Designation: F2702 – 15

Standard Test Method for Radiant Heat Performance of Flame Resistant Clothing Materials with Burn Injury Prediction[1]

This standard is issued under the fixed designation F2702; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method measures thermal protective characteristics of flame resistant textile materials subjected to a standardized radiant heat exposure relative to a predicted second-degree skin burn injury.

1.1.1 This test method is not applicable to textile materials that are not flame resistant.

NOTE 1—The determination of a textile material's flame resistance shall be made prior to testing and done according to the applicable performance or specification standard, or both, for the textile material's end-use.

1.1.2 This test method accounts for the thermal energy contained in an exposed test specimen after the standardized radiant heat exposure has ceased.

1.2 This test method is used to measure and describe the response of materials, products, or assemblies to heat under controlled conditions, but does not by itself incorporate all factors required for fire hazard or fire risk assessment of the materials, products, or assemblies under actual fire conditions.

1.3 The values stated in SI units are to be regarded as standard. The values given in parentheses are mathematical conversions to inch-pound or other units that are commonly used for thermal testing.

1.4 *This standard does not purport to address 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:*[2]

D123 Terminology Relating to Textiles

D1776 Practice for Conditioning and Testing Textiles

D1777 Test Method for Thickness of Textile Materials

D3776 Test Methods for Mass Per Unit Area (Weight) of Fabric

D4157 Test Method for Abrasion Resistance of Textile Fabrics (Oscillatory Cylinder Method)

E457 Test Method for Measuring Heat-Transfer Rate Using a Thermal Capacitance (Slug) Calorimeter

F1494 Terminology Relating to Protective Clothing

2.2 *Other Standards:*

CCC-C-419 Federal Specification for Cloth, Duck, Unbleached, Plied-Yarns, Army and Numbered

3. Terminology

3.1 *Definitions:*

3.1.1 *break-open, n—in testing thermal protective materials*, a material response evidenced by the formation of a hole in the test specimen during the thermal exposure that may result in the exposure energy in direct contact with the heat sensor.

3.1.1.1 *Discussion*—The specimen is considered to exhibit breakopen when a hole is produced as a result of the thermal exposure that is at least 3.2 cm^2 (0.5 in.^{2}) in area or at least 2.5 cm (1.0 in.) in any dimension. Single threads across the opening or hole do not reduce the size of the hole for the purposes of this test method.

3.1.2 *charring, n*—the formation of a carbonaceous residue as the result of pyrolysis or incomplete combustion.

3.1.3 *dripping, n*—a material response evidenced by flowing of the polymer.

3.1.4 *embrittlement, n*—the formation of a brittle residue as a result of pyrolysis or incomplete combustion.

3.1.5 *heat flux, n*—the thermal intensity indicated by the amount of energy transmitted divided by area and time; kW/m^2 (cal/cm^2·s).

3.1.6 *ignition, n*—the initiation of combustion.

3.1.7 *melting, n*—a material response evidenced by softening of the polymer.

3.1.8 *radiant heat performance (RHP), n—in testing of thermal protective materials*, the cumulative amount of transferred energy identified by the intersection of a measured

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[1] This test method is under the jurisdiction of ASTM Committee F23 on Personal Protective Clothing and Equipment and is the direct responsibility of Subcommittee F23.80 on Flame and Thermal.

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

time-dependent heat transfer response through a subject material to a time-dependent, empirical predicted second-degree skin burn injury performance curve[3], expressed as a rating or value; J/cm^2 (cal/cm^2).

3.1.9 *response to heat exposure, n—in testing of thermal protective materials*, the observable response of the textile to the energy exposure as indicated by break-open, melting, dripping, charring, embrittlement, shrinkage, sticking, and ignition.

3.1.10 *second-degree burn injury, n—in testing of thermal protective materials*, reversible burn damage at the epidermis/dermis interface in human tissue.

3.1.11 *shrinkage, n*—a decrease in one or more dimensions of an object or material.

3.1.12 *sticking, n*—a material response evidenced by softening and adherence of the material to the surface of itself or another material.

3.1.13 *sample test suite, n*—any number of test specimens used to derive a single thermal performance estimate value.

3.1.13.1 *Discussion*—the determination of a single radiant heat performance estimate value requires exposing a number of specimens under varying exposure conditions so that the thermal energy left in the sample after the radiant source is removed is considered and accounted for when determining performance against a burn injury prediction.

3.1.14 For the definitions of protective clothing terms used in this method, refer to Terminology F1494, and for other textile terms used in this method, refer to Terminology D123.

4. Summary of Test Method

4.1 A vertically positioned test specimen is exposed to a radiant heat source with an exposure heat flux of either (a) 21 kW/m^2 (0.5 cal/cm^{2}s) or (b) 84 kW/m^2 (2 cal/cm^{2}s).

NOTE 2—Other exposure heat flux values are allowed. The test facility shall verify the stability of the exposure level over the material exposure time interval (used to determine the radiant heat performance value) and include this in the test results report.

4.2 The transfer of heat through the test specimen is measured using a copper slug calorimeter. The change in temperature versus time is used, along with the known thermophysical properties of copper to determine the respective thermal energy delivered.

4.3 A Radiant Heat Performance value of the test specimen is determined iteratively as the intersection of the time-dependent cumulative radiant heat response as measured by the

1	Cast Aluminum Apparatus Body
2	Toggle Switch - DPST
3	Transite - Smooth Surfaces
4	5 Quartz Lamps - 500 T 3 115-125 V
5	Screw - 10-24 ¾ in. (19 mm)
6	Legs for Horizontal Test Position
7	Tapped 10-24
8	½ in. (12.7 mm) D Imbedded Magnet Center Screw Fastening
9	Holder - 20 Gage Cold Rolled Steel
10	Bolt - 3/16 in. (4.76 mm) D ½ in. (12.7 mm) Brazed Flush
11	Test Sample
12	Holder Plate - 20 Gage Cold Rolled Steel
13	Drilled Holes - 3/8 in. (9.5 mm) D
14	Affix "DANGER - May Be Hot" labels in prominent locations on apparatus

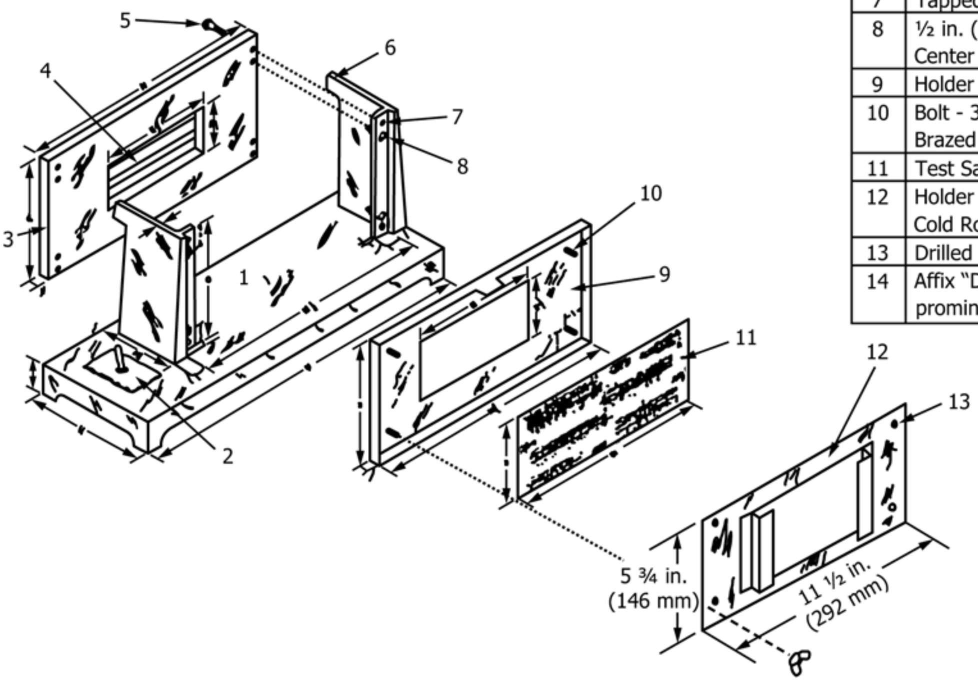

FIG. 1 General Expanded View of a Compliant Radiant Heat Performance Test Apparatus (see Figs. 2-4 for specific item details)

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[3] Derived from: Stoll, A.M. and Chianta, M.A., "Method and Rating System for Evaluations of Thermal Protection", Aerospace Medicine, Vol 40, 1969, pp. 1232-1238 and Stoll, A.M. and Chianta, M.A., "Heat Transfer through Fabrics as Related to Thermal Injury," Transactions – New York Academy of Sciences, Vol 33 (7), Nov. 1971, pp. 649-670.

calorimeter to a time-dependent, empirical predicted second-degree skin burn injury performance curve identified in 10.2.1.4.

4.4 Subjective observations of the thermal response of tested specimens are optionally noted.

5. Significance and Use

5.1 This test method is intended for the determination of the radiant heat performance value of a material, a combination of materials, or a comparison of different materials used in flame resistant clothing for workers exposed to radiant thermal hazards.

5.2 This test method evaluates a material's heat transfer properties when exposed to a heat exposure at a constant value and systematically varied durations. Air movement at the face of the specimen and around the calorimeter can affect the measured heat transferred due to forced convective heat losses. Minimizing air movement around the specimen and test apparatus will aid in the repeatability of the results.

5.3 This test method accounts for the thermal energy contained in the exposed test specimen after the radiant heat exposure has ceased. Higher values of Radiant Heat Performance rating determined in this test associate to higher values of radiant energy protection against a predicted skin burn injury.

5.4 This test method maintains the specimen in a static, vertical position and does not involve movement except that resulting from the exposure procedure.

5.5 This test method specifies two standard sets of exposure conditions, 21 kW/m^2 (0.5 cal/cm^{2}s) and 84 kW/m^2 (2.0 cal/cm^{2}s). Either can be used.

5.5.1 If a different set of exposure conditions is used, it is likely that different results will be obtained.

5.5.2 The optional use of other conditions representative of the expected hazard, in addition to the standard set of exposure conditions, is permitted. However, the exposure conditions used must be reported with the results along with a determination of the exposure energy level stability.

6. Apparatus and Materials

6.1 *General Arrangement*—The apparatus consists of a vertically oriented radiant heat source, specimen holder assembly, protective shutter, sensor assembly, and data acquisition/analysis system. The general arrangement of the radiant heat source, specimen holder, and protective shutter of a suitable apparatus is shown in Fig. 1.

6.1.1 *Radiant Heat Source*—A suitable, vertically oriented radiant heat source is shown in Fig. 1. It consists of a bank of five, 500 W infrared, tubular, translucent quartz lamps having a 127 mm (5.0-in.) lighted length and a mean overall length of 222 mm (8¾ in.). The lamps are mounted on 9.5 ± 0.4 mm (⅜ ± 1⁄64-in.) centers so that the lamp surfaces are approximately 0.4 mm (1⁄64-in.) apart. The bank or array of lamps are mounted and centered behind a 63.5 by 140 mm (2½ by 5½-in.) cut-out that is positioned in the center of a 12.7 mm (½-in.) thick, 86 mm (3⅜-in.) wide, by 292 mm (11-½ in.) long high temperature insulating board as shown in Fig. 2. The quartz lamps are heated electrically, and the power input controlled by means of a rheostat or variable power supply having a capacity of at least 25A.

