Designation: F2731 – 11

Standard Test Method for Measuring the Transmitted and Stored Energy of Firefighter Protective Clothing Systems[1]

This standard is issued under the fixed designation F2731; 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 provides procedures for measuring the combination of transmitted and stored energy that occurs in firefighter protective clothing material systems as the result of exposure to prolonged, relatively low levels of radiant heat.

1.1.1 This test method applies a predetermined compressive load to a preheated specimen to simulate conductive heat transfer.

1.1.2 This test method is not applicable to protective clothing systems that are not flame resistant.

1.1.3 *Discussion*—Flame resistance of the material system shall be determined prior to testing according to the applicable performance and/or specification standard for the material's end-use.

1.2 This test method establishes procedures for moisture preconditioning of firefighter protective clothing material systems.

1.3 The second-degree burn injury used in this standard is based on a limited number of experiments on forearms of human subjects.

1.3.1 *Discussion*—The length of exposures needed to generate a second-degree burn injury in this test method exceeds the exposures times found in the limited number of experiments on human forearms.

1.4 The values stated in SI units are to be regarded as the standard. The values given in parentheses are mathematical conversions to English units or other units commonly used for thermal testing.

1.5 *This standard is used to measure and describe the properties of materials, products, or assemblies in response to radiant heat under controlled laboratory 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.*

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* Specific precautionary information is found in Section 7.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D123 Terminology Relating to Textiles

D1777 Test Method for Thickness of Textile Materials

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

F1494 Terminology Relating to Protective Clothing

F1930 Test Method for Evaluation of Flame Resistant Clothing for Protection Against Fire Simulations Using an Instrumented Manikin

2.2 *AATCC Test Methods:*[3]

AATCC 70 Test Method for Water Repellency: Tumble Jar Dynamic Absorption Test

AATCC 135 Dimensional Changes in Automatic Home Laundering of Durable Press Woven or Knit Fabrics

2.3 *NFPA Standard:*[4]

NFPA 1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting

3. Terminology

3.1 *Definitions:*

3.1.1 *break-open, n*—in testing thermal protective materials, a material response evidence by the formation of a hole in the test specimen.

3.1.1.1 *Discussion*—The specimen is considered to exhibit break-open when a hole is produced as a result of the thermal exposure that is at least 3.2 cm^2 (0.25 $in.^2$) in area or at least 2.5

[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.

[3] Available from American Association of Textile Chemists and Colorists (AATCC), P.O. Box 12215, Research Triangle Park, NC 27709, http://www.aatcc.org.

[4] Available from National Fire Protection Association (NFPA), 1 Batterymarch Park, Quincy, MA 02169-7471, http://www.nfpa.org.

cm (1.0 in.) in any dimension. Single threads across the opening or hole do not reduce the size of the hole for purposes of this test method.

3.1.2 *charring, n*—the formation 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 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 per unit area and per unit time; kW/m^2 (cal/cm^2-s).

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

3.1.7 *melting, n*—in testing thermal protective materials, a response evidenced by softening of the polymer.

3.1.8 *response to heat exposure, n*—in testing for the transmitted and stored energy 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.

3.1.8.1 *Discussion*—For the purposes of this test method, response to heat exposure also includes any non-textile reinforcement material used as part of the protective clothing material system that is tested.

3.1.9 *second-degree burn injury, n*—reversible burn damage in the epidermis and upper layers of the dermis, resulting in blistering, severe pain, reddening, and swelling.

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

3.1.11 *sticking, n*—a response evidenced by softening and adherence of the material to other material.

3.1.11.1 *Discussion*—For the purpose of this test method, the observation of sticking applies to any material layer in the protective clothing material system.

3.1.12 *stored energy, n—in testing thermal protective materials,* thermal energy that remains in a fabric/composite after the heating source is removed.

3.1.12.1 *Discussion*—The stored energy measured by this standard only accounts for the energy released to the sensor after compressing. Stored energy is also lost to the compressor block and the surrounding environment.

3.1.13 *thermal protective clothing system, n*—any combination of materials which when used as a composite can limit the rate of heat transfer to or from the wearer of the clothing.

3.1.13.1 *Discussion*—The rate at which this heat transfer occurs can vary depending on the materials.

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

4. Summary of Test Method

4.1 A vertically positioned test specimen, representative of the lay-up in firefighter protective clothing, is exposed to a relatively low level of radiant heat flux at 8.5 ± 0.5 kW/m^2 (0.2 $\pm$ 0.012 cal/cm^2-s) for a fixed period of time.

4.2 During the time of radiant heat exposure, a data collection sensor, positioned 6.4 ± 0.1 mm (0.25 ± 0.004 in.) behind and parallel to the innermost surface of the test specimen, measures the heat energy transmitted through the test specimen.

4.3 In the same test apparatus, the test specimen is compressed against the data collection sensor at a pressure of 13.8 $\pm$ 0.7 kPa (2.0 psi $\pm$ 0.1 psi) for a fixed period of time. This load could possibly simulate a firefighter leaning against a wall, squatting or sitting down. This compression step occurs after the fixed radiant heat exposure time and after the specimen is moved away from the heating source.

4.4 During the time of compression against the data collection sensor, the data collection sensor continues to measure the heat energy transferred from the test specimen for a fixed duration of time.

4.5 The total energy transmitted and stored by the test specimen is used to predict whether a second degree burn injury can be predicted. If a second-degree burn injury is predicted, the time to a second degree burn injury is reported.

4.6 Two different sets of procedures are provided. In Procedure A, an iterative method is used to determine the minimum length of the radiant heat exposure followed by a 60 second compression that will result in the prediction of a second degree burn injury. In Procedure B, testing is conducted at fixed radiant heat exposure and a 60-second compression period. The report for Procedure B includes if a second degree burn injury has been predicted and if predicted, the time for a second degree burn injury.

