Designation: F1959/F1959M – 14$^{\varepsilon 1}$

Standard Test Method for Determining the Arc Rating of Materials for Clothing[1]

This standard is issued under the fixed designation F1959/F1959M; 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.

ε^1 NOTE—"Aerial" was corrected to "areal" in January 2017.

1. Scope

1.1 This test method is used to measure the arc rating of materials intended for use as flame resistant clothing for workers exposed to electric arcs that would generate heat flux rates from 84 to 25 120 kW/m^2 [2 to 600 cal/cm^{2}s].

1.2 This test method will measure the arc rating of materials which meet the following requirements: less than 150 mm [6 in.] char length and less than 2 s afterflame when tested in accordance with Test Method D6413.

1.2.1 It is not the intent of this test method to evaluate non flame-resistant materials except where used as under layers in multiple-layer specimens.

1.3 The materials used in this test method are in the form of flat specimens.

1.4 This test method shall be used to measure and describe the properties of materials, products, or assemblies in response to convective and radiant energy generated by an electric arc under controlled laboratory conditions.

1.5 The values stated in SI units shall be regarded as standard except as noted. Within the text, alternate units are shown in brackets. The values stated in each system may not be exact equivalents therefore alternate systems must be used independently of the other. Combining values from the systems described in the text may result in nonconformance with the method.

1.6 This test method does not apply to electrical contact or electrical shock hazards.

1.7 *This standard shall not be used to describe or appraise the fire hazard or fire risk of materials, products, or assemblies under actual fire conditions. However, results of this test may be used as elements of a fire assessment which takes into account all of the factors which are pertinent to an assessment of the fire hazard of a particular end use.*

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory requirements prior to use.* For specific precautions, see Section 7.

2. Referenced Documents

2.1 *ASTM Standards:*[2]
D123 Terminology Relating to Textiles
D1776 Practice for Conditioning and Testing Textiles
D4391 Terminology Relating to The Burning Behavior of Textiles
D6413 Test Method for Flame Resistance of Textiles (Vertical Test)
E457 Test Method for Measuring Heat-Transfer Rate Using a Thermal Capacitance (Slug) Calorimeter
F1494 Terminology Relating to Protective Clothing

2.2 *ANSI/IEEE Standard:*[3]
Standard Dictionary of Electrical and Electronics Terms

2.3 *AATCC Standard:*[4]
AATCC Method 135-2001 Dimensional Changes in Automatic Home Laundering of Woven and Knit Fabrics

3. Terminology

3.1 *Definitions:*

3.1.1 *ablation, n—in electrical arc testing*, a physical response evidenced by significant erosion or the formation of one or more large holes in a layer of a multilayer system.

3.1.1.1 *Discussion*—Any layer in a specimen (other than the innermost layer) is considered to exhibit ablation when the material removal or any hole is at least 16 cm^2 [2.5 in.^{2}] in area or at least 8 cm [3.1 in.] in length in any dimension. Single threads across the opening or hole do not reduce the size of the

[1] This test method is under the jurisdiction of ASTM Committee F18 on Electrical Protective Equipment for Workers and is the direct responsibility of Subcommittee F18.65 on Wearing Apparel.

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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.

[3] Available from Institute of Electrical and Electronics Engineers, Inc. (IEEE), 445 Hoes Ln., P.O. Box 1331, Piscataway, NJ 08854-1331.

[4] Technical Manual of the American Association of Textile Chemists and Colorists.

hole for the purposes of this test method. Ablation in one or more layers of material in a mulitlayer system may remove energy from the specimen. (See 11.2.7.)

3.1.2 *ablation response energy* (E_{ab})*, n*—the incident energy on a multilayer system that results in a 50 % probability of the physical response of ablation.

3.1.3 *arc duration, n*—time duration of the arc, s.

3.1.4 *arc energy, vi dt, n*—sum of the instantaneous arc voltage values multiplied by the instantaneous arc current values multiplied by the incremental time values during the arc, *J*.

3.1.5 *arc gap, n*—distance between the arc electrodes, cm [in.].

3.1.6 *arc rating, n*—value attributed to materials that describes their performance to exposure to an electrical arc discharge.

3.1.6.1 *Discussion*—The arc rating is expressed in cal/cm^2 and is derived from the determined value of ATPV or E_{BT} (should a material system exhibit a breakopen response below the ATPV value) derived from the determined value of ATPV or E_{BT} (should a material system exhibit a breakopen response below the ATPV value).

3.1.7 *arc thermal performance value (ATPV), n*—the incident energy on a material or a multilayer system of materials that results in a 50 % probability that sufficient heat transfer through the tested specimen is predicted to cause the onset of a second-degree skin burn injury based on the Stoll[5] curve, kW/m^2 [cal/cm^2].

3.1.8 *arc voltage, n*—voltage across the gap caused by the current flowing through the resistance created by the arc gap, *V*.

3.1.9 *asymmetrical arc current, n*—the total arc current produced during closure; it includes a direct component and a symmetrical component, *A*.

3.1.10 *blowout, n*—the extinguishing of the arc caused by a magnetic field.

3.1.11 *breakopen, n—in electric arc testing*, a material response evidenced by the formation of one or more holes in the material which may allow thermal energy to pass through the material.

3.1.11.1 *Discussion*—The specimen is considered to exhibit breakopen when any hole is at least 1.6 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. In multiple layer specimens of flame resistant material, all the layers must breakopen to meet the definition. In multiple layer specimens, if some of the layers are ignitable, breakopen occurs when these layers are exposed.

[5] 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.

3.1.12 *breakopen threshold energy* (E_{BT}) *, n*—the incident energy on a material or material system that results in a 50 % probability of breakopen.

3.1.12.1 *Discussion*—This is the value in J/cm^2 [cal/cm ^{2}] determined by use of logistic regression analysis representing the energy at which breakopen of the layer occurred.

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

3.1.14 *dripping, n—in testing flame-resistant clothing*, a material response evidenced by flowing of a specimen's material of composition.

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

3.1.16 *heat attenuation factor, HAF, n— in electric arc testing*, the percent of the incident energy that is blocked by a material at an incident energy level equal to ATPV.

3.1.17 *heatflux, n*—the thermal intensity indicated by the amount of energy transmitted divided by area and time kW/m^2 [cal/cm^{2}s].

3.1.18 i^2 *t, n*—sum of the instantaneous arc current values squared multiplied by the incremental time values during the arc, A^2/s.

3.1.19 *ignitability, n (ignitable, adj)—in electric arc exposure*, the property of a material involving ignition accompanied by heat and light, and continued burning resulting in consumption of at least 25 % of the exposed area of the test specimen.

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

3.1.21 *ignition*$_{50}$*, n*—the incident energy on a fabric or material that results in a 50 % probability that sufficient heat transfer through the tested specimen is predicted to cause ignition of a flammable underlayer.

3.1.22 *incident energy monitoring sensors, n*—sensors mounted on each side of the panel, using the calorimeters described in 6.3, not covered by test material, used to measure incident energy.

3.1.23 *incident energy* (E_i)*, n*—the total heat energy received at the surface of the panel as a direct result of an electric arc.

3.1.24 *material response, n*—material response to an electric arc is indicated by the following terms: breakopen, melting, dripping, charring, embrittlement, shrinkage, and ignition.

3.1.25 *melting, n—in testing flame resistant clothing*, a material response evidenced by softening of the material.

3.1.26 *mix zone, n—in arc testing*, the range of incident energies, which can result in either a positive or negative outcome for predicted second-degree burn injury, breakopen or underlayer ignition. The low value of the range begins with the lowest incident energy indicating a positive result, and the high value or the range is the highest incident energy indicating a negative result.

3.1.26.1 *Discussion*—A mix zone is established when the highest incident energy with a negative result is greater than the lowest incident energy with a positive result.

3.1.27 *peak arc current, n*—maximum value of the AC arc current, *A*.

3.1.28 *RMS arc current, n*—root mean square of the AC arc current, *A*.

3.1.29 *shrinkage, n—in testing flame resistant clothing*, a material response evidenced by reduction in specimen size.

3.1.30 *Stoll curve*[5], *n*—an empirical predicted second-degree skin burn injury model, also commonly referred to as the *Stoll Response*.

3.1.31 *X/R ratio*—the ratio of system inductive reactance to resistance. It is proportional to the L/R ratio of time constant, and is, therefore, indicative of the rate of decay of any DC offset. A large X/R ratio corresponds to a large time constant and a slow rate of decay.