6.1.1.1 Setting and monitoring the voltmeter readout on a voltage-controlled variable power supply is one method to calibrate and monitor the exposure level during the testing on

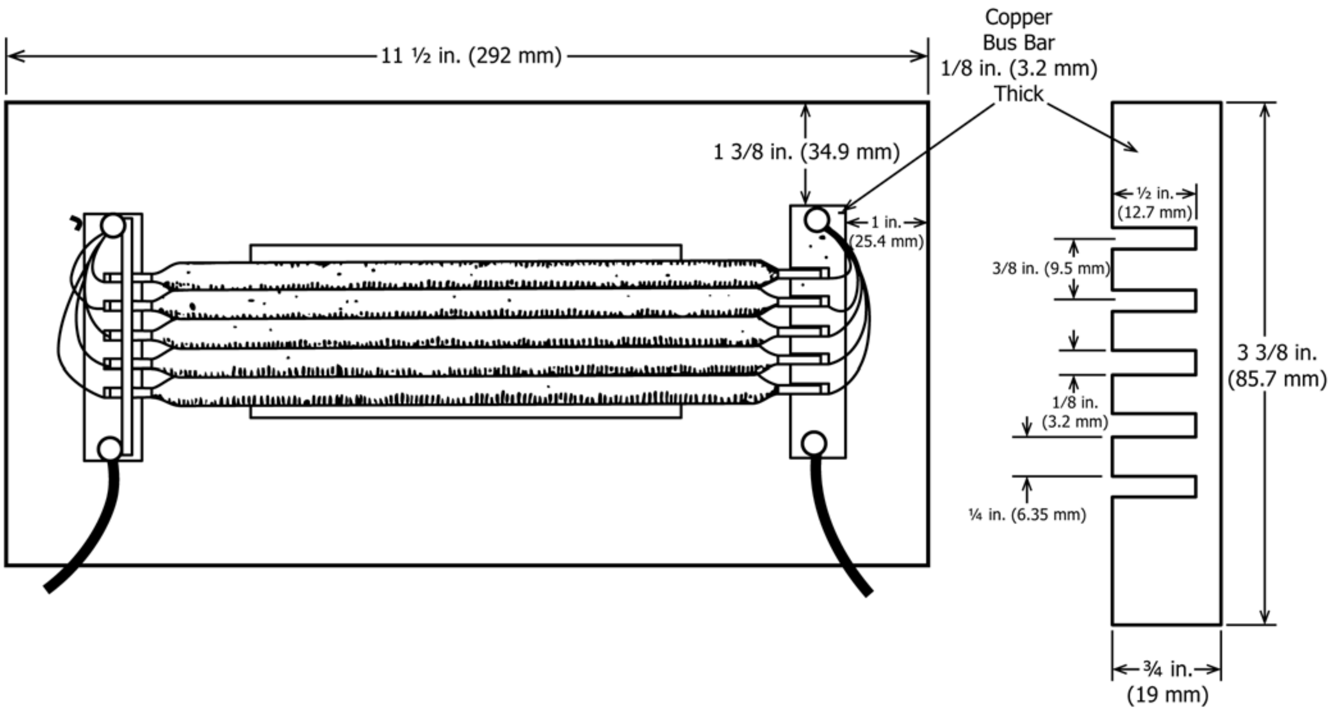

FIG. 2 Detailed View of Position of Quartz Lamps on Transite

a system so equipped. A voltmeter, accurate to ±1 V, is typically installed with the appropriate load circuit to indicate lamp operating power.

6.1.1.2 Any covers or guards installed on the quartz lamp assembly shall be designed such that any convective energy generated is not allowed to impinge on the sample specimen (vertical, unimpeded ventilation is required).

NOTE 3—Radiant measurement systems designed with closed lamp assembly covers and covers with minimal ventilation have been found to exhibit large measurement biases in round robin testing.

NOTE 4—Quartz infrared lamps, part description QH500T3/CL from General Electric Company, Consumer & Industrial Lighting Products and part description 500T3, No. 21651-5 from Philips Lighting Co., Specialty Lamps have been found to be effective.

NOTE 5—Transite monolithic, non-asbestos fiber cement board from BNZ Materials, Inc. has been found to be effective as a high temperature insulating board.

6.1.2 *Specimen Holder Assembly*—A specimen holder and holder plate with a 64 × 152 mm (2½ × 6-in.) center cut-out is positioned so that the distance from the nearest lamp surface to the test specimen is 25.4 ± 0.4 mm (1.0 ± 1⁄64 in.). The rear holder plate thickness is 0.9 ± 0.05 mm (0.036 ± 0.002 in.) and includes a bracket to hold the copper calorimeter sensor assembly. This rear plate holds the specimen in place so that it covers the complete cutout section (see typical designs in Figs. 3 and 4). Several specimen holders are recommended to facilitate testing.

NOTE 6—The copper calorimeter sensor assembly holder plate bracket is constructed such that the calorimeter assembly is in a reproducible fixed vertical position when installed and is held flush and rigidly against the rear holder plate.

6.1.3 *Protective Shutter*—A protective shutter, as shown in Fig. 3, is placed between the radiant energy source and the specimen. The protective shutter blocks the radiant energy just prior to the exposure of a specimen. Manual and mechanically operated shutter designs are allowed with and without water-cooling.

6.1.4 *Rheostat or Variable Power Supply*—A standard laboratory rheostat or appropriate power supply with a capacity of at least 25 A that is capable of controlling the output intensity of the radiant tubes over the range specified in 4.1.

6.1.5 *Sensor*—The radiant heat sensor is a 40 ± 0.5 mm diameter circular copper slug calorimeter[4] constructed from electrical grade copper with a mass of 18 ± 0.05 grams (prior to drilling) with a single ANSI type J (Fe/Cu-Ni) or ANSI type K (Ni-Cr/Ni-Al) thermocouple wire bead (0.254 mm wire diameter or finer—equivalent to 30 AWG) installed as identified in 6.1.5.2 and shown in Fig. 5. The sensor holder shall be constructed from non-conductive heat resistant material with a thermal conductivity value of ≤ 0.15 W/m•K, high temperature stability, and resistance to thermal shock. The board shall be nominally 1.3 cm (0.5 in.) or greater in thickness and meet the specimen holder assembly requirements of 6.1.2. The sensor is

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[4] See ASTM E457 for information regarding slug calorimeters.

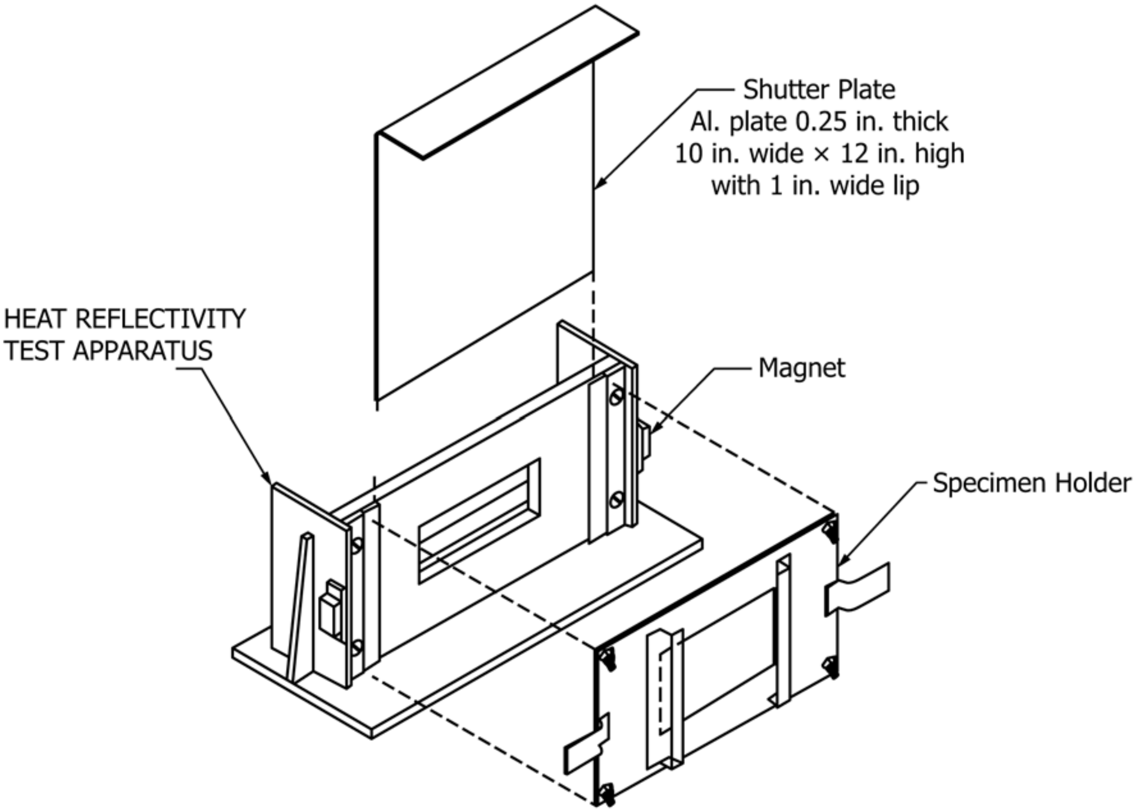


FIG. 3 Detailed View of a Typical Radiant Heat Performance Test Apparatus Showing Holder with Window, Shutter Plate, and Specimen Holder with Calorimeter Brackets. A Magnet/Tab Arrangement is Shown as an Equipment Design Option to Hold the Specimen Holder to the Assembly.

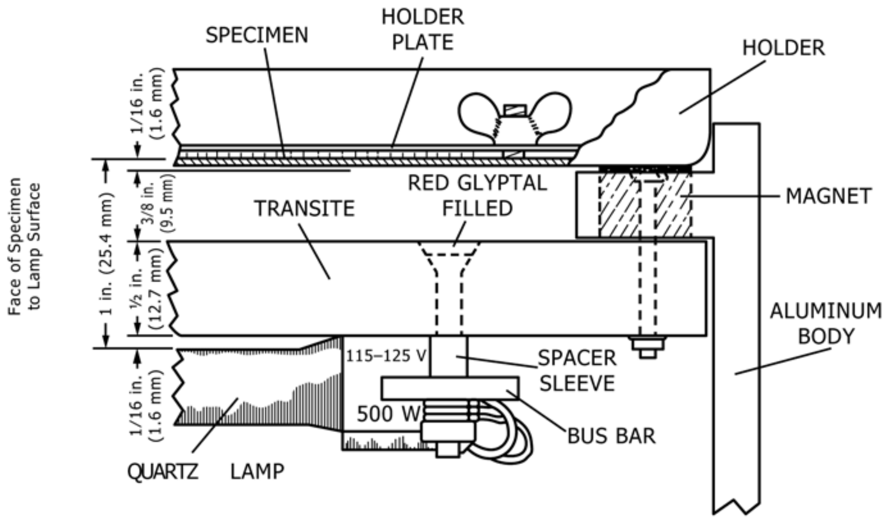
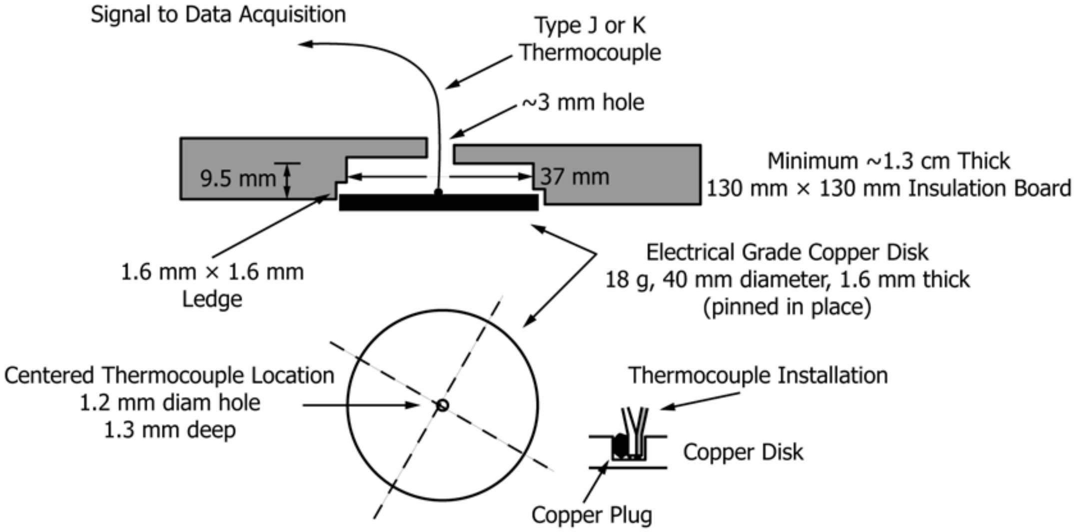


