j)b_{ij} \tag{A2.17}$$

Expanding equation (A2.17) for each surface of the airspace:

$$(E_{b1} - J_1)/c_1 = 0 + b_{12}(J_1 - J_2) + \ldots\ldots + b_{16}(J_1 - J_6) \tag{A2.18}$$

$$(E_{b2} - J_2)/c_2 = b_{21}(J_2 - J_1) + 0 + \ldots\ldots + b_{26}(J_2 - J_6)$$

$$\vdots$$

$$(E_{b6} - J_6)/c_6 = b_{61}(J_6 - J_1) + b_{62}(J_6 - J_2) \ldots + b_{65}(J_6 - J_5) + 0$$

Rearranging equation (A2.18) we get the following:

$$J_1(b_{12} + b_{13} + \ldots + b_{16} + 1/c_1) - b_{12}J_2 - b_{13}J_3 - \ldots - b_{16}J_6 = E_{b1}/c_1 \tag{A2.19}$$

$$J_2(b_{21} + b_{23} + \ldots + b_{26} + 1/c_2) - b_{21}J_1 - b_{23}J_3 - \ldots - b_{26}J_6 = E_{b2}/c_2$$

$$\vdots$$

$$J_6(b_{61} + b_{62} + \ldots + b_{65} + 1/c_6) - b_{61}J_2 - b_{63}J_2 - \ldots - b_{65}J_5 = E_{b6}/c_6$$

The above set of equations can be written in the matrix form as:

$$[\ K\ ]\$\{\ J\ \} = \{\ E\ \} \tag{A2.12}$$

where the column matrix (vector) { J } is defined as:

$$\{\ J\ \} = \begin{vmatrix} J_1 \\ J_2 \\ J_3 \\ J_4 \\ J_5 \\ J_6 \end{vmatrix} \tag{A2.20}$$

and the column matrix (vector) { E } is defined as:

$$\{\ E\ \} = \begin{vmatrix} E_{b1}/a_1 \\ E_{b2}/a_2 \\ E_{b3}/a_3 \\ E_{b4}/a_4 \\ E_{b5}/a_5 \\ E_{b6}/a_6 \end{vmatrix} \tag{A2.21}$$

and the components of the matrix [K] are defined as:

$$K_{11} = b_{12} + b_{13} + b_{14} + b_{15} + b_{16} + 1/c_1 \tag{A2.22}$$

$$K_{22} = b_{21} + b_{23} + b_{24} + b_{25} + b_{26} + 1/c_2$$

$$\vdots$$

$$K_{66} = b_{61} + b_{62} + b_{63} + b_{64} + b_{65} + 1/c_6$$

and

$K_{12} = -b_{12}$; $K_{13} = -b_{13}$; $K_{14} = -b_{14}$; $K_{15} = -b_{15}$; $K_{16} = -b_{16}$

Similarly, for K_{ij}, $i=2,3,4,5,6$ and $j \quad i$; $K_{ij} = -b_{ij}$

Therefore, a set of linear simultaneous equations in the radiosities, J_i, needs to be solved. This may be solved by several classical methods of matrix inversion like Gaussian Elimination or Gauss-Siedel Iteration. The result is depicted below:

$$\{ J \} = [K]^{-1} \$ \{ E \} \tag{A2.13}$$

Once vector { J } is obtained, the radiation heat transfer at surface i can be calculated as:

$$q_{ri} = (E_{bi} - J_i)/[(1 - e_i)/(e_i \$ A_i)] \tag{A2.8}$$

Figure 1
A Schematic Representation of Various Temperatures for Fenestration Systems

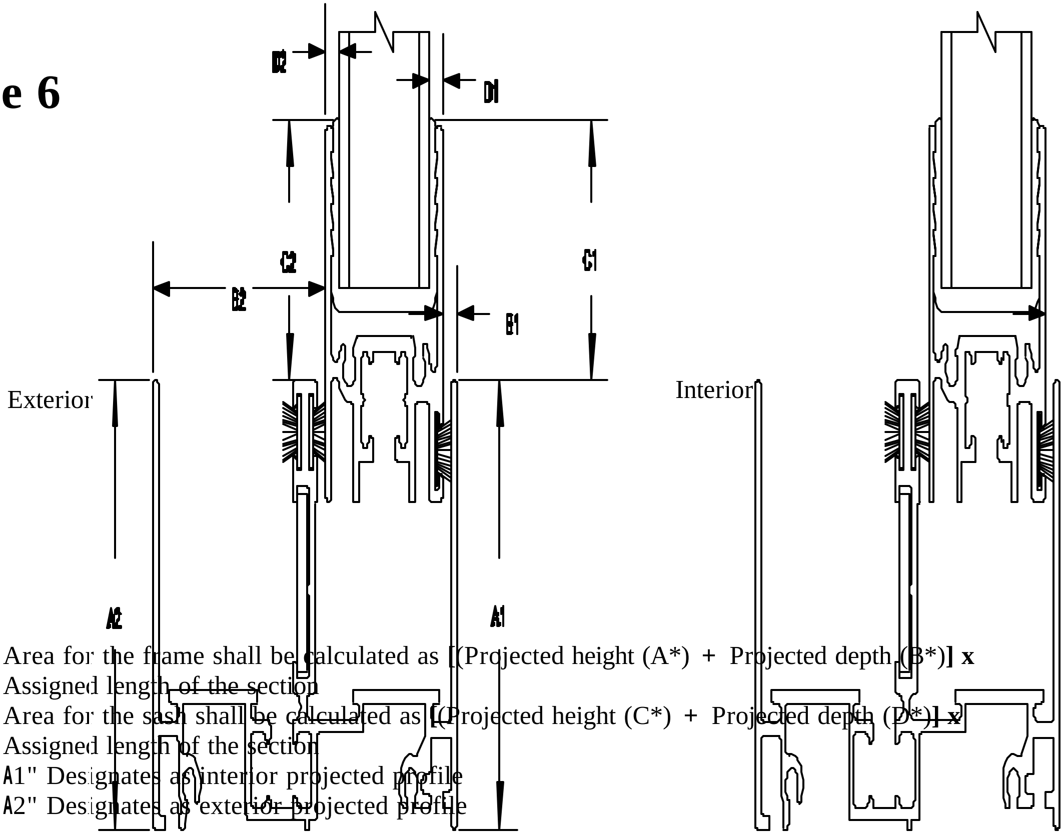
Figure 2
Calibration Transfer Standard (Not to Scale)

Figure 3
Surround Panel (Not to Scale)

Figure 4
Thermal Radiation Exchange Between Different Surfaces of a Rectangular Enclosure

Figure 5
Network Representation of Radiation Exchange
Between 6 Surfaces of a Rectangular Enclosure

Figure 6



Area for the frame shall be calculated as [(Projected height (A*) + Projected depth (B*)] **x** Assigned length of the section

Area for the sash shall be calculated as [(Projected height (C*) + Projected depth (D*)] **x** Assigned length of the section

A1" Designates as interior projected profile

A2" Designates as exterior projected profile