4.7 If a second degree burn injury is not predicted, the result is indicated as "no predicted burn."

4.8 Appendix X1 contains a general description of human burn injury, its calculation and historical notes.

5. Significance and Use

5.1 Firefighters are routinely exposed to radiant heat in the course of their fireground activities. In some cases, firefighters have reported burn injuries under clothing where there is no evidence of damage to the exterior or interior layers of the firefighter protective clothing.[5] Low levels of transmitted radiant energy alone or a combination of the transmitted radiant energy and stored energy released through compression can be sufficient to cause these types of injuries. This test method was designed to measure both the transmitted and stored energy in firefighter protective clothing material systems under a specific set of laboratory exposure conditions.

5.2 The intensity of radiant heat exposure used in this test method was chosen to be an approximate midpoint representative of ordinary fireground conditions as defined for structural firefighting (**1**), (**2**)[6]. The specific radiant heat exposure

[5] Development of a Test Method for Measuring Transmitted Heat and Stored Thermal Energy in Firefighter Turnouts, final report presented to National Institute for Occupational Safety and Health (NIOSH) National Personal Protective Technology Laboratory (NPPTL) under Contract No. 200-2005-12411, April 29, 2008.

[6] The boldface numbers in parentheses refer to a list of references at the end of this standard.

was selected at 8.5 ± 0.5 kW/m^2 (0.20 ± 0.012 cal/cm^2-s) since this level of radiant heat can be maintained by the test equipment and produces little or no damage to most NFPA 1971 compliant protective clothing systems.

5.2.1 *Discussion*—Utech defined ordinary fireground conditions as having air temperatures ranging from 60 to 300°C and having heat flux values ranging from 2.1 to 21.0 kW/m^2 (0.05 to 0.5 cal/cm^2-s).

5.3 Protective clothing systems include the materials used in the composite structure. These include the outer shell, moisture barrier, and thermal barrier. It is possible they will also include other materials used on firefighter protective clothing such as reinforcement layers, seams, pockets, flaps, hook and loop, straps, or reflective trim.

5.4 The transmission and storage of heat energy in firefighter protective clothing is affected by several factors. These include the effects of "wear" and "use" conditions of the protective clothing system. In this test method, conditioning procedures are provided for the laundering of composite samples prior to testing, and also composite sample moisture preconditioning. The amount of moisture added during preconditioning typically falls into a worst case amount in terms of predicted heat transfer, as suggested by Barker (**3**).

5.5 Two different procedures for conducting the test are provided in this test method. Procedure A involves an iterative approach to determine the minimum exposure time followed by a fixed 60-second compression time required to predict a second degree burn injury. In this approach, the length of the radiant exposure is varied systematically using a series of tests to determine the length of the radiant exposure that will result in the prediction of a second degree burn injury. Procedure B involves using a fixed radiant heat exposure time to determine if a second degree burn injury will or will not be predicted. If a second degree burn injury is predicted, the time to a second degree burn injury is reported. If a second degree burn injury is not predicted, the result is indicated as "no predicted burn." Procedure B involves a fewer number of tests. This procedure includes recommended fixed radiant exposure times.

6. Apparatus and Materials

6.1 *General Arrangement*—The transmitted and stored energy testing apparatus shall consist of a specimen holder, sensor assembly, transfer tray, data collection sensor, compressor assembly, heating source, and a data acquisition/controls/ burn damage analysis system. A overhead view of these components, minus the data acquisition/controls/ burn damage analysis system, is illustrated in Fig. 1.

6.2 *Specimen Holder*—The specimen holder shall consist of upper and lower mounting plates made of stainless steel. Each plate shall be 170 by 170 ± 1 mm (6.6 by 6.6 ± 0.04 in.) and the thickness shall be 6.4 ± 0.1 mm (0.25 ± 0.004 in.), with a centered 100 by 100 ± 1 mm (3.9 by 3.9 ± 0.04 in.) hole. The lower plate shall have an attached handle that is at least 75 mm (3 in.) in length. The lower specimen mounting plate shall have a minimum of two alignment posts attached perpendicular to the plane of the plate. The upper sample mounting plate shall have corresponding holes on each side so that the upper specimen mounting plate fits over the lower specimen mounting plate. The specimen holder components are shown in Fig. 2.

6.2.1 The handle of the sample holder shall be made of or surrounded by a material with a low thermal conductivity.

6.2.2 The alignment posts shall be positioned such that they do not interfere with the test specimen.

6.3 *Sensor Assembly*—The sensor assembly shall be composed of a water cooled plate and a sensor holder.

6.3.1 The water cooled plate is constructed from a 3.2 ± 1-mm thick copper sheet with 3.2 ± 1-mm outer diameter copper tubing soldered to the back side. The copper plate shall be machined at its centerline to accept the data collection sensor with a tolerance of +0.3 mm. The four corners of the plate shall be drilled to accept a countersunk screw.

6.3.1.1 The copper tubing shall be looped back and forth across the back side of the copper plate to provide a uniform temperature across the surface of the copper plate.

6.3.1.2 Water shall flow through the copper tubing at a rate of no less than 100 mL/min and the water shall have a temperature be 32.5 ± 1°C.

6.3.2 *Discussion*—The 32.5°C temperature was set based on the average surface temperature of the forearms of volunteers as measured by Pennes (**4**).