FIG. 4 Sample Position Example—Top View Enlargement



NOTE 1—Secure the copper disk into the supporting insulation board with three sewing pins cut to a nominal 5 mm (0.375 in.) in length positioned around the periphery so that the sewing pin heads hold the disk into the board.

FIG. 5 Radiant Heat Performance Test Sensor (Copper Calorimeter Mounted in Insulation Block) Showing the Mechanical Bonding Option of Thermocouple to Copper Disk

held into the recess of the board using three straight pins, trimmed to a nominal length of 5 mm, by placing them equidistant around the edge of the sensor so that the heads of the pins hold the sensor flush to the surface.

6.1.5.1 Paint the exposed surface of the copper slug calorimeters with a thin coating of a flat black high temperature spray paint with an absorptivity of 0.9 or greater[5]. The painted sensor must be dried and cured, according to the manufacturers instructions, before use and present a uniformly applied coating (no visual thick spots or surface irregularities). In the absence of manufacturers instructions, an external heat source, for example, an external heat lamp, shall be used to completely drive off any remaining organic carriers in a freshly painted surface before use.

NOTE 7—Absorptivity of painted calorimeters is discussed in the ASTM Report, "ASTM Research Program on Electric Arc Test Method Development to Evaluate Protective Clothing Fabric; ASTM F18.65.01 Testing Group Report on Arc Testing Analysis of the F1959 Standard Test Method—Phase 1"[6]

6.1.5.2 The thermocouple wire is installed in the calorimeter as shown in Fig. 5.

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[5] Zynolyte #635 from Aervoe Industries has been found suitable. Zynolyte is a registered trademark of the Glidden Company.

[6] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:F18-1001.

(1) The thermocouple wire shall be bonded to the copper disk either mechanically or by using high melting point (HMP) solder.

(2) A mechanical bond shall be produced by mechanically deforming the copper disk material (utilizing a copper filling slug as shown in Fig. 5) around the thermocouple bead.

(3) A solder bond shall be produced by using a suitable HMP solder with a melting temperature > 280 °C.

NOTE 8—HMP solders consisting of 5 %Sb-95 %Pb (~307°C melting point) and 5 %Sb-93.5 %Pb-1.5 %Ag (~300°C melting point) have been found to be suitable. The 280°Ctemperature minimum identified above corresponds to the point where melting of the solder bond would be experienced with an ~17 second exposure of an 84 kW/m^2 heat flux to a prepared copper calorimeter with a surface area of 12.57 cm^2 and a mass of 18.0 g. A careful soldering technique is required to avoid "cold" solder joints (where the solder has not formed a suitable bond of the thermocouple to the copper disk).

6.1.6 *Data Acquisition/Analysis System*—A data acquisition/analysis system is required that is capable of recording the calorimeter temperature response, calculating the resulting thermal energy, and determining the test endpoint by comparing the time-dependent thermal energy transfer reading to the empirical performance curve.

6.1.6.1 The data acquisition component must have a minimum sampling rate of four samples per second for temperatures to 250°C with a minimum resolution of 0.1°C and an accuracy of ±0.75°C. It must be capable of making cold junction corrections and converting the millivolt thermocouple signals to temperature (See NIST Monograph 175 or ASTM MNL12[7] Manual on the Use of Thermocouples in Temperature Measurement).

6.1.7 *Solvents,* alcohol or petroleum solvent for cleaning the copper slug calorimeter.

7. Hazards

7.1 This test method uses a high radiant energy source to test materials. The apparatus shall be adequately shielded to minimize any radiant exposure to personnel. Avoid viewing the lamps when energized.

7.2 Perform the test in an appropriate exhaust hood that is designed to contain and carry away combustion products, smoke, and fumes. Shield the apparatus or turn off the hood while running the test; turn the hood on to clear the fumes. Maintain an adequate separation between the radiant heat source and combustible materials.

7.3 The specimen holder and sensor assembly become heated during prolonged testing—use protective gloves when handling these hot objects.

7.4 Observe the appropriate precautions if a specimen ignites or generates combustible gases. Use only the appropriate fire suppression materials for electrical systems if it becomes necessary to extinguish a fire at the unit.

7.5 Refer to manufacturer's Material Safety Data Sheets (MSDS) for information on handling, use, storage, and disposal of chemicals used in this test method.

8. Sampling and Specimen Preparation

8.1 *Laboratory Sample*—Select a minimum of a 2.0 m^2 (2.4 yd^2) sample size from the material to be tested. Individual test specimens will be produced from this sample. Refer to Section 10, to determine number of samples required for the test.

8.2 *Laundering of Laboratory Sample:*

8.2.1 For specimens submitted without explicit test laundering specifications, launder the laboratory sample for one wash and dry cycle prior to conditioning. Use laundry conditions of AATCC Test Method 135, (1, V, A, i).

8.2.1.1 Stitching the edges of the laboratory sample is allowed to minimize unraveling of the sample material.

8.2.1.2 Restoring test specimens to a flat condition by pressing is allowed.

8.2.1.3 If an alternative laundry procedure is employed, report the procedure used.

8.2.2 For those materials that require cleaning other than laundering, follow the manufacturer's recommended practice using one cleaning cycle followed by drying and note the procedure used in the test report.

8.2.3 Samples submitted with instructions to not launder shall be tested as received.

8.2.4 Record the procedure used in the test report for materials that are submitted with explicit laundering instructions. For samples submitted with instructions not to launder, record in the test report that the samples were tested as received.

8.3 *Test Specimens*—Cut the required test specimens from each swatch in the laboratory sample. Make each test specimen at least 250 mm (10 in.) long and 100 mm (4 in.) wide with (a) two of the sides of the specimen parallel with the warp yarns in the woven material samples; (b) the wales in knit material samples; or (c) the length of the material in batts or nonwovens. Do not cut samples closer than 10 % of the material width from the edge; arrange the specimens diagonally across the sample swatch so as to obtain a representative sample of all yarns present. Mounted test specimens shall not extend outside the holder identified in 6.1.2.

8.3.1 A minimum of five sample suites is required for testing. The number of specimens in each suite will depend on the measurement response.

NOTE 9—Experience has shown that the first sample suite typically requires 5-7 test specimens (especially if no prior knowledge of the materials response is known), the remaining four suites will on average require 2-4 test specimens each.

8.3.2 If the laboratory sample edges have been stitched to reduce unraveling (8.2.1.1), test specimens shall be cut so they do not incorporate the stitching material.

8.3.3 Three independent test specimens from those identified above are required for determining average thickness and average surface density (see 8.5 and 8.6).

8.4 *Conditioning*—Condition each test specimen for at least 24 h at 21 ± 2°C (70 ± 5°F) and 65 ± 5 % relative humidity. The specimens shall be tested within 30 min of removal from the conditioning area.

8.4.1 If any specimens removed from conditioning cannot be tested within 30 min, return them to the conditioning area or

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[7] Available from ASTM Headquarters.

seal them in polyethylene bags (or other material with low water vapor permeability) until immediately prior to testing.

8.4.2 Bagged specimens have a four hour storage limit and are required to be tested within 20 min after removal from the bag.

8.4.3 Bagged specimens that exceed the four hour storage limit shall be removed from their bag and reconditioned according to 8.4 prior to testing.

8.4.4 *Metalized Fabrics*—Metalized fabrics shall be additionally conditioned using the oscillating drum apparatus identified in ASTM Standard Test Method D4157. Fabric specimens shall be mounted on the oscillating drum and subjected to 300 abrasion cycles.

8.4.4.1 The abradant shall be No. 6 hard-textured cotton duck conforming to the construction, weight, and strength of Type I of Federal Specification CCC-C-419. The abradant shall be cut into strips 45 mm (1.875 in.) wide by 230 mm (9 in.) long with the long dimension in the warp or wale direction and mounted in the specimen holding clamps under a tension of 13.5 N (3 lbf) and a head load of 1.36 kg (3 lb). A new abradant shall be used for each test, and the contact area of the abradant shall be free of slubs, knots, or other weave imperfections.

NOTE 10—Dimensional, force, and load tolerances are ±5 %.

8.5 *Determination of Test Specimens Average Thickness*—Determine the three specimens average thickness following ASTM Standard Test Method D1777.

8.6 *Determination of Test Specimens Average Surface Density*—Determine the three specimens average surface density (mass divided by surface area) identified in 8.3.3 following ASTM Standard Test Method D3776.

9. Preparation, Calibration, and Maintenance of Apparatus

9.1 *Radiant Heat Flux Calibration:*

9.1.1 Calibrating the test apparatus radiant heat flux value is an iterative process. Several calibration passes can be required to establish the standard value for testing within the specifications described below.

9.1.1.1 A radiant heat flux recalibration is required anytime the quartz bulb assembly is turned off after a calibration value has been established.

9.1.2 Select the standard radiant heat flux level that will be used for testing.

9.1.2.1 The standard values to select from are (a) 21 $kW/m^2 \pm 2\ kW/m^2$ ($0.5 \pm 0.05\ cal/cm^2s$) and (b) 84 $kW/m^2 \pm 2\ kW/m^2$ ($2 \pm 0.05\ cal/cm^2s$)

NOTE 11—Other values of radiant heat flux can be selected to represent the conditions of an expected hazard. However, this deviation must be reported within the results with a summary of the stability of the level reported consisting of an average and standard deviation from 10 calibration passes (with no changes to the power setting to the quartz bulb assembly).

9.1.3 Set the quartz bulb assembly power supply output to the approximate value expected for the selected radiant heat flux level.

9.1.4 Energize the lamps and allow the bulb assembly to warm-up before proceeding with the calibration.

9.1.4.1 A minimum of 60 s warm-up is required for radiant heat flux exposure values $\leq 42\ kW/m^2$ ($\leq 1\ cal/cm^2s$).