3.2 For definitions of other textile terms used in this test method, refer to Terminologies D123, D4391, and F1494.

4. Summary of Test Method

4.1 This test method determines the heat transport response through a material, fabric, or fabric system when exposed to the heat energy from an electric arc. This heat transport response is assessed versus the Stoll curve, an approximate human tissue tolerance predictive model that projects the onset of a second-degree burn injury.

4.1.1 During this procedure, the amount of heat energy transferred by the tested material is measured during and after exposure to an electric arc.

4.1.1.1 The thermal energy exposure and heat transport response of test specimens are measured with copper slug calorimeters. The change in temperature versus time is used, along with the known thermo-physical properties of copper to determine the respective heat energies delivered to and through the specimens.

4.2 Material performance for this procedure is determined from the amount of heat transferred by and through the tested material.

4.3 Heat transfer data determined by this test method is the basis of the arc rating for the material.

4.3.1 The arc rating determined by this test method is the amount of energy that predicts a 50 % probability of second-degree burn as determined by the Stoll Curve or breakopen (should the specimen exhibit breakopen before the skin burn injury prediction is reached.

4.4 Material response shall be further described by recording the observed effects of the electric arc exposure on the specimens using the terms in 12.6.

5. Significance and Use

5.1 This test method is intended for the determination of the arc rating of a material, or a combination of materials.

5.1.1 Because of the variability of the arc exposure, different heat transmission values may be observed at individual sensors. Evaluate the results of each sensor in accordance with Section 12.

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

5.3 This test method specifies a standard set of exposure conditions. Different exposure conditions may produce different results. In addition to the standard set of exposure conditions, other conditions representative of the expected hazard may be used and shall be documented in the reporting of the testing results.

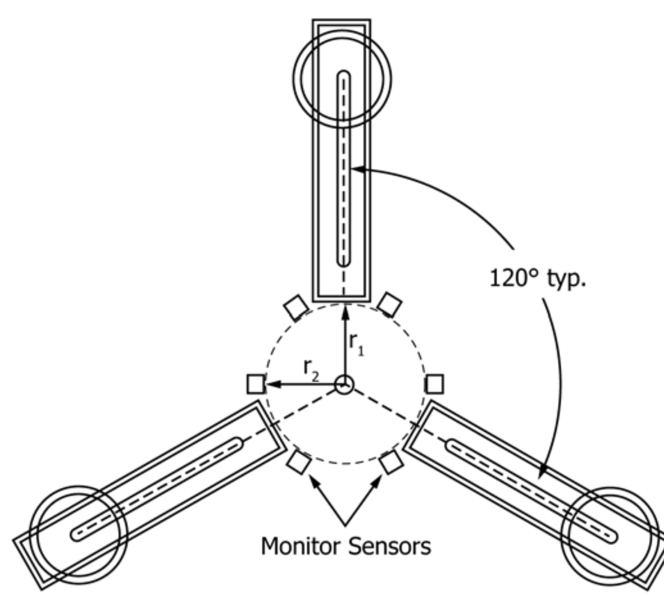
6. Apparatus

6.1 *General Arrangement For Determining Arc Rating Using Three Two-Sensor Panels and Monitor Sensors*—The test apparatus shall consist of supply bus, arc controller, recorder, arc electrodes, three two-sensor panels, and monitor sensors.

6.1.1 *Arrangement of the Two-Sensor Panels*—Three two-sensor panels shall be used for each test and be spaced equally as shown in Fig. 1. Each two-sensor panel shall have two monitoring sensors. One monitoring sensor shall be positioned on each side of the two-sensor panel as shown in Fig. 2.

6.1.1.1 Monitor sensors located at a radius different from the two-sensor panels shall be employed when the incident energy from the arc exposure results in monitor sensor temperature values that exceed the maximum allowed operating characteristic of the copper calorimeter. See 11.1.1. Monitor sensors shall be positioned whereby there is a clear, unobstructed path between the sensors and the arc electrode centerline.

6.1.2 *Panel Construction*—Each two-sensor panel and each monitor sensor holder shall be constructed from non-conductive heat resistant material with a thermal conductivity value of < 0.15 W/mK, high temperature stability, and resistance to thermal shock. The board shall be nominally 1.3 cm [0.5 in.] or greater in thickness.



r_1 = radius of two-sensor panels
r_2 = radius of monitor sensors
r_1; r_2 = 20-60 cm [8-24 in.]

FIG. 1 Arrangement of Three Panel Sensors with Monitor Sensors

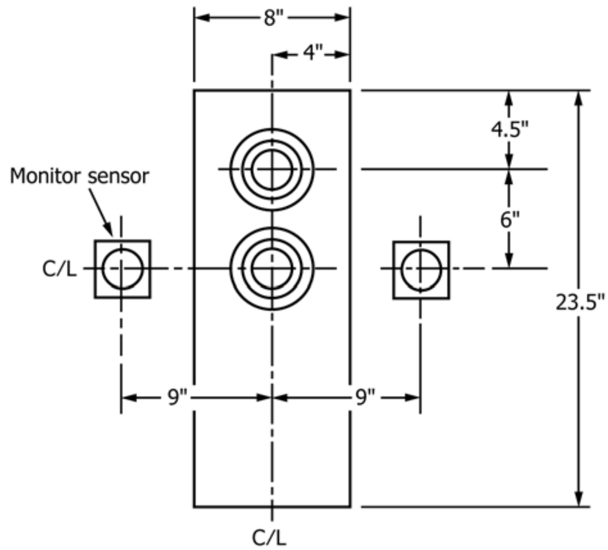


FIG. 2 Two Sensor Panel (Face View) with Monitor Sensors

6.1.3 Each two-sensor panel shall be 20.3 × 54.6 cm ± 1.3 cm [8 × 21.5 in. ± 0.5 in.] as shown in Fig. 2. Each two-sensor panel and monitoring sensors shall be independently adjustable from 20.0 cm [8 in.] to 60.0 cm [24 in.] from the centerline of the arc electrodes as shown in Fig. 1 and Fig. 3. R_1 is the radius from the centerline of the arc electrodes to the surface of the two-sensor panels and r_2 is the radius from the centerline of the arc electrodes to the surface of the monitor sensors.

6.1.4 Two sensors shall be mounted in the panel as shown in Fig. 2. Each sensor shall be mounted flush with the surface of the mounting board.

6.1.5 Additional calorimeters are allowed for installation as monitor and panel sensors for experimental purposes. The information from these sensors shall not be used as substitutes for the current test apparatus in the determination of ATPV, breakopen, or ignition performance.

6.2 *Sensors:*

6.2.1 The panel and monitor sensors shall be copper slug calorimeters constructed from electrical grade copper with a single thermocouple wire installed as identified in Fig. 5 (see Test Method E457 for information regarding slug calorimeters).

6.2.2 The exposed surface of the copper slug calorimeters shall be painted with a thin coating of a flat black high temperature spray paint with an emissivity of >0.9. The painted sensor shall be dried before use and present a uniformly applied coating (no visual thick spots or surface irregularities). Note that an external heat source, for example, an external heat lamp, may be required to completely drive off any remaining organic carriers in a freshly painted surface.

6.2.2.1 *Discussion*—An evaluation of the emissivity of the painted calorimeters used in this test method is available from ASTM; "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."