6.3.2.1 The exposed surface of water cooled plate shall be painted with a thin coating of flat black high temperature spray

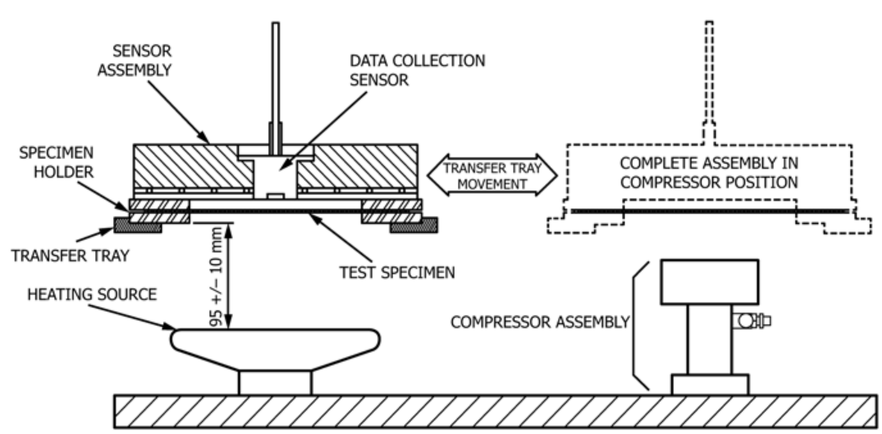

FIG. 1 Overhead View of Major Apparatus Components

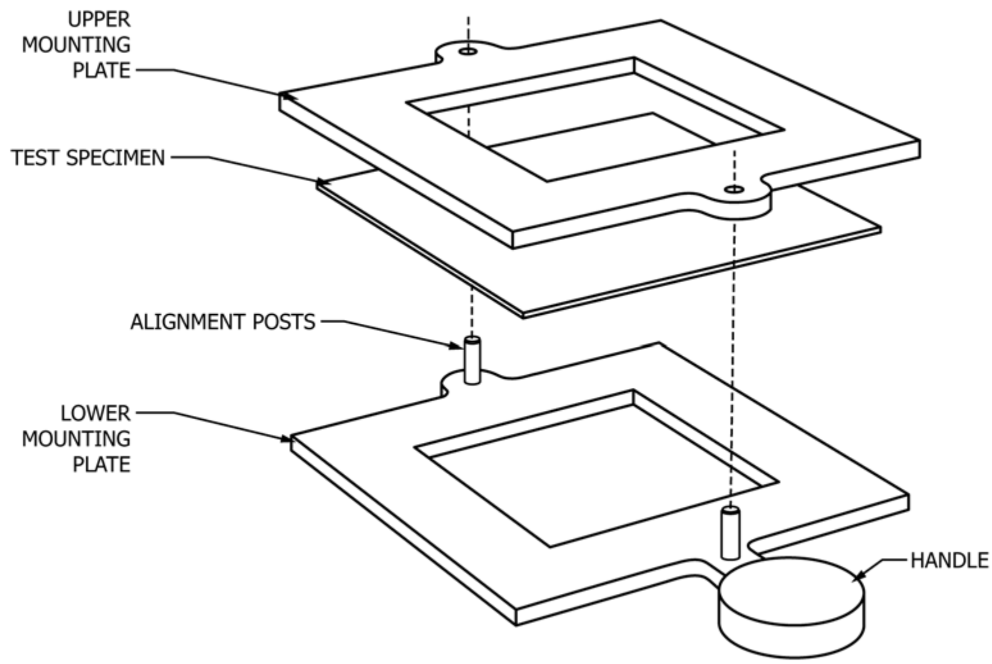

FIG. 2 Specimen Holder

paint with an emissivity of 0.9 or greater. The painted water-cooled plate shall be dried before use and shall present a uniformly applied coating (no visual thick spots or surface irregularities).

(1) Information about paints that can meet the emissivity requirement please refer to 6.5.2.

6.3.3 The sensor holder shall be a 166 by 166 ± 2 mm (6.54 by 6.54 ± 0.8 in.) aluminum block. The thickness of the block shall be no less that 25.4 mm (1 in.). The four corners of the block shall be drilled and tapped such that they align with the holes found in the water cooled plate. After the sensor holder and water cooled plate are attached with the flat head countersunk screws the sensor holder shall be machined at its centerline to accept the data collection sensor with a tolerance of +0.3 mm and -0.00 mm such that the sensor face is flush with the bottom face of the water cooled plate. Specifications for the sensor assembly are provided in Fig. 3.

6.3.3.1 When attaching the water cooled plate to the sensor holder, the flat head countersunk screws shall be below the surface of the water cooled plate.

6.4 *Transfer Tray*—The transfer tray shall be designed to transfer the combined specimen holder and sensor assembly between the heating source and the compressor and shall complete this transfer in 5.0 ± 0.5 second. This assembly shall be made to securely hold both the specimen holder and sensor assembly together.

6.4.1 When the specimen holder and the sensor assembly are held together an air gap of 6.4 mm (0.25 in.) is formed between the skin side of the specimen and the data collection sensor.

6.5 *Data Collection Sensor*—The data collection sensor shall be a water cooled Schmidt-Boelter thermopile type sensor with a diameter of 25.4 mm (1 in.). The heat flux range shall be from 0 to 11.4 kW/m^2 (0 to 0.267 cal/cm^2-s or 0 to 1 Btu/ft^2/s).

6.5.1 Water shall flow through the data collection sensor at a rate of no less than 100 mL/min and the water shall have a temperature be 32.5 ± 1°C.

6.5.2 The exposed surface of the data collection sensor shall be painted with a thin coating of flat black high temperature

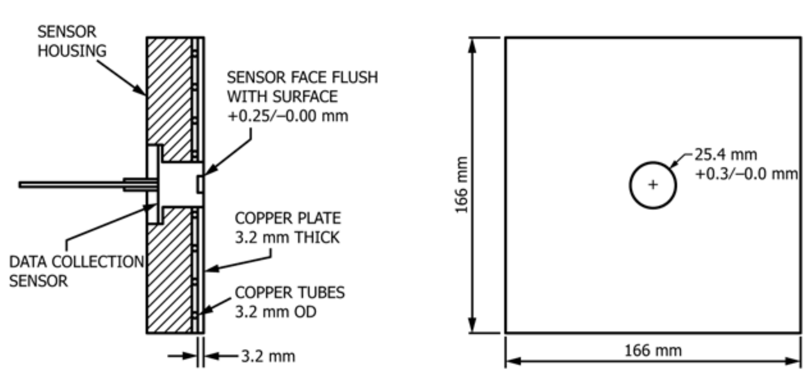

FIG. 3 Specification for Sensor Assembly

spray paint with an emissivity of 0.9 or greater. The painted sensor shall have a uniformly-applied coating and must be calibrated against a NIST-traceable sensor or heating source before use.