9.1.4.2 A minimum of 15 s warm-up is required for radiant heat flux exposure values $>42\ kW/m^2$ ($>1\ cal/cm^2s$).

9.1.5 Place the shutter device between the specimen holder location and the lamps to completely block the radiant heat.

9.1.6 Place the copper calorimeter sensor, which is initially at room temperature, into a specimen holder plate (with no specimen) and then place the assembly into the specimen holder testing location in front of the shuttered heat source. Ensure that the sensor that has a clean, black surface without signs of paint blistering, exposed copper, or any accumulation of deposits otherwise recondition the sensor surface as described in 9.3.2.

9.1.7 Start the data acquisition system, remove the shutter, and collect the copper calorimeter sensor information for a minimum period of 10 s of radiant energy exposure.

9.1.8 Replace the shutter.

9.1.9 If the shutter is not water cooled remove the specimen holder/copper calorimeter sensor and allow it to cool to room temperature. Also, remove the shutter and also allow it to cool to room temperature.

NOTE 12—Use protective gloves when handling the hot shutter and specimen/copper calorimeter assembly.

9.1.10 Calculate the average exposure heat flux value using a sampling interval that starts with the temperature measured at time = 0 (sample taken just before the shutter is removed) and ends with the temperature measured at exposure time = 10 s using the computational method identified in 11.1. This value is the measured radiant heat flux.

9.1.10.1 If this value is not within $\pm 2.1\ kW/m^2$ ($\pm 0.05\ cal/cm^2s$) of the standard value selected in 9.1.2, adjust the quartz bulb assembly power supply output appropriately and repeat the calibration sequence outlined in 9.1.5 – 9.1.10.

9.1.10.2 If this value is within $\pm 2.1\ kW/m^2$ ($\pm 0.05\ cal/cm^2s$) of the standard value selected in 9.1.2, the unit is considered calibrated and the resulting heat flux value is recorded.

9.2 *Verification of Quartz Bulb Assembly Output Uniformity:*

9.2.1 *Initial Output Verification of New Lamps:*

9.2.1.1 Complete the radiant heat flux calibration in 9.1 for an output of 84 kW/m^2 (2 cal/cm^2s), then use an optical pyrometer to obtain at least five (5) measured color temperatures of each lamp through the approximate center of the lamp. The optical pyrometer shall utilize a target reference (for example, internal calibrated lamp or filament) with an emission wavelength between 0.5 and 2.0 µm, a temperature measurement range of at least 1400 to 2200 K (2000 to 3400°F), and an effective target size of ≤1.5 mm.

NOTE 13—Single range disappearing filament-type and classic photoscreen wedge-type optical pyrometers have been found effective.

9.2.1.2 The alternate use of a radiometer in the sample specimen position to measure at least five (5) measured values of radiant energy output at the approximate center of each lamp (collimated so that only one lamp is visible to the radiometer for each measurement of the array) is permitted. The radiometer used shall have a detection wavelength range of at least 0.5 to 4 µm, with a measurement precision of at least ±5 %, and a viewing angle that subtends the individual lamp viewing collimation slit. For each of the individual lamp measurements, the collimation slit used shall be of uniform dimension that is less than or equal to the bulb diameter in use. During lamp output measurement, the collimation slit centerline shall align with the centerline of the respective lamp.

NOTE 14—The IR peak intensity of the quartz lamps occurs at ~1.2 µm.

9.2.1.3 Average the five measured values of each lamp and assign this its color temperature or radiant energy output (based on the measurement technology used).

9.2.1.4 Average the values from all five (5) lamps and assign this the array value.

9.2.1.5 *If an Optical Pyrometer is Used*—Compare the average value of each of the lamps in the array from 9.2.1.3 to the array average from 9.2.1.4. If any of the individual lamp averages are greater than ±15 K of the array average, replace the identified lamp and repeat 9.1 and 9.2.1.

9.2.1.6 *If a Radiometer is Used*—Compare the average radiometer value of each of the lamps in the array from 9.2.1.3 to the array average from 9.2.1.4. If any of the individual lamp averages are greater than ±15 % of the array average, replace the identified lamp and repeat 9.1 and 9.2.1.

9.2.1.7 *If a Variable Power Transformer Supply is Used to Power the Lamps*—Record the voltage of the new calibrated lamp array to the nearest 0.5 VAC.

9.2.2 *Output Verification of Lamps in Service:*

9.2.2.1 Follow the procedure in 9.2.1 to re-verify the individual lamps and the lamp array outputs at intervals not to exceed 150 h of lamp operating time at a heat flux output of 84 kW/m^2 (2 cal/cm^2/s), or intervals not to exceed 400 h of lamp operating time at a heat flux output of 21 kW/m^2 (0.5 cal/cm^{2}s), or a voltage change of more than 5 V for an output setting of 84 kW/m^2 (2 cal/cm^{2}s) from that noted in 9.2.1.7 (for systems using a variable power transformer supply to power the lamps).

NOTE 15—The operating life expectancy of the 500 W quartz infrared lamps specified in 6.1.1 is typically 5000 h at full output per the manufacturer (~130 kW/m^2 (3.1 cal/cm^{2}s)). However, experience has shown that the age and the variation in color temperature of the lamps in the array can affect the incident heat flux delivered to the test specimen.

9.3 *Sensor Care:*

9.3.1 *Initial Temperature*—Cool the sensor prior to and after an exposure with a jet of air or contact with a cold surface so that it is in thermal equilibrium and at room temperature prior to positioning the sensor behind the test specimen. Thermal equilibrium is obtained when the sensor temperature is within ±1°C of room temperature for a 60 second period prior to use.

9.3.2 *Surface Reconditioning*—Wipe the sensor face with a nonabrasive material immediately after each exposure, while hot, to remove any decomposition products that condense on the sensor since these could be a source of error. If a deposit collects and appears to be irregular or thicker than a thin layer of paint, the sensor surface requires reconditioning. Carefully clean the cooled sensor with solvent, making certain there is no ignition source nearby. If bare copper is showing, repaint the surface with a thin layer of flat black high temperature spray paint identified in 6.1.5.1. Perform at least one calibration run on the newly painted sensor before using it in a test run.

NOTE 16—An absorptivity change has been observed with certain high absorptivity, flat black paints after wiping the painted sensor surface with solvent or when water and other condensates are present. An assessment of the effect of cleaning the painted surface against the tolerance specification in 9.1.10.2 after specimen testing is recommended to determine if the paint being used is similarly affected. An increase in calibration frequency (calibrating after cleaning) is indicated if the tolerance specification is not met.

9.4 *Specimen Holder Care*—Use dry specimen holders at ± 1°C of ambient temperature for test runs. Alternate with several sets of holders to permit cooling between runs, or force cool with air or water. Clean the holder with a non-aqueous solvent when it becomes coated with tar, soots, or other decomposition products.

10. Procedure

10.1 A minimum of five sample test suites is required for determination of a radiant heat performance rating.

10.1.1 *Sample Test Suite*—The determination of a single sample test suite radiant heat performance value requires multiple sample specimens and an iterative exposure technique.

10.1.2 *Calibrate the Radiant Heat Source*—Calibrate the system as described in 9.1.

10.1.3 *Procedure for Testing at a Radiant Flux* $\leq$*42 kW/m*^{2} *(*$\leq$*1 cal/cm*^{2}*s):*

10.1.3.1 *Calibrate the Radiant Source*—Calibrate the system as described in 9.1.

10.1.3.2 Perform specimen testing following 10.1.5-10.3. Do not turn off the radiant heat source.

10.1.3.3 After the fifth specimen and every fifth that follows (for tests involving large specimen populations), verify and record the radiant source calibration following 9.1.5 to 9.1.10. Recalibrate the system if required as described in 9.1.

10.1.4 *Procedure for Testing at a Radiant Flux >42 kW/m*^{2} *(>1 cal/cm*^{2}*s):*

10.1.4.1 *Calibrate the Radiant Source*—Calibrate the system as described in 9.1.

10.1.4.2 Execute a single test exposure following 10.1.5-10.3.

10.1.4.3 Shut down the radiant lamps and let the system cool.

10.1.4.4 Repeat 10.1.4.1-10.1.4.3 for the remaining specimens.

NOTE 17—Operating the apparatus at high radiant flux values has been observed to place significant thermal stress on the quartz lamp system and significantly shorten their stable operating lifetime. As a result, the lamps are to be shut down after each measurement unless the system is documented to be stable (radiant heat source does not exceed the ±2.1 kW/m^2 (±0.05 cal/cm^{2}s) tolerance over a five specimen exposure testing period). If it has been demonstrated that the apparatus is stable, the procedure in 10.1.3 can be followed.

10.1.5 *Specimen Mounting*—Center a test specimen in the opening of the holder. For multilayered specimens, place the surface of the material intended as the outer layer of a protective system toward the radiant heat source. Secure the specimen in the holder (material is fixed between the specimen holder mounting plates).

10.1.5.1 Note in the testing report any specimen thickness change before exposure as the result of mounting it into the sample holder. Determine the average value of the material thickness values taken at the center of the sample holder and at any edge, after placement of the specimen in the holder assembly.

10.1.6 Ensure that the sensor has a clean, black surface without any accumulation of deposits otherwise recondition the sensor surface as described in 9.3.2.

10.1.7 Place the copper calorimeter sensor assembly into the specimen holder plate facing the back of the specimen.

10.1.7.1 Note in the report if the sensor is in contact with the specimen surface.

NOTE 18—Single layer, flat material specimens usually exhibit a small air gap, typically ~0.9 mm (see 6.1.2 for plate thickness dimensions) between it and the sensor prior to testing. Multi-layer samples, after being placed and fixed in the holder, can be deformed such that their surface extends past the back of the holder plate and make contact with the calorimeter.

10.2 *Test Exposure*—Follow the procedure outlined in 10.2.1 for samples with an unknown radiant heat performance value. Follow the procedure outlined in 10.2.2 for samples where the approximate radiant heat performance value is known (for example, repeats of sample test suites as identified in 10.1).

10.2.1 *Test Exposure of Samples with Unknown Radiant Heat Performance Values*—A method of successive halving is employed to determine the radiant heat performance value.

10.2.1.1 Place the manual or mechanically operated shutter between the specimen holder location and the lamps to completely block the radiant heat.

10.2.1.2 Place the copper calorimeter/specimen assembly prepared in 10.1.4 – 10.1.6, which is initially at room temperature, into the specimen holder testing location in front of the shuttered heat source.

10.2.1.3 Start the data acquisition system, remove the shutter, and collect and record the copper calorimeter sensor information.

10.2.1.4 Terminate the sample exposure (replace the shutter and remove the specimen holder/calorimeter assembly) after the total accumulated heat energy as measured by the calorimeter (see 11.1) meets/exceeds the following empirical predicted second-degree skin burn injury performance criteria:

$$J/cm^2 = 5.0204 \times t_i^{0.2901} \left(cal/cm^2 = 1.1991 \times t_i^{0.2901}\right) \quad (1)$$

where t_i is the time value in seconds of the elapsed time since the initiation of the radiant energy exposure (shutter fully removed). The exposure time value, t_{max} that satisfies Eq 1 represents an approximate second-degree predicted burn injury point for the continuous heating of the sample specimen without accounting for the energy remaining in the specimen.

10.2.1.5 Allow the specimen holder/calorimeter assembly to cool to room temperature before dissembling and removing the exposed specimen. Remove the shutter and also allow it to cool to room temperature if it is not water-cooled.

NOTE 19—Use protective gloves when handling the hot shutter and specimen/copper calorimeter assembly.