6.2.3 The thermocouple wire is installed in the calorimeter as shown in Fig. 6.

6.2.4 Alternate calorimeters are permitted for use as monitor sensors provided they are calibrated and have a similar response to those in 6.2.1. The use of a different thermocouple

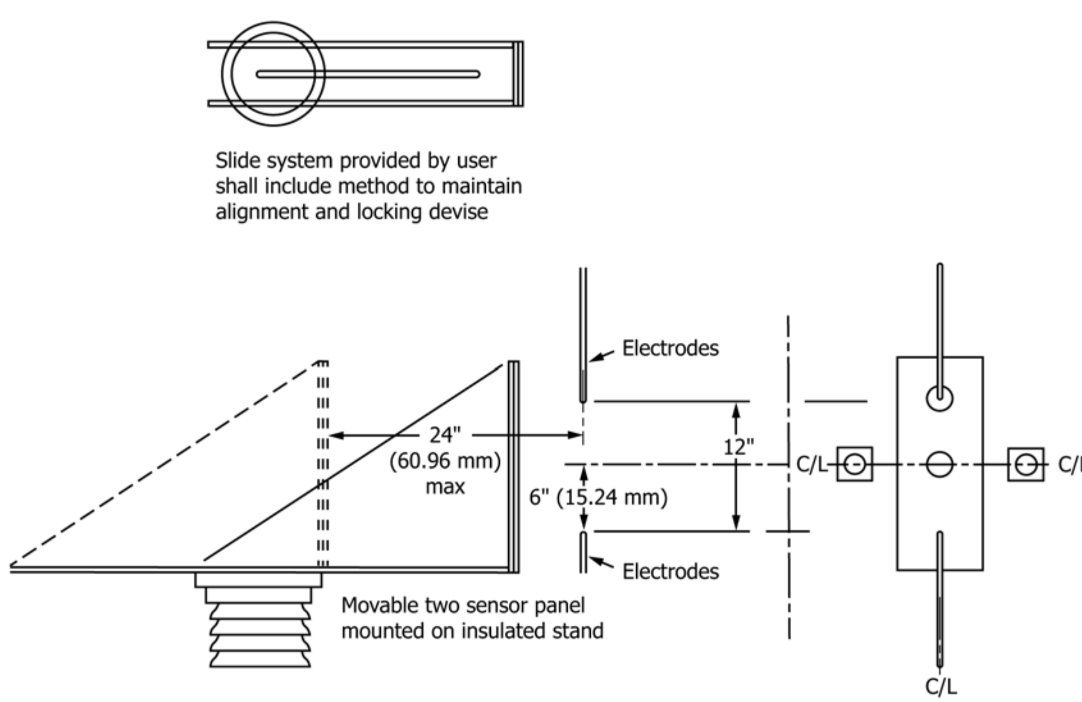


FIG. 3 Sliding Two Sensor Panel

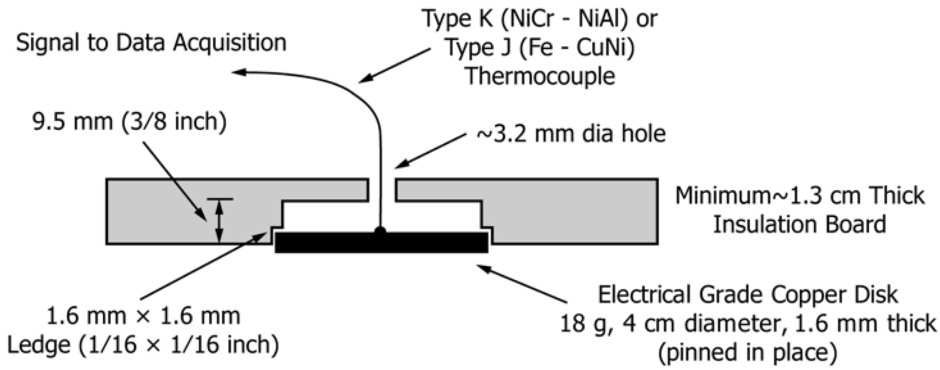


FIG. 4 Calorimeter and Thermocouple Detail

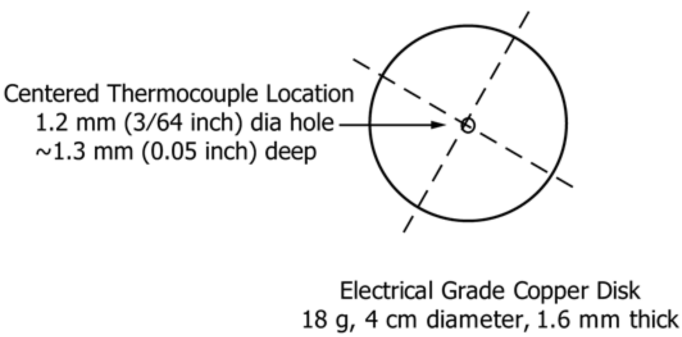


FIG. 5 Calorimeter

junction, exposed surface area, slug material, and mass are allowed and their performance shall be documented in the test results.

6.3 *Supply Bus and Electrodes*—A typical arrangement of the supply bus and arc electrodes is shown in Fig. 7. The arc shall be in a vertical position as shown.

6.3.1 *Electrodes*—Make the electrodes from stainless steel (Alloy Type 303 or Type 304) rod of a nominal 19 mm [0.75 in.] diameter. Lengths of 45.0 cm [18 in.] long initially have been found to be adequate.

6.3.2 *Fuse Wire*—A fuse wire, connecting the ends of opposing electrodes tips, is used to initiate the arc. This wire is consumed during the test; therefore, its mass shall be very small to reduce the chance of molten metal burns. The fuse wire shall be a copper wire with a diameter not greater than 0.05 mm [0.02 in.].

6.4 *Electric Supply*—The electric supply should be sufficient to allow for the discharge of an electric arc with a gap of up to 305 mm [12 in.] with alternating arc current from 4000 up to 25 000 amperes and with arc duration from 3 cycles (0.05 s) up to 90 cycles (1.5 s) from a 60 Hz supply. The X/R ratio of the test circuit shall be such that the test current contains a DC component resulting in the first peak of the test current having a magnitude of 2.3 times the symmetrical RMS value.

6.5 *Test Circuit Control*—Repeat exposures of the arc currents shall not deviate more than 2 % per test from the selected test level. The make switch shall be capable of point on wave closing within 0.2 cycles from test to test such that the closing angle will produce maximum asymmetrical current with an X/R ratio of the test circuit as stated in 6.4. The arc current, duration, and voltage shall be measured. The arc current, duration, voltage and energy shall be displayed in graph form and stored in digital format.

6.6 *Data Acquisition System*—The system shall be capable of recording voltage, current, and sufficient calorimeter outputs as required by the test.

6.6.1 The temperature data (copper slug calorimeter outputs) shall be acquired at a minimum sampling rate of 20 samples per second per calorimeter. The acquisition system shall be able to record temperatures to 400°C. The temperature acquisition system shall have at least a resolution of 0.1°C and an accuracy of ±0.75°C.

6.6.2 The system current and voltage data shall be acquired at a minimum rate of 2000 samples per second. The current and voltage acquisition system shall have at least a resolution of 1 % of the applied voltage and current.

6.7 *Data Acquisition System Protection*—Due to the nature of this type of testing, the use of isolating devices on the calorimeter outputs to protect the acquisition system is recommended.

7. Precautions

7.1 The test apparatus discharges large amounts of energy. In addition, the electric arc produces very intense light. Care should be taken to protect personnel working in the area. Workers should be behind protective barriers or at a safe distance to prevent electrocution and contact with molten metal. Workers wishing to directly view the test should use very heavily tinted glasses such as ANSI/ASC Filter Shade 12 welding glasses. If the test is conducted indoors there shall be a means to ventilate the area to carry away combustion products, smoke, and fumes. Air currents can disturb the arc reducing the heat flux at the surface of any of the calorimeters. Non-combustible materials suitable for the test area should shield the test apparatus. Outdoor tests shall be conducted in a manner appropriate to prevent exposure of the test specimen to moisture and wind (the elements). The leads to the test apparatus should be positioned to prevent blowout of the electric arc. The test apparatus should be insulated from the ground for the appropriate test voltage.

7.2 The test apparatus, electrodes, and calorimeter assemblies become hot during testing. Use protective gloves and sleeves when handling these hot objects.