NOTE 1—Emissivity 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."

6.5.3 The data collection sensor must be held rigidly in the sensor assembly.

6.6 *Compressor Assembly*—The compressor assembly shall consist of a compressor block, air cylinder, air regulator and a framework that rigidly holds the system in place. When activated, the regulated air shall activate the piston and force the circular heat resistant block against the sample and data collection sensor with a pressure of 13.8 ± 0.7 kPa (2.0 ± 0.1 psi) based on the top surface area of the compressor block. Specifications for the compressor assembly are provided in Fig. 4.

6.6.1 The compressor block shall be constructed of Marinite or other material(s) with an equivalent thermal conductivity (0.12 W/m K) and shall have a diameter of 57 ± 0.5 mm (2.25 in.) and a thickness of 25.4 ± 0.5 mm (1 ± 0.02 in.).

6.7 *Heating Source*—The heating source shall consist of a black ceramic thermal flux source.[7] The heating source shall be 120 by 120 mm ± 5 mm (4.7 by 4.7 ± 0.2 in.) and shall be set 95 ± 10 mm (3.75 ± 0.4 in.) away from the specimen holder.

6.7.1 Equip the heating source with a thermocouple attached to the upper surface. The thermocouple shall be no more than 2-mm thick and shall be well bonded, both mechanically and thermally, to the heating source. Temperature data from the thermocouple are fed to a temperature controller used to maintain a constant heat flux.

6.8 *Data Acquisition/Controls/Burn Damage Analysis System*—This system includes all software and hardware needed for data acquisition and storage, control of the experiment and burn damage calculations.

6.8.1 *Data Acquisition*—The system shall be capable of measuring the maximum output from the sensor with sufficient sensitivity. The system shall also collect data at a rate no less than ten times per second and record the data with an appropriate time stamp.

6.8.2 *Controls*—The system shall be able to send analog or digital signals to the testing apparatus. These signals will be used to move the transfer tray and to activate and deactivate the compressor.

6.8.3 *Burn Damage Analysis System*—The calculated heat flux history shall be recorded and applied to a skin model using software that calculates the temperature history at the base of epidermis and dermis using the skin model prescribed in Section 11.

NOTE 2—These calculations will predict either no predicted burn or a time to second-degree burn.

6.9 *Analytical Balance*—Capable of measuring weight to a precision of at least 0.01 g.

6.10 *Thickness Gauge*—Meeting requirements of Test Method D 1777.

6.11 *Plastic Bags*—Resealable plastic bags that are sufficiently large to accommodate a single 152 by 152 by 6.4-mm (6.0 by 6.0 by 0.25-in.) specimen.

NOTE 3—A quart size resealable plastic bag has been found to be suitable.

7. Hazards

7.1 Perform all testing and calibration in a hood or ventilated area to carry away byproducts, smoke, or fumes due to the heating process. Procedures for testing and calibration shall be performed using the same hood and ventilation conditions.

7.2 Exercise care in handling the specimen holder and sensor assembly, as specimens become heated during prolonged testing. Use heat-protective gloves when handling these hot objects.

7.3 Caution must be used around the testing device as it has moving parts which can create pinch-points.

[7] The sole source of supply of the apparatus known to the committee at this time is Ogden Manufacturing Company, 64 W. Seegers Rd, Arlington Heights, IL 60005, Part number EL-3-650. 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.

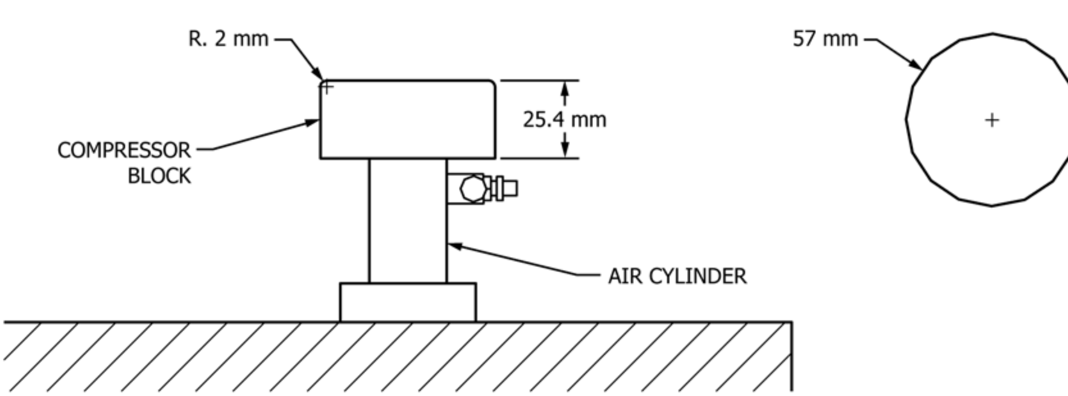

FIG. 4 Compressor Assembly

8. Specimens

8.1 Test a minimum of five specimens per firefighter protective clothing system to be evaluated.

8.2 Cut specimens to measure 152 by 152 ± 5 mm (6.0 by 6.0 ± 0.2 in.). Specimens shall consist of all layers representative of the clothing system to be tested, including reinforcement layers, reflective trim, or other layers as applicable.

8.3 Measure the weight of each individual layer and of the assembled protective clothing material system in accordance with Test Method D3776. Measure the thickness of each layer and of the assembled protective clothing material system in accordance with Test Method D1777.