10.2.1.6 Prepare another test specimen as outlined in 10.1.4 – 10.1.6.

10.2.1.7 Determine the exposure time trial value for the next iterative exposure by dividing t_{max} (determined in 10.2.1.4) by two,

$$trial\ exposure\ time,\ t_{trial} = t_{max}/2$$

10.2.1.8 Place the cooled manual or mechanically operated device between the specimen holder location and the lamps to completely block the radiant heat. Place the copper calorimeter/new specimen assembly, which is initially at room temperature, into the specimen holder testing location in front of the shuttered heat source.

10.2.1.9 Start the data acquisition system (collect and record the copper calorimeter sensor information), remove the shutter, and expose the copper calorimeter / new specimen assembly to the radiant energy for t_{trial} seconds. Replace the shutter and immediately remove the copper calorimeter / exposed specimen assembly from the apparatus holder and carefully set it aside, maintaining a vertical geometry, away from the radiant heat source and in a location free of drafts or other heating/cooling sources.

10.2.1.10 Continue to acquire calorimeter data for at least 30 seconds after removing the assembly from the radiant exposure and until the energy stored in the specimen has been released (into the calorimeter and environment). Acquisition times greater than 30 seconds after removal can be required on heavy single and multilayer specimens.

10.2.1.11 From the measured calorimeter response, determine if a predicted second-degree burn injury occurred by comparing the time-dependent cumulative heat response to the empirical second-degree burn injury performance curve, Eq 1 (see 11.1).

(1) If a second-degree burn injury is not predicted (the measured heat response did not intersect the burn injury performance curve), determine a new exposure time value that is half way between the just completed t_{trial} value and the higher previous exposure time value (for the first time through, the higher previous exposure time value will be t_{max}). Assign t_{trial} time to this value and repeat 10.2.1.8 – 10.2.1.11.

(2) If a second-degree burn injury is predicted, determine a new exposure time value that is half way between the just completed t_{trial} value and lower previous exposure time value (for the first time through, the lower previous exposure time value with be zero). Assign t_{trial} time to this value and repeat 10.2.1.8 – 10.2.1.11.

(3) If the difference between the current t_{trial} and the previous t_{trial} is 0.5 seconds, then the radiant heat performance value for this test suite is

$$radiant\ heat\ performance\ value,\ J/cm^2 = current\ t_{trial},\ seconds \times radiant\ exposure\ heat\ flux\ value,\ kW/m^2/10$$

$$\left(radiant\ heat\ performance\ value,\ cal/cm^2 = current\ t_{trial},\ seconds \times radiant\ exposure\ heat\ flux\ value,\ cal/cm^2 s\right)$$

(4) Subjective information observed during all testing can be optionally recorded with each specimen exposure (see Appendix X1 and Appendix X2 for examples).

10.2.2 *Test Exposure of Samples with Approximately Known Radiant Heat Performance Values*—A method of successive halving is employed to determine the radiant heat performance value.

10.2.2.1 Assign the t_{trial} value as

$$t_{trial}\ \textit{value, s} = 1.2 \times \textit{approx radiant heat performance value, } J/cm^2 \times 10/\textit{radiant heat flux, } kW/m^2$$

$$\left(t_{trial}\ \textit{value, s} = 1.2 \times \textit{approx radiant heat performance value, } cal/cm^2/\textit{radiant heat flux, } cal/cm^2 s\right)$$

and a previous t_{trial} value as

$$\textit{previous } t_{trial}\ \textit{value, s} = 0.8 \times \textit{approx radiant heat performance value, } J/cm^2 \times 10/\textit{radiant heat flux, } kW/m^2$$

$$\left(\textit{previous } t_{trial}\ \textit{value, s} = 0.8 \times \textit{approx radiant heat performance value, } cal/cm^2/\textit{radiant heat flux, } cal/cm^2 s\right)$$

10.2.2.2 Prepare a test specimen as outlined in 10.1.4 – 10.1.6.

10.2.2.3 Place the cooled manual or mechanically operated shutter device between the specimen holder location and the lamps to completely block the radiant heat. Place the copper calorimeter/new specimen assembly, which is initially at room temperature, into the specimen holder testing location in front of the shuttered heat source.

10.2.2.4 Start the data acquisition system (collect the copper calorimeter sensor information), remove the shutter, and expose the copper calorimeter/new specimen assembly to the radiant energy for t_{trial} seconds. Replace the shutter and immediately remove the copper calorimeter/exposed specimen assembly from the apparatus holder and carefully set it aside, maintaining a vertical geometry, away from the radiant heat source and in a location free of drafts or other heating/cooling sources.

10.2.2.5 Continue to acquire calorimeter data for at least 30 seconds after removing the assembly from the radiant exposure and until the heat stored in the specimen has been released (into the calorimeter and environment). Acquisition times greater than 30 seconds after removal can be required on heavy single and multilayer specimens.

10.2.2.6 From the measured calorimeter response, determine if a predicted second-degree burn injury occurred by comparing the time-dependent cumulative heat response to the empirical second-degree burn injury performance curve, Eq 1 (see 11.1).

(1) If a second-degree burn injury is not predicted, determine a new exposure time value that is half way between the just completed t_{trial} value and the higher previous exposure time value (for the first time through, select a higher previous exposure time value as 1.5 × t_{max}). Assign t_{trial} time to this value and repeat 10.2.2.2 – 10.2.2.6.

(2) If a second-degree burn injury is predicted, determine a new exposure time value that is half way between the just completed t_{trial} value and lower previous exposure time value (for the first time through, the lower previous exposure time value with be the previous t_{trial} value determined in 10.2.2.1). Assign t_{trial} time to this value and repeat 10.2.2.2 – 10.2.2.6.

(3) If the difference between the current t_{trial} and the previous t_{trial} is 0.5 seconds, then the radiant heat performance value for this test suite is

$$\textit{radiant heat performance value, } J/cm^2 = \textit{current } t_{trial}\textit{, seconds} \times \textit{radiant exposure heat flux value, } kW/m^2/10$$

$$\left(\textit{radiant heat performance value, } cal/cm^2 = \textit{current } t_{trial}\textit{, seconds} \times \textit{radiant exposure heat flux value, } cal/cm^2 s\right)$$

(4) Subjective information observed during testing is optionally recorded with each specimen exposure (see Appendix X1 and Appendix X2).

10.3 Prepare and test enough specimens as outlined in 10.2 until five complete suites of values are obtained.

11. Calculation of Results

11.1 *Sensor Response*—The sensor response is determined shortly before and all during the radiant heat exposure to the test specimen.

11.1.1 The temperature value just prior to raising the shutter marks the sampling time initiation point, or t = 0 value.

11.1.2 The heat capacity of each copper slug at the initial temperature is calculated using[8]

$$C_p = \frac{4.1868 \times (A + B \times t + C \times t^2 + D \times t^3 + E/t^2)}{63.546 g/mol} \qquad (2)$$

where

t = (measured temperature °C + 273.15) / 1000
A = 4.237312
B = 6.715751
C = −7.46962
D = 3.339491
E = 0.016398

NOTE 20—The heat capacity of copper in J/g°C at any temperature between 289 K and 1358 K is determined by way of Eq 2.

11.1.3 The time-dependent cumulative energy values are determined from the temperatures at the beginning and end of the sampling intervals.

11.1.3.1 The copper slug heat capacity is determined at the appropriate time intervals. This is done by calculating an average heat capacity for each sensor from the initial heat capacity, determined in 11.1.2, and the measured temperature at time interval of interest,

$$\bar{C}_p = \frac{C_p\ @\ Temp_{initial} + C_p\ @\ Temp_{final}}{2} \qquad (3)$$

11.1.3.2 The measured cumulative energy exposure value at any exposure time duration is determined in J/cm^2 by using the relationship,

$$\textit{Cumulative radiant heat exposure, } Q = \frac{mass \times \bar{C}_p \times (Temp_{final} - Temp_{initial})}{area} \qquad (4)$$

---

[8] Equation 2 represents the Shomate Equation for temperature dependent heat capacity. The listed coefficients are from NIST.

where

Q = Cumulative energy detected by the calorimeter, J/cm^2,
$mass$ = mass of the copper disk/slug (g),
$\bar{C}_p$ = Average heat capacity of copper during the temperature rise (J/g°C),
$temp_{final}$ = Temperature of copper disk/slug at time interval of interest (°C),
$temp_{initial}$ = Initial temperature of the copper disk/slug at time = 0 (°C),
$area$ = Area of the exposed copper disk/slug (cm^2).

11.1.3.3 For a copper disk/slug that has a mass of 18.0 g and exposed area of 12.57^2 the determination of cumulative thermal energy delivered at any time interval reduces to:

$$\textit{Cumulative thermal energy},\ Q = 1.432 \times \bar{C}_p \times (Temp_{final} - Temp_{initial}) \tag{5}$$

NOTE 21—If a copper disk/slug with a different mass and or exposed area is used, the constant factor in Eq 5 above must be adjusted correspondingly. If required, the value in cal/cm^2 can be determined by multiplying the cumulative thermal energy in Eq 5 by the conversion factor 1/4.1868 cal/J.

11.1.3.4 *Calculating Radiant Heat Flux for Sensor Calibration*

(1) Incident heat flux to the copper calorimeter can be calculated over any time interval using:

$$\textit{Incident heat flux},\ q = \frac{mass \times \bar{C}_p \times (Temp_{final} - Temp_{initial})}{absorptivity \times area \times (time_{final} - time_{initial})} \tag{6}$$

where the absorptivity is the value for the black paint used for the calorimeter surface (typically ~0.9).

(2) For a copper disk/slug that has a mass of 18.0 g, an exposed area of 12.57 cm^2, and a 10 second calibration sampling interval the determination of incident heat flux reduces to:

$$\textit{Incident heat flux},\ kW/m^2 = 1.591 \times \bar{C}_p \times (Temp_{t=10s} - Temp_{t=0s}) \tag{7}$$

NOTE 22—If a copper disk/slug with a different mass and or exposed area is used, or the calibration time interval is changed from 10 s the constant factor in Eq 8 must be adjusted correspondingly. If required, the value in cal/cm^{2}s can be determined by multiplying the incident heat flux in kW/m^2 by the conversion factor 0.02389 cal m^2/kW cm^2 s.

11.2 *Determination of Radiant Heat Performance Rating*

11.2.1 *Radiant Heat Performance rating*—Take the average of at least five sample test suites of radiant heat performance values determined in Section 10 and report this value as the laboratory sample radiant heat performance (RHP) rating, J/cm^2 (cal/cm^2). Any additional specimen suites tested from the laboratory sample shall be included in the averaged value.

12. Report

12.1 State that the test has been performed as directed in Test Method F2702, using Method A, 21 kW/m^2 (0.5 cal/cm^{2}s) or B, 84 kW/m^2 (2 cal/cm^{2}s).

12.1.1 If a different exposure level is selected, report this value and document the stability of the exposure level as the average and standard deviation from 10 calibration passes where:

12.1.1.1 For radiant flux values ≤42 kW/m^2 (≤1 cal/cm^{2}s), no changes are made to the power setting to the quartz bulb assembly after each pass.

12.1.1.2 For radiant flux values >42 kW/m^2 (>1 cal/cm^{2}s), the power is cycled off to the quartz bulb assembly for a minimum of 60 seconds after each pass.