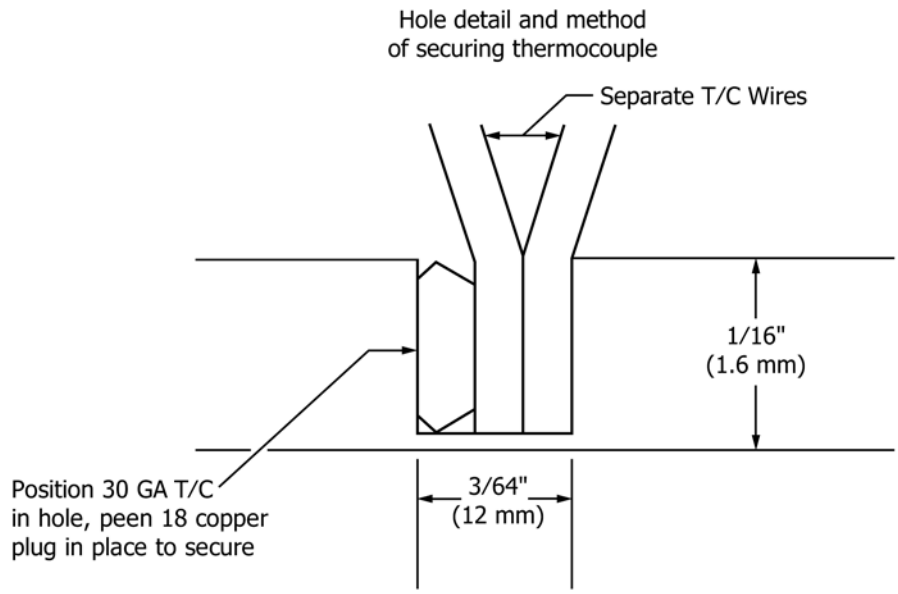


FIG. 6 Thermocouple Wire Installation

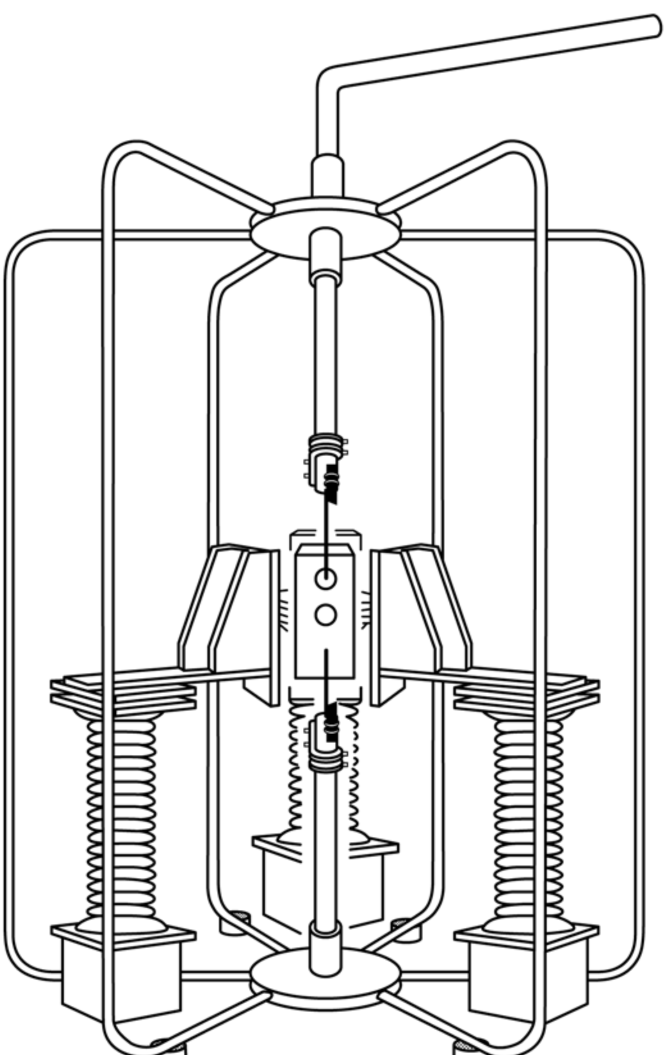


FIG. 7 Supply Bus and Arc Electrodes for Panels

7.3 Use care if the specimen ignites or releases combustible gases. An appropriate fire extinguisher should be readily available. Ensure all materials are fully extinguished.

7.4 Immediately after each test, the electric supply shall be shut off from the test apparatus and all other lab equipment used to generate the arc. The apparatus and other lab equipment shall be isolated and grounded. After data acquisition has been completed, appropriate methods shall be used to ventilate the test area before personnel entry. No one should enter the test area prior to exhausting all smoke and fumes.

8. Sampling and Specimen Preparation

8.1 *Test Specimens for Two-Sensor Panel Test*—From the material to be tested, make the post-laundered specimen size at least 61.0 cm [26 in.] long and at least 30.5 cm [12 in.] wide. Refer to Section 11, to determine number of samples required for the test.

8.1.1 The length direction shall be cut in the warp or wale direction of the material.

8.2 *Laundering of Test Specimens:*

8.2.1 Launder the required amount of test material for the test specimens allowing for fabric shrinkage in the laundering procedure using AATCC Test Method 135, Procedure 3, IV, A, iii.

8.2.1.1 Launder three times following this procedure.

NOTE 1—Drying is not required following the first two launderings.

8.2.1.2 Following the three laundry cycles, tumble dry following the prescribed procedure. Do not over dry.

8.2.1.3 Samples may be restored to a flat condition by pressing.

8.2.1.4 If an alternative laundry procedure is employed, report the procedure used (see 13.1.4).

8.2.2 For those materials that require cleaning other than laundering, follow the manufacturer's recommended practice using three cleaning cycles followed by drying and note the procedure used in the test reports (see 13.1.4).

8.3 *Conditioning*—Condition the test materials following Practice D1776.

8.4 *Determination of Test Materials Average Areal Density:*

8.4.1 Following laundering, drying, and cutting the samples to the specified size for testing, randomly select 3 (three) test panels and determine the areal density as follows:

8.4.1.1 Die-cut a circle of 3.8 cm (1.5 in.) to 7.6 cm (3.0 in.) in diameter from the lower corner of at least three different test specimens randomly selected to cover the length and width of the test sample.

8.4.1.2 Weigh all specimens in grams on a scale to three decimal places.

8.4.1.3 Calculate the areal density of each of the test fabric specimens in grams per square meter as follows:

$$\text{Areal Density, g/m}^2 = \frac{\text{Mass, g}}{\pi \times \left[\frac{\text{Circle Diameter, m}}{2}\right]^2}$$

where:

Mass, g	=	weight in grams of the fabric sample circle cutout,
Circle Diameter, m	=	diameter in meters of the die-cut circle, and
π	=	3.14159.

The areal density may also be expressed in ounces per square yard:

$$\text{Areal Density, oz/yd}^2 = \text{Areal Density, g/m}^2 \times 0.02949$$

8.4.1.4 Report the average of the three random specimens areal densities as the Average Areal Density value.

9. Calibration and Standardization

9.1 *Data Collection System Precalibration*—The data collection system shall be calibrated by using a thermocouple calibrator/simulator. This will allow calibrations to be made at multiple points and at levels above 100°C. Due to the nature of the tests frequent calibration checks are recommended.

9.2 *Calorimeter Calibration Check*—Calorimeters shall be checked to verify proper operation. Measure and graph the temperature rise of each calorimeter and system response. At 30 seconds no one calorimeter response shall vary by more than 4°C from the average of all calorimeters. Any calorimeter not meeting this requirement shall be suspected of faulty connections and shall be replaced or repaired.

NOTE 2—One acceptable method is to expose each calorimeter to a fixed radiant energy source for 30 s. For example, place the front surface of a 500 W spot light[6] 26.7 cm [10.5 in.] from the calorimeter. The spot shall be centered on and perpendicular to the calorimeter.

9.3 *Arc Exposure Calibration*—Prior to each calibration, position the electrodes of the test apparatus to produce a 30.5 cm. [12 in.] gap. The face of the monitor sensors is set parallel and normal to the centerline of the electrodes. The midpoint of the electrode gap shall be at the same elevation as the center point of the monitor sensors (see Fig. 1). Connect the fuse wire to the end of one electrode by making several wraps and twists and then to the end of the other electrode by the same method. The fuse wire is pulled tight and the excess trimmed. The test controller is then adjusted to produce the desired arc current and duration.

9.4 *Apparatus Calibration for the Two-Sensor Panels and Monitor Sensors*—Position each two-sensor panel so that the surface of each panel (r_1) is 30.5 cm [12 in.] from, parallel and normal to the centerline of the electrodes. Monitor sensors shall be positioned so that the surface of each monitor sensor (r_2) is 34.3 cm [13.5 in.] from, parallel and normal to the centerline of the electrodes.

9.4.1 Set the asymmetrical arc exposure current to the test amperage level and the arc duration at 10 cycles (0.167 s).

9.4.2 Discharge the arc.

9.4.3 Determine the maximum temperature rise for each of the sensors, and multiply by the appropriate factor, determined in 11.10, to obtain the total incident energy in cal/cm^2 [J/cm^2] measured by each sensor.

9.4.4 Compare the highest sensor reading and the average value obtained for all sensors. For example, with the measured result of 10.1 cal/cm^2 [42.3 J/cm^2] for the calibration exposure of 8 kA for 0.167 s. Compare the total heat value determined by the sensors to the value shown.

9.4.5 The average total heat calculated for the sensors shall be at least 60 % of the value determined by calculation or that shown. The highest measured total heat of any one sensor shall be within 10 % of the calculated value. If these values are not obtained, inspect the test setup and correct any possible problems that could produce less than desired results.