8.3.1 Specimens shall not be stitched to hold individual layers together during testing.

8.3.2 When tested with reflective trim or outer reinforcement material that has a dimension less than 152 mm (6 in.), the trim or reinforcement specimen shall be sewn to the center of outer shell of the composite so that it will be directly positioned over the thermal sensor of the test apparatus.

8.3.3 Reinforcement materials that are less than 60 mm in one dimension shall not be tested. These materials are likely not to cover the entire surface of the compressor block and would alter the applied pressure.

9. Conditioning

9.1 When specified, launder sample materials representative of the protective clothing material system for five wash and drying cycles in accordance with AATCC 135, Machine Cycle 1, Wash Temperature IV, Drying Condition Ai.

9.2 For tests to be conducted under dry conditions, condition specimens at 21 ± 3°C and 65 ± 10 % relative humidity for a minimum of 24 hours.

9.3 For tests to be conducted under wet conditions, the following preconditioning procedure shall be used for each specimen:

9.3.1 Condition the specimen in a room environment at 21 ± 3°C and 65 ±10 % relative humidity for a minimum of 24 hours.

9.3.2 Weigh the specimen using an analytical balance, described in section 6.9, and record the weight.

9.3.3 Immerse two pieces of standard 152 by 152-mm (6 by 6-in.) AATCC blotter paper in distilled water for 10 ± 2 seconds.

9.3.4 Place one blotter paper on top of the other and run them through a wringer, that meets the requirements of 10.2 of AATCC 70, Test Method for Water Repellency: Tumble Jar Dynamic Absorption Test, with a 30 lb load on the rolls.

9.3.5 Place the innermost separable layer of the protective clothing material system between the two wrung blotter papers.

NOTE 4—For firefighter protective clothing material systems, the normal innermost separable layer is typically the thermal barrier.

9.3.6 Place the remaining layers of the protective clothing system on the uppermost wrung blotter paper. Place each layer as they would be found in the protective clothing ensemble minus the wrung blotter paper.

9.3.7 Place both the blotter papers and the specimen in a plastic bag, then place a 152 by 152 ± 5-mm (6.0 by 6.0 ± 0.2-in.) block weighing 275 ± 5 g in the center and on top of the bag, to remove the air, and seal it. Remove the weight and allow the bagged specimen to equilibrate in an environmentally controlled room (21 ± 3°C and 65 ± 10 % relative humidity) for a period of at least twelve hours, but not more than 24 hours.

9.3.7.1 Place only one specimen in each plastic bag.

9.3.7.2 Ensure that bagged samples are not stacked.

9.3.8 Remove the specimen from the plastic bag.

9.3.9 Remove the blotter paper from between the specimen layers.

9.3.10 Weigh the samples after blotter paper removal and record the moisture add-on.

9.3.10.1 Moisture add-on is the difference between the final weight and the initial weight.

9.3.11 Perform testing within three minutes from the time the specimen is removed from the sealed plastic bag.

10. Procedures

10.1 *Calibration Procedure:*

10.1.1 Allow the heating source to heat up for a minimum of 30 minutes after being turned on.

10.1.2 Prepare water bath to deliver 32.5 ± 1°C to sensor and sensor assembly at a rate of no less than 100 mL/min.

10.1.3 Reduce or turn off the hood airflow to minimize forced convective air currents from disturbing the heat flux sensor response.

10.1.4 Calibrate the apparatus to deliver an average thermal flux of 8.5 ± 0.5 kW/m^2 (0.20 ± 0.012 cal/cm^2-s) as measured with the data collection sensor and data acquisition system.

10.1.4.1 Use the data collection sensor as the only heat sensor in setting the total 8.5 kW/m^2 (0.20 cal/cm^2-s) exposure condition.

10.1.4.2 Measure the total heat flux directly and only from the voltage output of the data collection sensor.

10.1.4.3 Do not use other heat sensing devices to reference or adjust the total heat flux read by the data collection sensor.

10.1.5 Without a mounted specimen, place the sensor assembly minus the upper mounting plate of the specimen holder on top of the specimen holder with the sensor surface facing towards the heating source, and then expose the sensor assembly directly to the radiant heat source.

10.1.6 Adjust the temperature of the heating source until the total heat flux is 8.5 ± 0.5 kW/m^2 (0.20 ± 0.012 cal/cm^2-s) using the data collection sensor as specified in 6.5.

10.1.7 Once an initial setting of 8.5 ± 0.5 kW/m^2 (0.20 ± 0.012 cal/cm^2-s) has been made, record the operating parameters for test purposes.

10.1.8 Record the response of the data collection sensor for 60 seconds.

10.1.9 Calculate the average of the last 50 seconds and use the calculated average to determine the heat flux level.

10.2 *Test Procedure A*—Radiant Heat Exposure Time to Predict Second Degree Burn Injury.

10.2.1 With the specimen holder in the non-exposure position, mount the specimen in the test apparatus by placing the outside of the garment face down on the lower mounting plate of the specimen holder. The subsequent layers shall be placed on top in the order used in the garment, with the surface worn toward the skin facing up. Then place the upper mounting plate of the specimen holder above the specimen.

10.2.2 Position the sensor assembly on top of the specimen holder and test specimen.

10.2.3 Place the sensor assembly and specimen holder in the transfer tray.

10.2.4 Select an initial time for the period of radiant heat exposure.

NOTE 5—For 3-layer firefighter protective clothing material systems, an initial radiant exposure time of 90 s is recommended.

10.2.5 Move the transfer tray over the heating source and begin collecting data with the data acquisition system as soon as the tray starts to move.

NOTE 6—It is required to automate the process of moving the transfer tray over the heating source and beginning data collection; the automation is required to be further extended to the controlling the exposure period and the overall data collection period of each test for parameters set by the test operator.

10.2.6 Continue the radiant exposure for the selected period of time.

10.2.7 At the end of the selected exposure period, move the transfer tray away from the heating source and over the compressor while the data acquisition system continues to collect data.