12.2 Describe the material sampled and the method of sampling used. In the material description, include:

12.2.1 Sample identification.

12.2.2 Sample conditioning employed.

12.2.3 Number and ordering of layers in the specimen.

12.2.4 Description of each material used to make up the specimen including type of fiber, construction, average surface density (basis weight), thickness, and color.

12.3 *Report the following information:*

12.3.1 *Conditions of test, including:*

12.3.1.1 Calibrated exposure energy.

12.3.1.2 Reason for exposure level for example specification requirement or representative of anticipated end use.

12.3.1.3 *Number of Layers Tested*—single or multiple with the order of lay-up and any thickness changes prior to exposure as determined in 10.1.4.1.

12.3.2 The individual radiant heat performance values from each tested specimen from the laboratory sample.

12.3.3 The radiant heat performance (RHP) rating.

12.3.4 Optional subjective observations (see Appendix X2).

13. Precision and Bias

13.1 A single operator intra-laboratory test series was performed on four different fabric types to determine method precision using the apparatus and procedure described above.

13.1.1 Four commercially available flame resistant fabrics used in thermal energy personal protective equipment were selected and tested as received:

(a) 18.3 oz/yd^2 three layer composite,
(b) 8.8 oz/yd^2 aluminized fabric,
(c) 6.0 oz/yd^2 single layer plain weave, and
(d) 7.8 oz/yd^2 single layer twill weave.

The composite and aluminized specimens, identified in Table 1 as A and B, respectively, were tested at an exposure heat flux of 1.99 cal/cm^{2}s. The two single layer fabrics, identified in Table 1 as C and D, respectively, were tested at an exposure heat flux of 0.49 cal/cm^{2}s. Three separate test suites were conducted on fabrics A and B and eight separate test suites were conducted on fabrics C and D using the number of specimens identified in 10.1 above.

13.1.2 The results of single operator intra-laboratory precision study are shown in Table 1 in cal/cm^2. Note that repeatability standard deviation values are unavailable due to all specimens having identical quantized exposure time values.

13.1.3 *Repeatability*—Due to this test method's quantized time interval specification for determining the RHP value, an estimation of repeatability, *r*, has been established based on a propagation of error analysis.

13.1.3.1 The variation for the test method is estimated based on the allowed variations of radiant flux and quantized exposure time resolution as shown below:

TABLE 1 Single Laboratory Precision of the Test Method (RHP values in cal/cm^2, exposure heat flux shown for each fabric). The repeatability standard deviation and %CV could not be determined as all samples exhibited identical quantized time values to predicted 2nd degree burn injury.

NOTE 1—s_r = repeatability standard deviation (pooled within-laboratory standard deviation)

Test	Fabric A (3 layer) composite 18.3 oz/yd^2	Fabric B (aluminized) 8.8 oz/yd^2	Fabric C (plain weave) 6.0 oz/yd^2	Fabric D (twill weave) 7.8 oz/yd^2
	(1.99 cal/cm^{2}s)	(1.99 cal/cm^{2}s)	(0.49 cal/cm^{2}s)	(0.49 cal/cm^{2}s)
1	17.9	43.78	6.9	7.4
2	17.9	43.78	6.9	7.4
3	17.9	43.78	6.9	7.4
4			6.9	7.4
5			6.9	7.4
6			6.9	7.4
7			6.9	7.4
8			6.9	7.4
Average	17.9	43.78	6.9	7.4
s_r	-	-	-	-
%CV	-	-	-	-

$$\left[\frac{\Delta RHP}{RHP}\right]^2 \cong \left[\frac{\Delta Q}{Q}\right]^2 + \left[\frac{\Delta Time}{Time}\right]^2 \tag{8}$$

or

$$s_{RHP}^2 \cong \Delta RHP^2 = RHP^2 \times \left[\left(\frac{\Delta Q}{Q}\right)^2 + \left(\frac{\Delta Time}{Time}\right)^2\right] \tag{9}$$

13.1.3.2 Substitution of the allowed variations in heat flux and the quantized time interval yields:

$$for\ RHP\ (84\ kW/m^2\ heat\ flux)\ in\ J/cm^2,\ s_{RHP}^2 \cong 17.64 + 0.0441 \times Time^2 \tag{10}$$

$$for\ RHP\ (21\ kW/m^2\ heat\ flux)\ in\ J/cm^2,\ s_{RHP}^2 \cong 1.1025 + 0.0441 \times Time^2 \tag{11}$$

$$for\ RHP\ (2\ cal/cm^2\ heat\ flux)\ in\ cal/cm^2,\ s_{RHP}^2 \cong 1 + 0.0025 \times Time^2 \tag{12}$$

$$for\ RHP\ (0.5\ cal/cm^2s\ heat\ flux)\ in\ cal/cm^2,\ s_{RHP}^2 \cong 0.0625 + 0.0025 \times Time^2 \tag{13}$$

where,

Q = Exposure radiant flux, 84 & 21 kW/m^2 (2.0 & 0.5 cal/cm^{2}s)
Δ *Q* = 2.1 kW/m^2 (0.05 cal/cm^{2}s)
Time = Measured exposure time, s
Δ *Time* = 0.5 s (quantized time interval)
RHP = Q × Time/10, J/cm^2 (Q × Time, cal/cm^2)

13.1.3.3 A set of tabulated values of estimated repeatability, r, spanning the exposure time values of 5-24 seconds for 2 cal/cm^{2}s radiant flux are shown in Table 2and for exposure time values of 9-28 seconds for 0.5 cal/cm^{2}s heat flux are shown in Table 3 (RHP values are in cal/cm^2). Based on these estimates, two single test results, obtained in the same laboratory under normal test method procedures that differ by more the indicated tabulated r must be considered as derived from different or nonidentical sample populations.

13.1.3.4 Estimated repeatability values for other time intervals and RHP values are directly determined using Eq 10-13 found in 13.1.3.2.

13.1.4 *Reproducibility*—The reproducibility of this test method is being determined and will be available on or before June 2009.

13.2 *Bias*—The value for RHP rating can only be defined in terms of a test method. Within this limitation, this test method has no known bias.

14. Keywords

14.1 apparel; protective clothing; radiant heat protection; radiant heat performance, flame resistance

TABLE 2 Test Method Propagation of Error Analysis for 2.0 ± 0.05 cal/cm^{2}s Radiant Flux (RHP values in cal/cm^2)

NOTE 1—s^2 = minimum value determined from variation allowed in heat flux (±0.05 cal/cm^{2}s) and quantized time interval (± 0.5 s) – from 13.1.3.2
r = repeatability = 2.80 s_r

Exposure Time, s	5	6	7	8	9	10	11	12	13	14
RHP, cal/cm^2	10	12	14	16	18	20	22	24	26	28
s^2 (variance)	1.06	1.09	1.12	1.16	1.20	1.25	1.30	1.36	1.42	1.49
%CV	10.3	8.7	7.6	6.7	6.1	5.6	5.2	4.9	4.6	4.4
r	2.89	2.92	2.97	3.02	3.07	3.13	3.20	3.27	3.34	3.42

Exposure Time, s	15	16	17	18	19	20	21	22	23	24
RHP, cal/cm^2	30	32	34	36	38	40	42	44	46	48
s^2 (variance)	1.56	1.64	1.72	1.81	1.90	2.00	2.10	2.21	2.32	2.44
%CV	4.2	4.0	3.9	3.7	3.6	3.5	3.5	3.4	3.3	3.3
r	3.50	3.59	3.67	3.77	3.86	3.96	4.06	4.16	4.27	4.37

TABLE 3 Test Method Propagation of Error Analysis for 0.5 ± 0.05 cal/cm^{2}s Radiant Flux (RHP values in cal/cm^2)

NOTE 1—s^2 = minimum value determined from variation allowed in heat flux (±0.05 cal/cm^{2}s) and quantized time interval (± 0.5 s) – from 13.1.3.2
r = repeatability = 2.80 s_r

Exposure Time, s	9	10	11	12	13	14	15	16	17	18
RHP, cal/cm^2	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9
s^2 (variance)	0.27	0.31	0.37	0.42	0.49	0.55	0.63	0.70	0.79	0.87
%CV	11.4	11.2	11.0	10.8	10.7	10.6	10.5	10.5	10.4	10.4
r	1.44	1.57	1.69	1.82	1.95	2.08	2.21	2.35	2.48	2.62

Exposure Time, s	19	20	21	22	23	24	25	26	27	28
RHP, cal/cm^2	9.5	10	10.5	11	11.5	12	12.5	13	13.5	14
s^2 (variance)	0.97	1.06	1.17	1.27	1.39	1.50	1.63	1.75	1.89	2.02
%CV	10.3	10.3	10.3	10.3	10.2	10.2	10.2	10.2	10.2	10.2
r	2.75	2.89	3.02	3.16	3.30	3.43	3.57	3.71	3.84	3.98

APPENDIXES

(Nonmandatory Information)

X1. SPECIMEN RESPONSE TO RADIANT ENERGY EXPOSURE

X1.1 The effect of the radiant energy exposure on the specimen observed in Section 10 can be optionally included in the report. Observe the effect of the exposure on the test specimen, including each of the layers in a multiple layer specimen. Describe this effect as one or more of the following: break open, charring, dripping, embrittlement, ignition, melting, shrinkage, sticking.

X2. SUBJECTIVE VISUAL EXAMINATION AND EVALUATION OF THE EXPOSED SPECIMEN

X2.1 The subjective observations on the specimen ignition during the exposure can be reported using the rating system below:

X2.1.1 *Ignition:*
X2.1.1.1 1 = no ignition, no smoke.
X2.1.1.2 2 = slight ignition, slight smoke.
X2.1.1.3 3 = moderate ignition, dark smoke.
X2.1.1.4 4 = significant ignition, thick blackish smoke.
X2.1.1.5 5 = heavy ignition, thick blackish smoke or flames, or both.

X2.2 Except for the subjective observation on ignition, the exposed specimen may be evaluated in each of the categories as listed in 10.3 on each side of the specimen.

X2.2.1 The surface of the specimen exposed to the radiant heat source shall be identified as the front side.

X2.2.2 The surface facing the heat sensor shall be identified as the back side.

X2.2.3 For visual examination, lay the exposed specimen parallel on a flat surface with proper illumination.

X2.3 Subjective ratings in the following categories can utilize the 1 to 5 system with 1 = best and 5 = worst behavior. The total value of the assigned ratings for each category will determine the specimen ranking.

X2.4 Rate each specimen after exposure using the following subjective terms:

X2.4.1 *Break open:*
X2.4.1.1 1 = no break open.
X2.4.1.2 2 = slight break open.
X2.4.1.3 3 = moderate, cracks in specimen.
X2.4.1.4 4 = significant, cracks in specimen.
X2.4.1.5 5 = extensive cracks and holes in specimen.

X2.4.2 *Melting:*
X2.4.2.1 1 = no melting.
X2.4.2.2 2 = slight melting.
X2.4.2.3 3 = moderate melting.
X2.4.2.4 4 = significant melting.
X2.4.2.5 5 = extensive melting.

X2.4.3 *Dripping:*
X2.4.3.1 1 = no dripping.
X2.4.3.2 2 = slight dripping.
X2.4.3.3 3 = moderate dripping.
X2.4.3.4 4 = significant dripping.
X2.4.3.5 5 = heavy dripping.