9.4.6 An arc exposure calibration test is conducted at the desired test level after each adjustment, and prior to the start and end of each day's testing and after any equipment adjustment or failure.

9.4.7 The arc generated in the testing apparatus may not follow a path that is equidistant from each sensor and can result in a variation in measured values. To be considered calibrated, the highest total heat measured from any single sensor from a 10 cycle, 8000 A fault current shall not exceed 11 cal/cm^2 [46.1 J/cm^2] and the average total heat measured for all sensors in the apparatus shall be at least 6 cal/cm^2 [25.1 J/cm^2]. If these values are not achieved, check the calibration of the sensor system, electrical conditions, and the physical setup of the apparatus and repeat the calibration exposure until the required results are obtained.

9.4.8 If during testing the exposure values specified in 9.4.5 are not achieved in three consecutive tests, then suspend testing and re-calibrate the system. If a change is made as a result of the re-calibration, reject the data from the last three tests.

9.5 *Confirmation of Test Apparatus Setting*—Confirm the test apparatus setting for each test from the controller equipment. Values to be reported are peak arc current, RMS arc current, arc duration, arc energy, and arc voltage. A graph of

[6] The sole source of supply of the apparatus known to the committee at this time is the Strand Electric and Engineering Co. Ltd., Part No. 83 (500W, 120V light source). If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee [1], which you may attend.

the arc current is plotted to ensure proper waveform. Record the ambient temperature and relative humidity.

10. Apparatus Care and Maintenance

10.1 *Initial Temperature*—Cool the sensors after exposure with a jet of air or by contact with a cold surface. Confirm that the sensors are at a temperature of 25 to 35°C.

10.2 *Surface Reconditioning*—While the sensor is hot, wipe the sensor face immediately after each test to remove any decomposition products that condense and could be a source of future error. The sensor surface requires reconditioning if a deposit collects and appears to be thicker than a thin layer of paint or the surface is irregular. Carefully clean the cooled sensor with acetone or petroleum solvent making certain to follow safe handling practices. Repaint the surface as noted in 6.2.2. Ensure that the paint is dry before running the next test.

10.3 *Panel and Monitor Sensor Assembly Care*—The boards shall be kept dry. For outdoor tests the panels and monitoring sensors shall be covered during long periods between tests to prevent excess temperature rise resulting from exposure to the sun. Due to the destructive nature of the electric arc, the monitoring sensor holders should be covered with the same paint as the sensors. The holders should be re-coated periodically to reduce deterioration.

11. Procedure

11.1 Test parameters shall be 8 ± 1 kA arc current, 30.5 cm (12 in.) electrode gap, stainless steel electrodes, 30.5 cm [12 in.] distance (r_1) between the arc centerline and the two-sensor panels. Additional test parameters may also be used and the results reported on an optional basis. Radius r_1 and r_2 shall not be changed during a testing sequence for a given sample.

11.1.1 *Discussion*—A distance from the arc centerline (r_2) 34.3 cm [13.5 in.] has been found effective for staying within the temperature operating limits of the copper calorimeters in arc testing where $E_i \leq 60$ cal/cm^2. A distance from the arc centerline (r_2) of 40.6 cm [16 in.] for the monitor sensors has been found effective for staying within the temperature operating limits of the copper calorimeters in arc testing where $E_i > 60$ cal/cm^2 (see 11.2.3).

11.2 *Order of Tests:*

11.2.1 Each test shall consist of three specimens of the same material, one for each of the three two-sensor panels.

11.2.2 To evaluate a single sample of a material, a series of at least seven tests shall be run over a range of incident energies. A minimum of 20 average incident energy monitor and panel sensor results meeting 11.2.2.2 through 11.2.2.4 is required for an ATPV determination.

11.2.2.1 The incident energy range shall be achieved by increasing or decreasing the arc duration (cycles).

11.2.2.2 The measured incident energy (average value of the two respective monitor sensors) on at least 15 % of the two-sensor panels exposed must result in values that always exceed the Stoll curve predicted second-degree burn injury criteria (as determined by 12.1.4). In other words, values in this energy range always exceed the Stoll criteria.

11.2.2.3 The measured incident energy (average value of the two respective monitor sensors) on at least 15 % of the two-sensor panels exposed must result in values that never exceed the Stoll curve predicted second-degree burn injury criteria (as determined by 12.1.4). In other words, values in this energy range never exceed the Stoll criteria.

11.2.2.4 The measured incident energy (average value of the two respective monitor sensors) on at least 50 % of the two-sensor panels exposed shall result in values that are approximately equally populated within ±20 % of the final ATPV (as determined by 12.1.4; see 11.2.6 discussion). Values in this energy range typically have mixed results—some values exceed and some values do not exceed the Stoll criteria.

11.2.3 All data points are valid unless a copper calorimeter temperature exceeds 400°C for the monitor sensor described in 6.2.1, there is a malfunction of the test or data acquisition equipment, or the specimen mounting fails.

11.2.4 If more than the minimum number of tests are performed, for whatever reason, all valid data points shall be used (see 11.2.6 discussion).

11.2.5 Handling data from specimens that exhibit breakopen or underlayer ignition (multilayer systems).

11.2.5.1 Specimens that exhibit breakopen or underlayer ignition (multilayer systems) are valid data points for ATPV determination.

11.2.5.2 If two or more occurrences of material breakopen are noted at incident energies below a value of 20 % above the ATPV determination, a breakopen response shall be determined. In this case, more than seven tests may be required so that the breakopen response can be evaluated (above or below the Stoll curve criteria, see 12.2 for treatment of breakopen).

11.2.6 *Discussion*—An iterative process will be needed to achieve the requirement that 50 % of the data points are within 20 % of the material systems ATPV. After the first two arc exposures (six panels) are completed, assuming response above and below the Stoll curve criteria, an estimated ATPV can be determined. Using this estimation, the remaining tests can be selected so that 50 % of the sensor panel data fall within 20 % of the ATPV, for example, if the approximated ATPV is 6.5 cal/cm^2 [27.2 J/cm^2] then test parameters are selected so that the incident energies on the three panels will fall with the range of 5.2 to 7.8 cal/cm^2 [21.8 to 32.7 J/cm^2]. As each successive test is performed, the accuracy of the ATPV estimation will improve so that the incident energy target range of ATPV ±20 % can also be more accurately established. The goal is to achieve the required 50 % of the data within 20 % of ATPV by the time the required 20 data points are complete. Generally, assuming all data points are valid, this would mean that 11 of the 21 data points would need to have incident energy values within 20 % of the ATPV. In the example above, 11 of the data points would need to have incident energy values within the range of 5.2 to 7.8 cal/cm^2 [21.8 to 32.7 J/cm^2] for a material with an ATPV of 6.5 cal/cm ^{2} [27.2 J/cm^2]. If less than 11 data points fall in this range, additional tests will be needed until 50 % of the total data points have incident energy values within 20 % of the ATPV.

11.2.6.1 A least-squares fit of the maximum difference between the average measured panel sensor thermal energy response and the corresponding Stoll response (independent value) and the average measured incident energy for each panel (dependent variable) can be used to guide the selection of appropriate incident exposure energies. The *y*-intercept value is the approximate ATPV result.

11.2.7 ATPV determination of multilayer systems with two or more FR layers.

11.2.7.1 If an ATPV of a multilayer FR system is determined to be greater than the incident energy at which any FR layer except the innermost FR layer (closest to the sensor panel) exhibits ablation, an ablation response energy (E_{ab}) shall be determined. If the innermost layer exhibits ablation or breakopen, a breakopen threshold energy (E_{BT}) shall be determined (see 12.2 for determination procedure and 3.1.11.1 for breakopen hole dimension criteria).

(1) Discussion—Multilayer systems designed with, or demonstrating, ablative layers have been shown to remove significant amounts of thermal energy and result in arc rating values (ATPV) greater than systems without this effect. In some cases for a multilayer system of materials, this ablative layer effect can create a very broad mix zone which generates an ATPV which is well above the point which burn injury can occur. In other cases, the low level exposures that create a burn injury can be missed if testing is confined to exposures at or above the level where ablation occurs. Extra panel tests are therefore required to assess if a lower ATPV is evident in systems that exhibit this behavior during testing

11.2.7.2 The breakopen determination method in this test method (see 12.2 for treatment of the breakopen) shall be used for determining the ablation response energy (E_{ab}) for the FR layer exhibiting ablation. The ablation reponse energy, E_{ab}, shall be substituted for the E_{BT} term in the above referenced procedure for this determination. The ablation hole dimension criteria in 3.1.1.1 shall be applied. A simultaneous determination of the prediction of burn injury shall also be conducted according to 12.4.1.