NOTE 7—The end of the radiant exposure is when the transfer tray starts to move away from the heating source.

10.2.8 The compression period shall begin 5 ± 0.5 s after the end of the radiant exposure. Compress the specimen against the data collection sensor at an applied pressure of 13.8 kPa (2.0 psi). Continue to compress the specimen and collect data for 60 s after the compression is started.

10.2.9 Stop the data acquisition following the end of the compression period.

10.2.10 Using calculation procedures found in Section 11 determine if a second degree burn injury is predicted for the selected radiant exposure time.

10.2.10.1 If a second degree burn injury is not predicted, determine a new radiant exposure time that is higher than the initially selected radiant exposure time. For successive trials where a second degree burn injury is not predicted, choose a radiant exposure time that is halfway between the completed test and the highest previous radiant exposure time that resulted in burn injury.

NOTE 8—For three-layer firefighter protective clothing material systems, it is recommended to initially increase the radiant exposure time by 30 seconds.

10.2.10.2 If a second degree burn injury is predicted, determine a new radiant exposure time that is lower than the initial selected. For successive trials where a second degree burn injury is predicted, choose a radiant exposure time that is halfway between the completed test and the lower previous radiant exposure time that resulted in burn injury.

NOTE 9—For three-layer firefighter protective clothing material systems, it is recommended to initially decrease the radiant exposure time by 30 seconds.

10.2.10.3 If the difference between the current test radiant exposure time and the previous test radiant exposure time is ≤10 s, then the time to a predicted second degree burn injury is the current radiant exposure time.

10.2.11 Observe and record the condition of the specimens following the testing.

10.2.12 Verify the test result with at least four additional test specimens.

10.3 *Test Procedure B—Fixed Exposure Period for Predicting Second Degree Burn Injury.*

10.3.1 With the specimen holder in the non-exposure position, mount the specimen in the test apparatus by placing the outside of the garment face down on the lower mounting plate of the specimen holder. The subsequent layers shall be placed on top in the order used in the garment, with the surface worn toward the skin facing up. Then place the upper mounting plate of the specimen holder above the specimen.

10.3.2 Position the sensor assembly above the specimen holder and the test specimen.

10.3.3 Place the sensor assembly and the specimen holder in the transfer tray.

10.3.4 Move the transfer tray over the heating source and begin collecting data with the data acquisition system.

10.3.5 Continue the exposure for either 60, 90, or 120 seconds.

NOTE 10—Recommended fixed radiant exposure times are 60, 90, or 120 s based on prior experience in the testing of unreinforced and reinforced firefighter protective clothing material systems.

10.3.6 At the end of the selected exposure period, move the transfer tray away from the heating source and over the compressor while the data acquisition system continues to collect data.

NOTE 11—The end of the radiant exposure is when the transfer tray starts to move away from the heating source.

10.3.7 The compression period shall begin 5 ± 0.5 s after the end of the radiant exposure. Compress the specimen against the data collection sensor at an applied pressure of 13.8 kPa (2.0 psi). Continue to compress the specimen and collect data for 60 s after the compression is started.

10.3.8 Stop the data acquisition following the end of the compression period.

10.3.9 Using calculation procedures found in Section 11, determine if a second degree burn injury is predicted for the selected radiant exposure time. If no burn is predicted record "no predicted burn."

10.3.10 Observe the condition of the specimen following the testing.

10.3.11 Repeat 10.3.2 through 10.3.10 to test four additional specimens.

10.4 *Post Test Sensor Care Procedure:*

10.4.1 Check the sensor surface immediately after each run. If a deposit collects and appears to be thicker than a thin layer of paint, or is irregular, recondition the sensor surface.

10.4.1.1 Carefully clean the cooled sensor with acetone or petroleum solvent, making certain there is no ignition source nearby.

10.4.1.2 If copper is showing or the deposits cannot be removed from the data collection sensor, the sensor must be repainted and recalibrated as specified in 6.5.2. The heating source will also need to be recalibrated after repainting and recalibration of a sensor.

10.4.1.3 At least one calibration run shall be performed comparing the calibration of the data collection sensor.

11. Calculation of Results

11.1 Determination of the predicted skin and subcutaneous fat (adipose) internal temperature field.

11.1.1 Assume the thermal exposure is represented as a transient one dimensional heat diffusion problem in which the temperature within the skin and subcutaneous layers (adipose) varies with both position (depth) and time, and is described by the linear parabolic differential equation (Fourier's Field Equation).

$$\rho C(x)\partial[T(x,t)]/\partial t = \partial[k(x)\partial[T(x,t)]/\partial x]/\partial x \quad (1)$$

where:

$\rho Cp(x)$ = Volumetric heat capacity, J/m^3•K (cal/s•cm^3•K)
t = Time, s
x = Depth from skin surface, m [cm]
$T(x,t)$ = Temperature at depth x, time t, K
$k(x)$ = Thermal Conductivity, W/m•K (cal/s•cm•K)

11.1.2 *Discussion*—Use of absolute temperatures is recommended when solving Eq 1because Eq 2, which is used for the calculation of Ω, the burn injury parameter, requires absolute temperatures.

11.1.3 Solve Eq 1 numerically using a three-layer skin model that takes into account the depth dependency of the thermal conductivity and volumetric heat capacity values as identified in Table 1. Each of the three layers shall be constant thickness, lying parallel to the surface.

11.1.4 *Discussion*—The property values stated in Table 1 are representative of *in vivo* (living) values for the forearms of the test subjects who participated in the experiments by Stoll and Greene (**5**). They are average values. The thermal conductivity of each of the layers is known to vary with temperature due to the generalized thermo-physical characteristics of the layer components (simplified composition: water, protein and fat). Laboratories accounting for this report an improved correlation to the reference dataset presented in Table 2. This is done by modeling the temperature dependence of the thermal conductivity of each layer after that of water. See Appendix X1.13.