X2.4.4 *Charring:*
X2.4.4.1 1 = no charring.
X2.4.4.2 2 = slight specimen scorching.
X2.4.4.3 3 = moderate specimen charring.
X2.4.4.4 4 = significant specimen chars and embrittlement.
X2.4.4.5 5 = severe charring, specimen embrittles and has cracks or holes, or both.

X2.4.5 *Embrittlement:*

X2.4.5.1 1 = no embrittlement.

X2.4.5.2 2 = slight, specimen starts to harden.

X2.4.5.3 3 = moderate, small hardened areas.

X2.4.5.4 4 = significant, specimen completely embrittles.

X2.4.5.5 5 = heavy specimen embrittlement or cracks or holes, or both.

X2.4.6 *Shrinkage:*

X2.4.6.1 1 = no shrinkage.

X2.4.6.2 2 = slight shrinkage.

X2.4.6.3 3 = moderate shrinkage.

X2.4.6.4 4 = significant shrinkage.

X2.4.6.5 5 = extensive shrinkage.

X2.4.7 *Sticking:*

X2.4.7.1 1 = no sticking.

X2.4.7.2 2 = slight sticking.

X2.4.7.3 3 = moderate sticking.

X2.4.7.4 4 = significant sticking.

X2.4.7.5 5 = extensive sticking.

X2.4.8 The visual ratings of the specimen exposed can be reported using the format of Table X2.1.

TABLE X2.1 Suggested Visual Response Report Form

Categories	Front Side Rating					Back Side Rating					Total
	1	2	3	4	5	1	2	3	4	5	
Break open											
Melting											
Dripping											
Charring											
Embrittlement											
Shrinkage											
Sticking											
Ignition											

X3. ITERATIVE DETERMINATION OF THERMAL PROTECTION ESTIMATE VALUE EXAMPLE

The following example provides an overview of this test method's iterative technique to determine a radiant heat performance from a sample suite using a fictitious sample material

X3.1 *Step #1*—When the specimen radiant heat performance (RHP) value is unknown, run the test identified in 10.2.1. This involves running the exposure until the sensor response crosses the "Stoll" criteria from Eq 1 in 10.2.1.4. The fictitious material response returns (for this example, assume an 84 kW/m^2 (2.0 cal/cm^{2}s) heat flux) is shown in Fig. X3.1:

The sensor response, calculated using 11.1 (11.1.3.3) and plotted for each time step, crosses the "Stoll" criteria (Eq 1) at a continuous exposure time of 12.5 seconds. This sets t_{max} = 12.5 s (see 10.4.1.5). Note that the cumulative energy (sensor response) continues to climb quite rapidly after the heat source is removed reflecting the thermal energy still in the specimen (being delivered to the copper calorimeter surface).

X3.2 *Step #2* (see 10.2.1.7 – 10.2.1.10)—Calculate a new trial exposure of t_{max}/2 or 6 seconds (round to the nearest

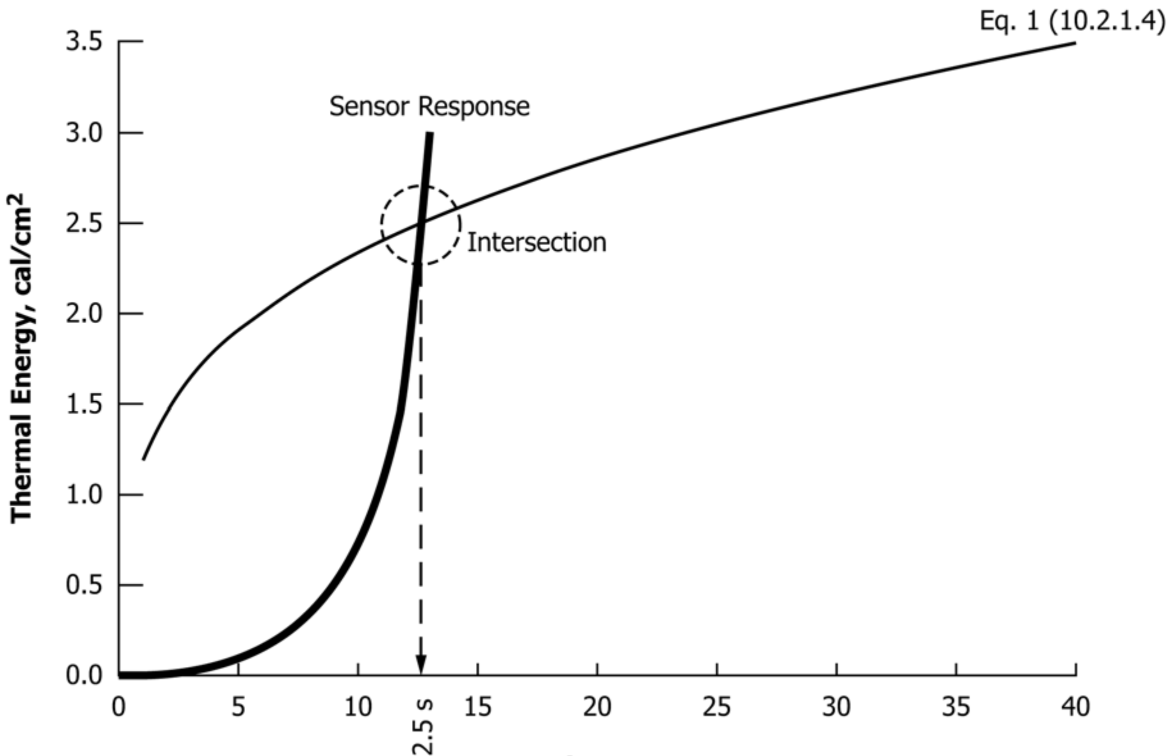

FIG. X3.1 Sensor Response to Continuous Heating Radiant Exposure second). Expose the sample for this amount of time then insert the blocking shutter and carefully move the sensor/sample holder away from the heat source and continue to acquire sensor data for at least another 30 seconds (note that the cumulative energy begins to decrease at ~28 s). For the fictitious material, this resulted in a plotted response in Fig. X3.2.

X3.3 *Step #3* (10.2.1.11)—From the exposure in Step #2 it is apparent from the plot (Fig. X3.2) that the sensor response did not cross the "Stoll" criteria (Eq 1). So Item #1 under 10.2.1.11 applies and a new trial exposure would be calculated that is half way in between 12.5 s (previous value - t_{max}) and 6 s (current trial exposure - $t_{max}/2$) or 9 seconds (rounding to the second). Repeating 10.2.1.7 – 10.2.1.10, expose the sample for the new trial time of 9 s then insert the blocking shutter and carefully move the sensor/sample holder away from the radiant heater and continue to acquire sensor data for at least another 30 seconds. For the fictitious material, this resulted in a plotted response in Fig. X3.3.

X3.4 *Step #4* (10.2.1.11)—From the exposure in Step #3 it is apparent in Fig. X3.3 that the sensor response did cross the "Stoll" criteria (Eq 1). So Item #2 under 10.2.1.11 applies and a new trial exposure would be calculated that is half way in between 6 s (previous trial value) and 9 s (current trial exposure) or 8 s (rounding to the nearest second). Repeating 10.2.1.7 – 10.2.1.10, expose the sample for the new trial time of 8 s then insert the blocking shutter and carefully move the sensor/sample holder away from the radiant heater and continue to acquire sensor data for at least another 30 seconds. For the fictitious material, this resulted in a plotted response in Fig. X3.4.

X3.5 *Step #5* (10.2.1.11)—From the exposure in Step #4 it is apparent from Fig. X3.4 that the sensor response did cross the "Stoll" criteria (Eq 1). So Item #2 under 10.2.1.11 applies and a new trial exposure would be calculated that is half way in between 6 s (previous low trial value) and 8 s (current trial exposure) or 7 seconds. Repeating 10.2.1.7 – 10.2.1.10, expose the sample for the new trial time of 7 s then insert the blocking shutter and carefully move the sensor/sample holder away from the radiant heater and continue to acquire sensor data for at least another 30 seconds. For the fictitious material, this resulted in a plotted response in Fig. X3.5.

X3.6 *Step #6* (10.2.1.11)—From the exposure in Step #5 it is apparent in Fig. X3.5 that the sensor response did not cross the "Stoll" criteria (Eq 1). So Item #1 under 10.2.1.11 applies and a new trial exposure would be calculated that is half way in between 8 s (previous high trial value) and 7 s (current trial exposure) or 7.5 seconds. However, note that whatever is obtained for a 7.5 s exposure, it will be 0.5 s away from the previous 7 s and the latter 8 s exposures. So now Item #3 under 10.2.1.11 applies and the radiant heat performance (RHP) value would be:

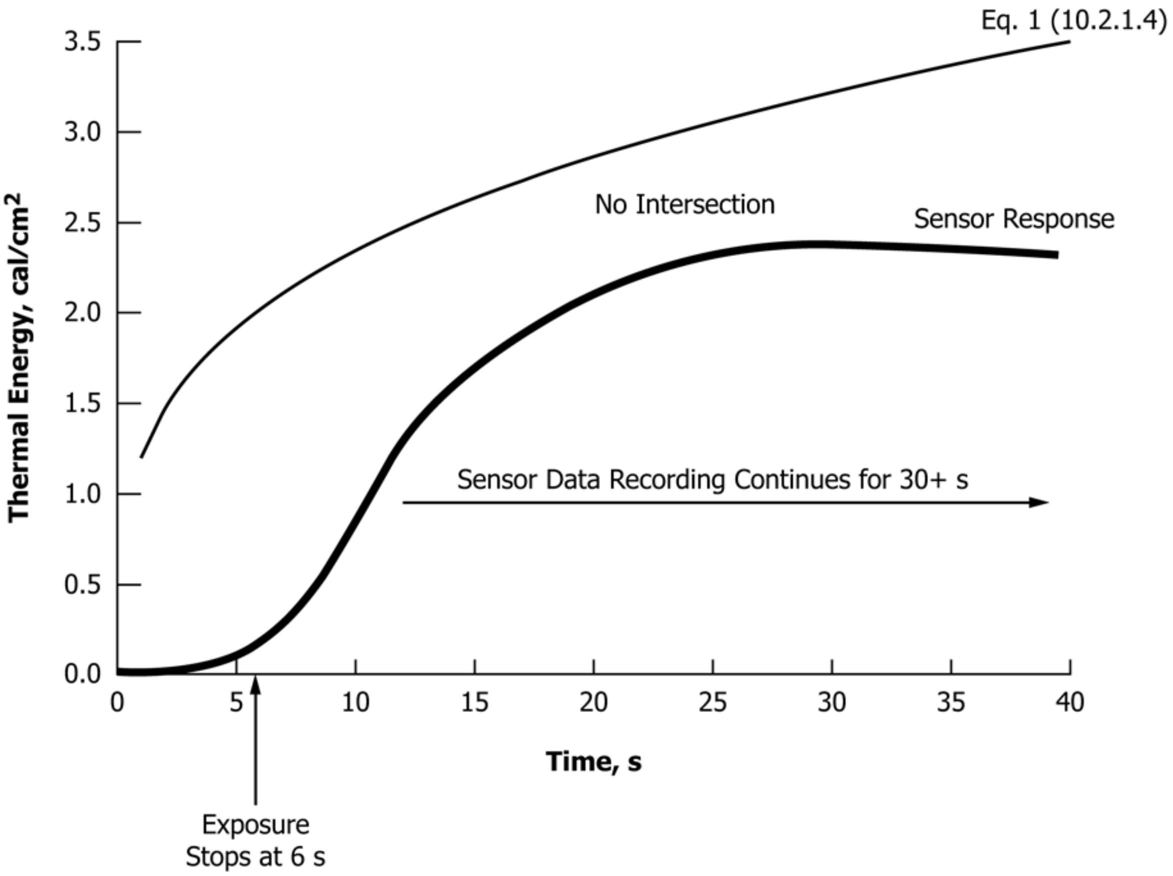

FIG. X3.2 Sensor Response to First Heating Iteration (Second Specimen)