(1) The ablation response energy, E_{ab}, of this FR layer using the breakopen determination procedure shall not be equated to the E_{BT} value for the multilayer system.

(2) If none of the panel tests in the determination of the ablation response energy, E_{ab}, predicted a burn injury (no panels exceeded the Stoll criteria), the ATPV measured prior to determining E_{ab}, shall be reported.

(3) If any of the panel tests in the determination of ablation response energy predict a burn injury (panels exceeded the Stoll criteria) below the E_{ab} value, a new ATPV shall be determined following 12.1.4 with the exception that any panel that exhibits the ablation response (hole dimension criteria in 3.1.1.1) shall be counted as exceeding the Stoll criteria (a value of 1 assigned).

11.3 *Heat Transfer Determination with the Three Two-Sensor Panel Test:*

11.3.1 Adjust the temperature of the sensors between 25 and 35°C.

11.3.2 *Specimen Mounting*—The specimen shall be fixed to the panel without stretching the material and in a manner that permits the specimen to shrink during arc exposure. This can be achieved with a material clamping system (see Fig. 8). The clamping system consists of four clamps that hold the specimen to the panel and allow the specimen to shrink during arc exposure. Each clamp within the clamping system applies between 4.4 and 6.7 N (1 and 1.5 lbf) to secure the material to the panel. Other means of mounting, which meet the above

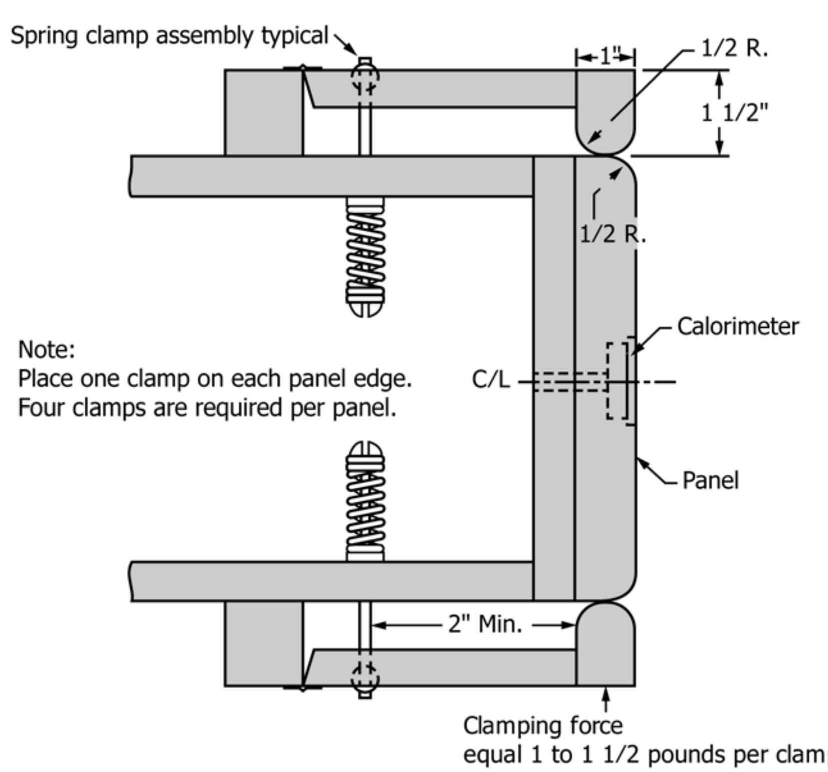


FIG. 8 Material Clamping Assembly

objectives, may also be employed. If multiple layer specimens are used, they are to be mounted in a manner that represents normal layering of the protective systems design.

11.4 *Specimen Data*—Record specimen data including: *(1)* identification number, *(2)* the order of layering with outer layer listed first, *(3)* material type, *(4)* actual areal density before testing (after laundering and pressing), *(5)* weave/knit type, *(6)* color, and *(7)* number of specimens tested.

11.5 Mount the fuse wire on the electrodes.

11.6 Exercise all safety precautions and ensure all persons are in a safe area.

11.7 Expose test specimens to the electric arc.

11.8 Shut off the electric supply, ventilate the test area at the completion of the data acquisition period and apply the protective grounds. (Refer to Section 7).

11.9 Extinguish any flames or fires unless it is predetermined to let the specimen(s) burn until consumed.

11.10 Record the thermal and electrical data and material response as required in Section 13.

11.10.1 *Sensor Response*—The sensor response of each calorimeter is determined shortly before, during, and for 30 s after an arc thermal exposure has been initiated.

11.10.2 Once the arc initiation point is determined, the temperature data collected from the calorimeters before and up to the initiation point are averaged to obtain a starting calorimeter temperature, $T_{initial}$ (°C) for each respective sensor.

11.10.3 The heat capacity in cal/g°C of each copper slug calorimeter at the initial temperature is calculated using:

$$C_p = \frac{(A + B \times t + C \times t^2 + D \times t^3 + E/t^2)}{63.546 \text{ g/mol}} \quad (1)$$

where:

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

11.10.3.1 *Discussion*—The heat capacity of copper in cal/g°C at any temperature between 289 K and 1358 K is determined via Eq 1 (Shomate equation with coefficients from NIST). The value in J/g°C can be obtained by multiplying the result in Eq 1 by 4.1868 J/cal.

11.10.4 The copper slug heat capacity is determined at each time step for all the copper slug calorimeters (monitor and panel sensors). This is done by calculating an average heat capacity for each sensor using the initial temperature determined in 11.10.2 for the initial heat capacity and the time step measured temperature for the final heat capacity in Eq 2 below.

$$\bar{C}_p = \frac{C_p@\text{Temp}_{\text{initial}} + C_p@\text{Temp}_{\text{final}}}{2} \quad (2)$$

11.10.5 The measured incident energy at each time step is determined using the initial temperature value determined in 11.10.2, the temperature at the respective time step, and the copper slug heat capacity determined in 11.10.4, in J/cm^2 [cal/cm^2] by using the relationship:

$$\text{Total Heat Energy, } Q = \frac{\text{mass} \times \bar{C}_p \times (\text{Temp}_{\text{final}} - \text{Temp}_{\text{initial}})}{\text{area}} \quad (3)$$

where:

Q = heat energy in J/cm^2 [cal/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 [cal/g°C],
$\text{Temp}_{\text{final}}$ = final temperature of copper disk/slug at $\text{time}_{\text{final}}$ (°C),
$\text{Temp}_{\text{initial}}$ = initial temperature of copper disk/slug at $\text{time}_{\text{initial}}$ (°C), and
area = area of the exposed copper disk/slug (cm^2).

11.10.6 For a copper disk/slug that has a mass of 18.0 g and exposed area of 12.57 cm^2, the determination of heat energy reduces to:

$$\text{Total Heat Energy, Q} = 1.432 \times \bar{C}_p \times (\text{Temp}_{\text{final}} - \text{Temp}_{\text{initial}}) \quad (4)$$

11.10.6.1 *Discussion*—If a copper disk/slug with a different mass or exposed area, or both, is used for the calorimeter, the constant factor in Eq 4 must be adjusted correspondingly.

11.10.7 When the monitor sensor radius r_2 is different than 30.5 cm [12 in.], a multiplying factor of $(r_2/30.5 \text{ cm [12 in.]})^2$ shall be applied to the incident energy temperature rise data collected during the test exposure.

11.10.8 The total incident thermal energy versus time at each panel is determined by averaging the results from the respective pair of monitor heat energy sensors at each time interval.

11.10.9 The total thermal energy transmitted through the specimen to the panel versus time for each exposed panel is determined by averaging the results from the respective pair of panel heat energy sensors at each time interval.

11.11 Inspect and recondition the sensors if required and adjust the electrodes to proper position and gap.

12. Interpretation of Results

12.1 *Heat Transfer:*

12.1.1 *Determining Time Zero*—Due to the electrical noise typically associated with conducting tests of this type, it is difficult to get a reliable trigger signal at the initiation of the arc. The starting time of the arc can be reliably determined however, for each test through the following analysis. For each sensor's curve, plot the difference between the curve and a line drawn from the start of the data stream to some point on the rising temperature region of the curve. Find the maximum of this difference plot. The point at which this maximum occurs is the best estimate of the arc initiation time for that sensor. These arc initiation points are usually very consistent within a test, but the median of these points or all sensors should be used as the initiation point for all of the sensors.