TABLE 1 Physical Properties for Skin Burn Injury Model

Parameter	Epidermis	Dermis	Subcutaneous Tissue
Thickness of layer (m) (μm)	7.5×10^{-5} (75)	1.125×10^{-3} (1125)	3.885×10^{-3} (3885)
Thermal conductivity k (W/m• K) (cal/s•cm•K)	0.6280 (0.0015)	0.5902 (0.00141)	0.2930 (0.0007)
Volumetric heat capacity ρCP (J/m3 •K) (cal/s•cm3•K)	4.40×10^6 (1.05)	4.186×10^6 (1.0)	2.60×10^6 (0.62)

11.1.4.1 The discretization methods to solve Eq 1 that have been found effective are: the finite differences method (following the "combined method" central differences representation where truncation errors are expected to be second order in both Δt and Δx), finite elements method (for example the Galerkin method), and the finite volume method (sometimes called the control volume method).

11.1.5 Use the following boundary and initial conditions:

11.1.5.1 The initial temperature within the three layers shall have a linear increase with depth from 305.65 K (32.5°C) at the surface to 306.65 K (33.5°C) at the back of the subcutaneous layer (adipose). The deep temperature shall be constant for all time at 306.65 K (33.5°C).

11.1.6 *Discussion*—Pennes (**4**) measured the temperature distributions in the forearms of volunteers. For the overall thickness of the skin and subcutaneous layers listed in Table 1, the measured rise was 1 K (1°C). The skin surface temperature of the volunteers in the experiments by Stoll and Greene (**5**) was kept very near to 305.65 K (32.5°C).

11.1.6.1 The incident heat flux is applied only at the skin surface. The energy incident upon the surface of the skin is assumed to be absorbed at the surface and heat conduction is the only mode of heat transfer in the skin and subcutaneous layers (adipose).

11.1.7 *Discussion*—Assuming heat conduction only within the skin and deeper layers ignores enhanced heat transfer due to changing blood flow in the dermis and subcutaneous layers (adipose). The *in vivo* (living) values listed in Table 1 are back calculated from the experimental results of Stoll and Greene (**5**) and numerical extensions by Weaver and Stoll (**6**). The values account to a large degree for the blood flow in the test subjects.

11.1.7.1 The incident heat flux at the skin surface at time t = 0 (start of the exposure) is zero.

11.1.7.2 The incident heat flux values at the skin surface at all times $t > 0$ are the time dependent heat flux values collected during testing. No corrections are made for radiant heat losses or emissivity/absorptivity differences between the sensors and the skin surface used in the model.

11.1.8 Calculate an associated internal temperature field for the skin model at each sensor sampling time interval for the entire sampling time by applying each of the sensor's time-dependent heat flux values to individual skin modeled surfaces (a skin model is evaluated for each measurement sensor). These internal temperature fields shall include, as a minimum, the calculation of temperature values at the surface (depth = 0.0 m), at a depth of 75×10^{-6} m (the skin model epidermis/dermis interface used to predict second-degree burn injury), and at a depth of 1200×10^{-6} m (the skin model dermis/subcutaneous interface used to predict a third-degree burn injury).

11.1.9 *Discussion*—Equally spaced depth intervals (Δx), denoted as "nodes" or "meshes", are the recommended for highest accuracy in all numerical models. A value for Δx of

TABLE 2 Skin Model Validation Data Set

NOTE 1—Skin models using the absorbed heat flux and exposure times in this table shall result in Ω values of 1 ± 0.10 for all test cases at the epidermis/dermis interface when using the skin layer properties listed in Table 1 and the calculation constants in Table 3. In addition, the time when Ω = 1 shall always be greater than the exposure duration listed as tissue damage continues to occur after the exposure ends while the epidermis/dermis interface temperature cools to below 317.15 K (44°C).

Absorbed Exposure Heat Flux		Exposure Duration, s	Required Size of Time Step, s
W/m²	(cal/s•cm²)		
3 935	(0.094)	35.9	0.01
5903	(0.141)	21.09	0.01
11 805	(0.282)	8.30	0.01
15 740	(0.376)	5.55	0.01
27 276	(0.564)	3.00	0.01
31 479	(0.752)	1.95	0.01
39 348	(0.940)	1.41	0.01
47 218	(1.128)	1.08	0.01
55 088	(1.316)	0.862	0.001
62 957	(1.504)	0.713	0.001
70 827	(1.692)	0.603	0.001
78 697	(1.880)	0.522	0.001

15×10^{-6} m has been found effective. Sparse or unstructured meshes are not recommended for use in the finite difference method.

11.2 Determination of the predicted skin burn injury.

11.2.1 The Damage Integral Model of Henriques (**7**), Eq 2, is used to predict skin burn injury based on skin temperature values at each measurement time interval at skin model depths of 75×10^{-6} m (second-degree burn injury prediction) and 1200×10^{-6} m (third-degree burn injury prediction).

$$\Omega = \int Pe^{-\Delta E/RT} dt \quad (2)$$

where:

Ω	=	Burn Injury Parameter; Value,≥1 indicates predicted burn injury
t	=	time of exposure and data collection period, s
P	=	Pre-exponential term, dependent on depth and temperature, 1/s
Δ*E*	=	Activation energy, dependent on depth and temperature, J/kmol
R	=	Universal gas constant, 8314.472, J/kmol K
T	=	Temperature at specified depth (in kelvin), K

11.2.2 The calculation method used shall meet the validation requirements identified in Table 2.

11.2.2.1 When validating the skin burn injury model, use the layer thickness, thermal conductivity and volumetric heat capacity values specified in Table 1 and the boundary and initial conditions of 11.1.5. The total calculation time shall be chosen so that the temperatures at the epidermis/dermis and dermis/subcutaneous interfaces both fall below 317.15 K (44ºC) during the cooling phase. The skin surface shall be assumed to be adiabatic during the cooling phase, that is, no heat losses from the surface during cooling. Minor changes in the values of thermal conductivity and volumetric heat capacity are permitted providing the validation requirements specified in Table 2 are met with one set of values for all twelve test cases.