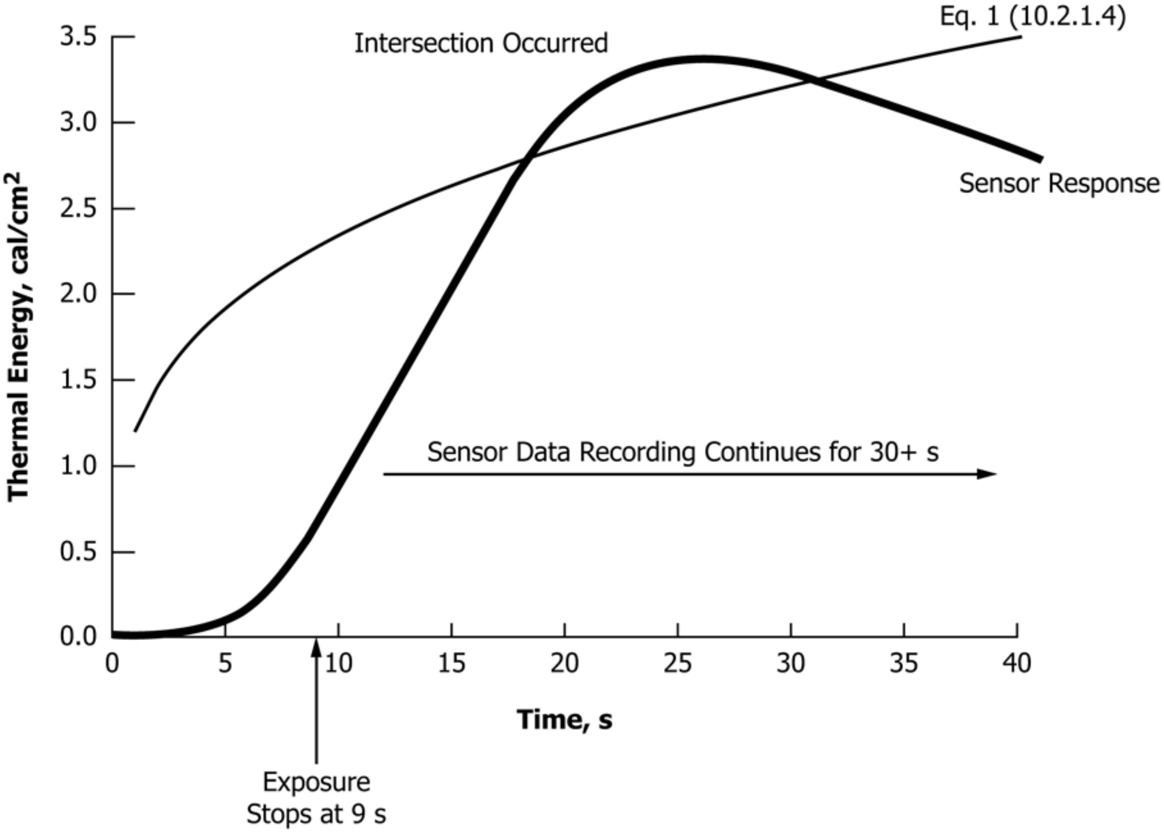

FIG. X3.3 Response to Second Heating Iteration (Third Specimen)

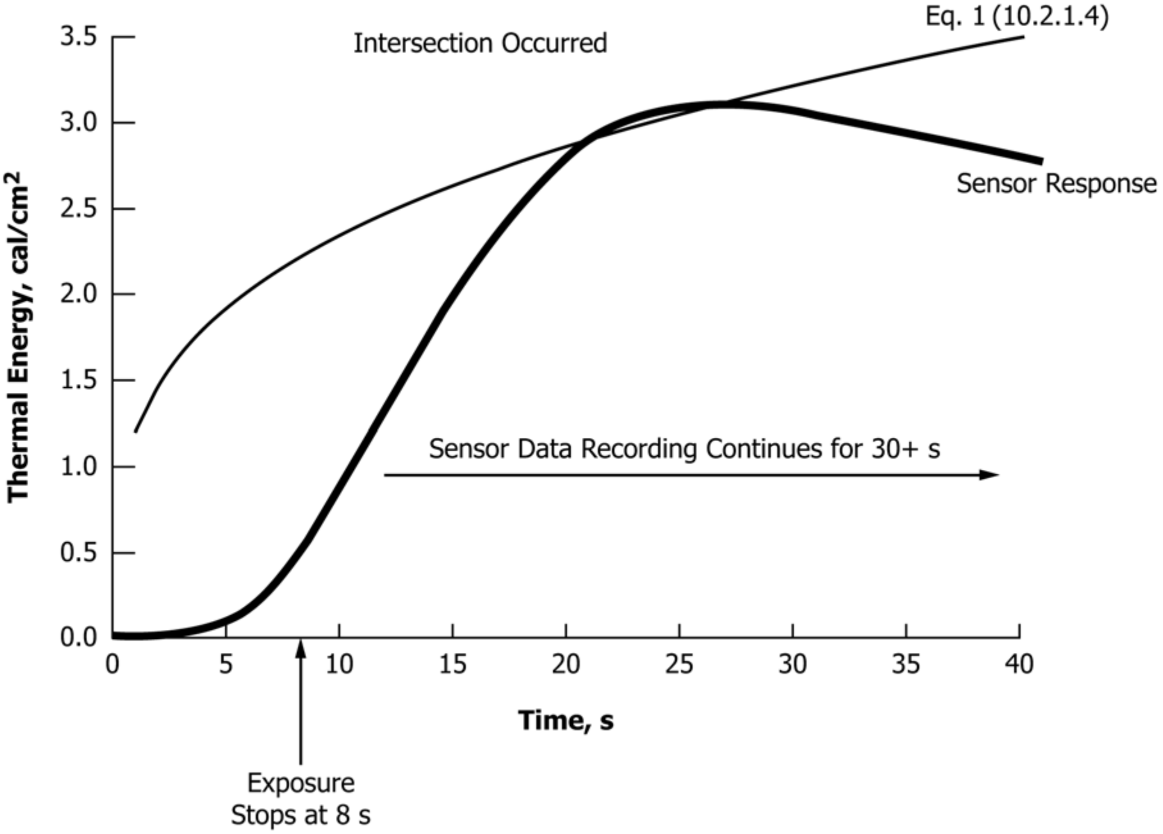

FIG. X3.4 Sensor Response to Third Heating Iteration (Fourth Specimen)

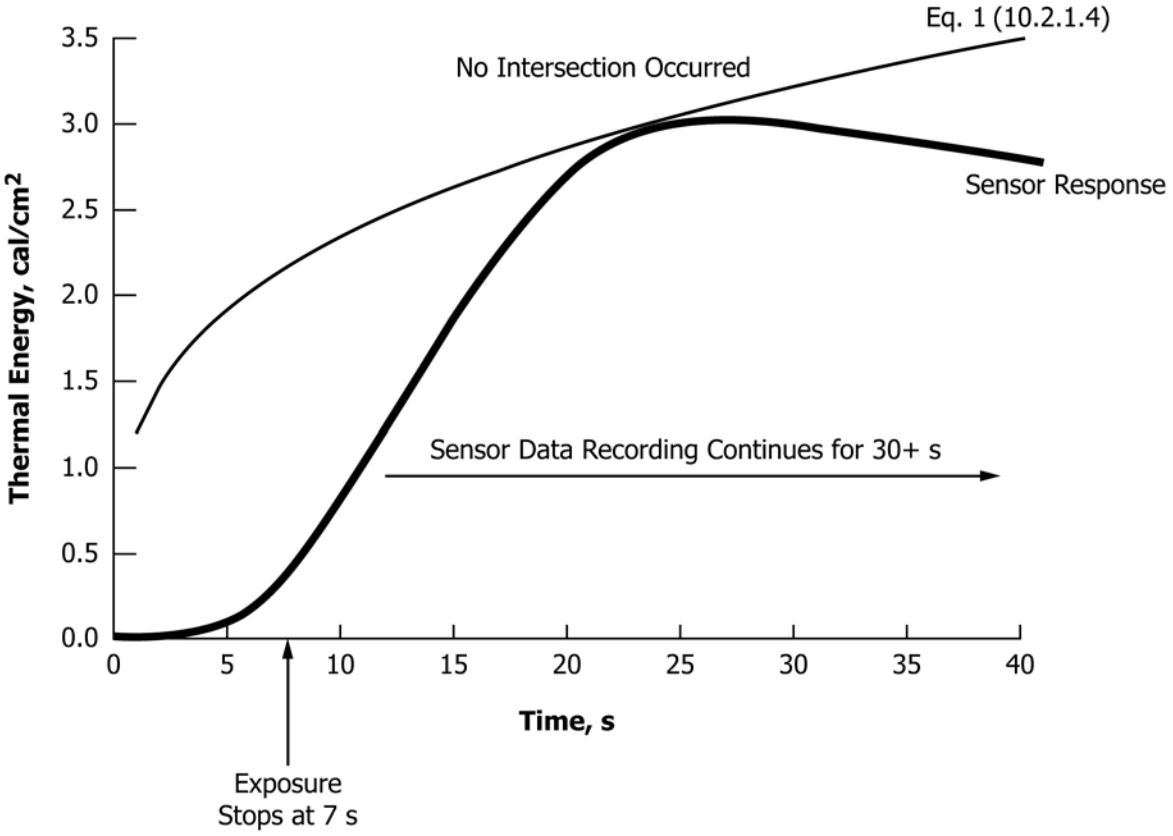

FIG. X3.5 Sensor Response to Fourth Heating Iteration (Fifth Specimen)

$$7.5\ s \times 84\ kW/m^2/10 = 63.0\ J/cm^2$$
$$(7.5\ s \times 2\ cal/cm^2 s = 15\ cal/cm^2)$$

(One could technically run the 7.5 s exposure and then follow Item #3 under 10.2.1.11 if so inclined and the equipment was capable of resolving a 0.5 s exposure interval).

X3.7 Note that the method of "halving" converges very quickly on an answer. For the remainder of the sample suite measurements, 10.2.2 would apply. From the fictitious case above, one would select the initial starting points (new trial and previous value) for the remaining sample suites as (after rounding to the nearest second):

$$t_{trial}\ value,\ s = 1.2 \times 63.0\ J/cm^2 \times 10$$
$$(1.2 \times 15\ cal/cm^2/2.0\ cal/cm^2 s) = 9\ s$$
$$previous\ t_{trial}\ value,\ s = 0.8 \times 63.0\ J/cm^2 \times 10$$
$$(0.8 \times 15\ cal/cm^2/2.0\ cal/cm^2 s) = 6\ s$$

and repeat the iterative process (10.2.1.2 – 10.2.1.6). Experience shows that subsequent determinations converge quite rapidly – 2 to 3 specimen exposures are all that are required to get subsequent radiant heat performance estimate values (in this case repeating steps similar to X3.4 – X3.6 above to get the values).

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