NOTE 3—Other satisfactory methods are available to determine time zero and may be utilized.

12.1.2 *Plotting Panel Sensor Responses*—The average panel calorimeter sensor response is plotted for each panel versus time (as determined in 11.10).

12.1.3 *Incident Energy (E_i) Monitor Sensor Responses*—Calculate the average value of each panels monitor sensor values to determine the average incident energy for each respective panel. Record the maximum heat energy value from the averaged monitor sensor pair for each panel during the data collection period. The resulting maximum values are the incident heat energies, E_i, delivered to each respective panel.

12.1.4 *Predicted Second-Degree Skin Burn Injury Determination (Stoll Curve Comparison)*—The time dependent averaged heat energy response for each panel (from the calorimeters under the specimen being tested) determined in 11.10.5 is compared to the Stoll Curve empirical human predicted second-degree skin burn injury model:

$$\text{Stoll Response, cal/cm}^2 = 1.1991 \times t_i^{0.2901} \quad (5)$$

where t_i is the time value in seconds of the heat energy determination and elapsed time since the initiation of the arc exposure. A second-degree skin burn injury is predicted if either panel sensor heat energy response exceeds the Stoll Response value (at time t_i).

12.1.4.1 *Note*—The Stoll Response can also be expressed in J/cm^2 via:

$$\text{Stoll Response, J/cm}^2 = 5.0204 \times t_i^{0.2901} \quad (6)$$

12.1.4.2 Record a value of 1 for each panel that at any time exceeds the Stoll criteria, and a value of 0 for those that do not.

12.1.5 *Determining Arc Thermal Performance Values (ATPV)*—Utilize a minimum of 20 measured panel responses following the procedure outlined in 11.2 to calculate an ATPV value. If more than 20 points are collected during a specific test exposure sequence, all valid results shall all be used in determining ATPV.

12.1.5.1 Perform a nominal logistic regression on the resulting test data. The maximum average incident energy monitor sensor response is used as the continuous variable, *X* for each panel. The corresponding nominal binary *Y* value response is the averaged panel sensor response, exceeding = 1/not exceeding = 0, the Stoll criteria (from 12.1.4.2). See Appendix for discussion of the logistic regression technique.

12.1.5.2 Use the logistic regression determined values of slope and intercept to calculate (inverse prediction) the 50 % probability value of exceeding the Stoll curve criteria. This is the ATPV result, or the incident energy value that would just intersect the Stoll curve criteria. The value is determined as:

$$ATPV = \left| \frac{\text{Intercept}}{\text{Slope}} \right| \quad (7)$$

12.1.6 *Determination of Heat Attenuation Factor (HAF)*—Determine the maximum average heat energy response for each of the panels from the plots generated in 12.1.2, and divide these responses by their respective maximum average incident energy monitor sensor responses, from 12.1.3. Identify each of these values as $E_{transmitted}$ (fraction of the incident energy which is transmitted through the specimen) for each panel.

12.1.6.1 A HAF data point (haf) for each panel is calculated according to the formula: haf = 100 × (1 − $E_{transmitted}$).

12.1.6.2 The HAF factor is then determined by calculating the average of all the haf values. At least 20 data points representing 20 panels shall be used.

12.1.6.3 Calculate the standard deviation of the points (Std), the standard error of the average (given by the ratio of the standard deviation to the square root of the number of panels used), and the 95 % confidence interval using:

$$\text{Upper Confidence Limit} = \text{HAF value} + \frac{t_{95\%} \times \text{Std}}{\sqrt{N}}$$

$$\text{Lower Confidence Limit} = \text{HAF value} - \frac{t_{95\%} \times \text{Std}}{\sqrt{N}}$$

where:

$t_{95\%}$ = Student's *t* 95% confidence interval value for *N*-1 degrees of freedom, and
N = number of panel values used (for *N* = 20; $t_{95\%}$ = 2.093).

12.2 *Determination of Breakopen Energy*—Breakopen energy response is evaluated in a similar manner to an ATPV determination. This is done using the test panel breakopen information (see 3.1.12) coupled with the incident energy, E_i, determined in 12.1.3. The breakopen panel responses shall be distributed such that at least 15 % of the panels seeing lower incident energy values show no breakopen, at least 15 % of the panels seeing higher incident energy values always breakopen, and 50 to 70 % of the panels have incident energy values that are within 20 % of the determined E_{BT} value. If there is not enough data in these ranges, perform additional panel tests at the respective incident energy range and record the material response. A minimum of 20 data values with incident energy values distributed, as noted above, is required.

12.2.1 The following technique can be used to determine a material systems breakopen response irrespective of the resulting incident energy and its relationship to the Stoll curve or ATPV determination. This can be useful in determining a material breakopen response in multilayer systems.

12.2.2 Record a value of 1 for each panel that at any time exhibits breakopen, and a value of 0 for those that do not.

12.2.3 Perform a nominal logistic regression on the resulting test data. The maximum average incident energy monitor sensor response is used as the continuous variable, *X*. The corresponding nominal binary *Y* value response is the panel material breakopen response, breakopen = 1/no breakopen = 0.

12.2.4 Use the logistic regression determined values of slope and intercept to calculate (inverse prediction) the 50 % probability value of material breakopen. This is the E_{BT} value, or the incident energy value that would just predict breakopen. The value is determined as:

$$E_{BT} = \left| \frac{\text{Intercept}}{\text{Slope}} \right| \quad (8)$$

12.3 *Arc Rating*—Report the ATPV as the material specimens Arc Rating (ATPV), if no breakopen occurs below or within the mix zone during determination of the ATPV. Otherwise, perform sufficient panel tests, as identified in 12.2 to allow determination of the E_{BT} value.

12.3.1 If an E_{BT} value is determined and it is found to be equal to or below a determined ATPV, then the E_{BT} value shall be reported as the arc rating value of the tested system and noted in the test report as Arc Rating (E_{BT}).

12.3.2 If an E_{BT} value is determined and it is found to be above a determined ATPV, then the ATPV result shall be reported as the Arc Rating (ATPV) of the tested specimen.

12.4 *Determination of a Flammable Underlayer Ignition*—A50 % probability of ignition response for a flammable underlayer (for example, a material system with a 100 % cotton t-shirt layer) can be determined, if desired, in a similar manner to the breakopen determination. This is done using the test panel underlayer ignition information (see 3.1.12) coupled with the incident energy, E_i, determined in 12.1.3. The underlayer ignition panel responses shall be distributed such that at least 15 % of the panels incident energy values are in a range that never ignite the underlayer, at least 15 % of the panels incident energy values are in a range that always ignite the underlayer, and 50 to 70 % of the panels have incident energy values that are within 20 % of the determined flammable underlayer ignition energy value. If there is not enough data in these ranges, perform additional panel tests at the respective incident energy range and record the material response. A minimum of 20 data values with incident energy values distributed, as noted above, is required.

12.4.1 The following technique can be used to determine a material systems underlayer ignition response irrespective of the resulting incident energy and its relationship to the Stoll curve or ATPV determination and breakopen performance. This method can be applied to single and multiple flammable underlayers.

12.4.2 Record a value of 1 for each panel that exhibits underlayer ignition, and a value of 0 for those that do not.

12.4.3 Perform a nominal logistic regression on the resulting test data. The maximum of each panel's averaged incident energy monitor sensor response is used as the continuous variable, *X*. The corresponding nominal binary *Y* value response is the panel's material underlayer ignition response, ignition = 1/no ignition = 0.

12.4.4 Use the logistic regression determined values of slope and intercept in Eq 8 to calculate (inverse prediction) the 50 % probability value of underlayer ignition. This is the Ignition_{50} value, or the incident energy value that would just predict underlayer ignition.

12.5 *Electrical Data*—Consistency in maintaining the arc voltage, arc current, arc duration and closing may vary from test laboratory to test laboratory. Section 6.6 requires no more than 2 % variation from test to test, given identical test parameters. Tests that exceed this 2 % variation should be investigated.

12.6 *Subjective Data*—Observe the effect of the exposure on the material systems and, after the exposed specimens have cooled, carefully remove the fabric and other layers from the panel noting any additional effects from the exposure. This may be described by one or more of the following terms which are defined in Section 3: *(1)* breakopen, *(2)* melting, *(3)* dripping, *(4)* charring, *(5)* embrittlement, *(6)* shrinkage, and *(7)* ignition.

13. Report

13.1 State that the test has been performed as directed in this test method, F1959/F1959M and report the following information:

13.1.1 Specimen data as indicated in 11.4.

13.1.2 Conditions of each test, including: *(1)* test number, *(2)* RMS arc current, *(3)* peak arc current, *(4)* arc gap, *(5)* arc duration, *(6)* arc energy, and *(7)* plot of arc current.

13.1.3 Test data including; *(1)* test number, *(2)* specimen(s), *(3)* order of layers, *(4)* distance from the arc center line to the panel surface, *(5)* subjective evaluation as outlined in 12.5, *(6)* plot of the response of the two monitor sensors and the two panel sensors for each panel test, *(7)* plot of the average response from the two panel sensors and from the two monitor sensors for each panel test, *(8)* arc rating from ATPV or from E_{BT}, *(9)* heat attenuation factor (HAF) and HAF 95 % confidence intervals, *(10)* plot of HAF on E_i, *(11)* plot of the incident energy distribution E_i (bare) from the bare shot analysis, *(12)* for multilayered systems, weight of each of the layer(s) tested, *(13)* the breakopen value, E_{BT} , if determined in addition to ATPV, but not used as the arc rating, *(14)* the ignition value, ignition_{50} (if determined during testing), *(15)* the burn injury probability plot versus E_i used for the determination of ATPV, *(16)* the breakopen probability plot versus E_i used for the determination of E_{BT} (if determined), and *(17)* the underlayer ignition probability plot versus E_i used for the determination of underlayer ignition (if determined).

13.1.3.1 Arc rating values (ATPV or E_{BT}) below 10 cal/cm^2 shall be reported to the nearest 0.1 cal/cm^2. Arc rating values (ATPV or E_{BT}) above 10 cal/cm^2 shall be reported to the nearest 1 cal/cm^2.

13.1.4 Report alternate cleaning procedures if used.

13.2 Report any abnormalities relating to the test apparatus and test controller.

13.3 Return the exposed specimens, plots, test data, and unused specimens to the person requesting the test, in accordance with any prior arrangement. All test specimens shall be marked with a reference to the test number, date, etc.

TABLE 1 Precision of the Test Method

NOTE 1—s_r = repeatability standard deviation (pooled within-laboratory standard deviation).
r = repeatability = 2.80 s_r.

Test Number	Sample A ATPV cal/cm^2	Sample B ATPV cal/cm^2	Sample A HAF, %	Sample B HAF, %	Sample C E_{BT}, cal/cm^2	Sample C Ignition_{50}, cal/cm^2
1	5.1	7.3	54.3	67.5	17.4	25.1
2	5.1	6.4	56.8	65.8	17.3	27.0
3	5.3	7.4	57.3	69.5	16.8	25.4
4	5.6	6.9	58.7	66.0	17.5	27.4
5	5.3	7.0	57.6	70.7	16.8	26.4
6	5.4	7.3	56.4	68.6	16.4	
Average	5.3	7.0	56.8	68.0	17.0	26.2
s_r	0.18	0.36	1.47	1.93	0.44	1.00
%CV	3.4	5.1	2.6	2.8	2.6	3.8
r	0.50	0.99	4.08	5.35	1.22	2.78

14. Precision and Bias

14.1 An intra-laboratory test program to determine method precision was sponsored by ASTM and funded by industry donations. The testing was conducted by the F18.65.01 working group at Kinectrics, Inc., Toronto, Ontario, Canada. The data were generated Feb. 21–24, 2005 at the High Current testing facility using the test method and apparatus specified in this standard. The report on this phase of the testing can be found in ASTM/CPMS Research Report F18-1001.[7]

14.1.1 Three different commercially available fabrics used in typical electric arc thermal protective apparel were selected for testing (identified in the results table as fabrics A, B, and C). Samples A and B were used to determine precision of the ATPV and HAF measurements. Sample C (fabric over 100 % cotton T-shirt) was used to determine E_{BT} and $Ignition_{50}$ values. Six suites of 21 panel tests were conducted for ATPV, HAF, and E_{BT}. Five suites of 21 panel tests were conducted for the $Ignition_{50}$ value (one of the five suites utilized 24 panels).

14.1.2 The results of the intra-laboratory precision study are shown in Table 1.

14.1.3 *Repeatability*—The repeatability, *r*, of this test method has been established as the value tabulated in Table 1. Two single test results, obtained in the same laboratory under normal test method procedures that differ by more than this tabulated *r* must be considered as derived from different or nonidentical sample populations.

14.1.4 *Reproducibility*—The reproducibility of this test method was not established as there is only one testing facility in North America currently capable of performing the test.

14.2 *Bias:*

14.2.1 Values of ATPV, E_{BT}, HAF, $Ignition_{50}$, and Arc Rating can be defined only in terms of a test method. There is no independent test method, nor any established standard reference material, by which any bias in the test method may be determined. The test method has no known bias.

[7] Available from ASTM International Headquarters. Request: F18-1001.

APPENDIX

(Nonmandatory Information)

X1. LOGISTIC REGRESSION TECHNIQUE (see 12.1.5.1)[8]

X1.1 Binomial logistic regression is a form of regression used when the dependent variable is limited to two states (dichotomy) and the independent variable is continuous (it can also be applied to multiple continuous independent variables). The logistic regression technique applies maximum likelihood estimation after transforming the dependent variable into a probability variable, the natural log of the odds of the dependent occurring or not. It thus generates an estimate of the probability of a certain event occurring by solving the following:

$$\ln\left[\frac{p}{1-p}\right] = a + bx + error$$

or

$$\left[\frac{p}{1-p}\right] = e^{a} \times e^{bx} \times e^{error}$$

where:

ln	=	natural logarithm,
p	=	probability that the event Y occurs, $p(Y = 1)$,
$p/(1–p)$	=	odds ratio; $(1–p)$ is the probability that event Y does not occur, and
$\ln[p/(1–p)]$	=	log odds ratio.

NOTE X1.1—The right hand side of the equation is the standard linear regression form.

X1.2 The logistic regression model is simply a non-linear transformation of the linear regression model. The logistic distribution is an S-shaped distribution function that is somewhat similar to the standard normal distribution. The logit distribution estimated probabilities lie between 0 and 1. This can be seen by rearranging the equation above and solving for *p*:

$$p = \left[\frac{e^{(a+bx)}}{1+e^{(a+bx)}}\right]$$

or

$$p = \frac{1}{\left[1+e^{(-a-bx)}\right]}$$

X1.3 If $(a+ bx)$ becomes large, p tends to 1, when $(a+bx)$ becomes small, p tends to 0, and when $(a+bx) = 0$, $p = 0.5$ (the value used for ATPV and E_{BT} in the methods above). The 50 % probability value is the point where the probability of occurring / not occurring is identical and would represent, in the case of the ATPV measurement, the point at which you just crossed the Stoll curve.

X1.4 The analysis technique makes no assumptions about linearity of the relationship between the independent variable and the dependent, does not require normally distributed variables, does not assume the error terms are homoskedastic (the variance of the dependent variable is the same with different values of the independent variable—a criteria for ordinary least squares regression), and in general has less stringent requirements.

X1.5 Operationally, a dummy variable of 1 or 0 is utilized to represent the particular state of the dependent item measured. In the ATPV example above, the coding of the dependent

[8] See also Hosmer, D. W., and Lemeshow, S., "Applied Logistic Regression," 1989, John Wiley & Sons, New York.

variable corresponds to:

$Y = 1$ if the heat response of the calorimeter exceeded the Stoll curve
$Y = 0$ if the heat response of the calorimeter did not exceed Stoll curve

X1.6 The independent, continuous variable in this case is the incident energy from the thermal arc exposure.

X1.7 A logistic regression is performed from a series of measurements and the values for *a* and *b* are determined (plus a host of other descriptive features – see the particular documentation for the software package used). The Stoll criteria (or breakopen response) is then determined by calculating *x* at the *p* = 0.5 or 50 % probability value, which from above is simply where (*a*+*bx*) = 0 or:

$$x = \left| \frac{a}{b} \right|$$

The absolute value is used here since some packages express their model calculation in the reverse manner (*p* = probability not occurring, etc.), which flips the S-shaped distribution. This can introduce a negative sign on the value of *a* or *b*, however the value at the 50 % probability point is the same.

X1.8 There are a several commercial and free software packages that can be used to perform this analysis.