11.2.3 *Discussion*—Numerical experiments show that accounting for potential heat losses due to convection and thermal radiation from the surface during the cool down time change the predicted Ω by 0 % to 10 %, as the exposure time increases from 0.522 to 35.9 s. The average correction for the twelve test points in Table 2 was 2.6 %. Note as well that a 1 % change in the exposure time also results in about a 10 % change in the calculated value of Ω.

11.2.4 Determine the second-degree and third-degree burn injury parameter values, Ω's, by numerically integrating Eq 2 using the closed composite, extended trapezoidal rule or Simpson's rule, for the total time that data was gathered.

11.2.4.1 The integration is performed at each measured time interval for each of the sensors at the second-degree and third-degree skin depths (75×10^{-6} m and 1200×10^{-6} m respectively) when the temperature, T, is ≥ 317.15 K (44°C).

11.2.4.2 For the second-degree and third-degree burn injury predictions, the temperature dependent values for *P* and Δ*E/R* are listed in Table 3.

12. Report

12.1 Report that the specimens were tested as directed in ASTM Test Method F2731, Procedure A or B, as appropriate.

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

12.2.1 Sample identification and lot information.

12.2.2 Number and ordering of layers in the specimen.

12.2.3 Description of each material used to make up the specimen including type of material, construction, average thickness, and average weight.

12.2.4 Number of wash/dry or dry cleaning cycles applied and specific method of laundering samples, if different than specified in this test method.

TABLE 3 Constants for Calculation of Omega Using Eq 2.

Skin Injury	Temperature Range	P	ΔE/R
Second-degree	317.15 K ≤ T ≤ 323.15 K (44°C ≤ T ≤ 50°C)	2.185×10^{124} s^{-1}	93 534.9 K
	T > 323.15 K, use: (T > 50°C)	$1.823 \times 10^{51} s^{-1}$	39 109.8 K
Third-degree	317.15 K ≤ T ≤ 323.15 K (44°C ≤ T ≤ 50°C)	4.322×10^{64} s^{-1}	50 000 K
	T > 323.15 K, use: (T > 50°C)	9.389×10^{104} s^{-1}	80 000 K

12.2.5 The type of preconditioning applied to the samples as dry, wet, or other method to be described in detail.

12.3 Report the following results for Procedure A:

12.3.1 The duration of radiant heat exposure in seconds to predict a second-degree burn injury for the protective clothing material system tested.

12.3.2 The visually observed condition of the specimen following the exposure.

12.4 Report the following results for Procedure B:

12.4.1 The radiant heat exposure time used.

12.4.2 Whether or not second-degree burn injury is predicted for each specimen.

12.4.3 The predicted time to second-degree burn injury if a second-degree burn injury is predicted.

12.4.4 The average predicted time to second-degree burn injury for all specimens tested for the specific protective clothing material system at the same test conditions. If specimens are tested using different sample preconditioning, separately calculate and report the average test results.

12.4.5 The visually observed condition of the specimen following the exposure.

13. Precision and Bias

13.1 *Intermediate Precision*—A single-operator intra-laboratory test series was performed on two different turnout composites over a span of five days to determine the methods intermediate precision using the apparatus and Procedure B described above.

13.1.1 Three commercially available turnout fabrics consisting of a thermal liner, a moisture barrier and an outer shell were used along with trim to construct the following two composites: *a*) a 20.1 oz/yd^2 three layer composite without trim, and *b*) the same 20.1 oz/yd^2 composite with 3 in. trim attached. Both composites were tested in accordance with the procedures detailed in the preceding sections. For each fabric, test specimens were selected randomly from a single quantity of homogeneous material. Each composite was tested twenty-five times over a period of five days (five tests per day). Each test result is the average of five test determinations for a total of five test results (one result per day). Because the tests were carried out over a period of five days the term "intermediate precision" is used instead of precision and refers to the repeatability of test results.

13.1.2 The results of the single operator, mutli-day, intra-laboratory precision study are shown in Table 1 for time (seconds) to second degree burn.

13.1.3 *Repeatability*—Repeatability, *r*, values are given (see Table 4) for two fabric composites representing two distinctive composite configurations, a turnout composite without trim and a turnout composite with reflective trim.

13.1.4 *Reproducibility*—The reproducibility of this test method is being determined.

13.2 *Bias*—The time to a second degree stored energy burn to a human's skin is unknown and, due to the nature of the subject, can only be predicted based on simulation through a test method. Within this limitation, this test method has no known bias.

14. Keywords

14.1 firefighters; material systems; protective clothing; radiant heat; transmitted energy; second-degree burn injury; stored energy

TABLE 4 Single Operator Apparatus, Multi-day Precision of the Test Method (Second degree burn times in seconds shown for each composite.)

Test	A (Composite without Trim)	B (Composite with Trim)
1	131.812	103.840
2	133.022	107.456
3	130.976	109.742
4	129.954	107.914
5	131.278	112.032
–	–	–
Average	131.408	108.197
s_r	1.128	3.029
$CV\%_r$	0.858	2.800
s^2 (variance)	1.272	9.177
R	3.157	8.482

APPENDIXES

(Nonmandatory Information)

X1. SKIN BURN INJURY MODEL

X1.1 The parameter used in evaluating the performance of thermal protective clothing is the severity and extent of damage predicted to occur to human skin that results from the laboratory exposure. The calculations are based on a limited number of test results reported on the behavior of human and pig skin when subjected to elevated temperatures through heating by direct contact with hot fluids and radiant sources.

X1.1.1 *Discussion*—Human skin is part of the integumentary system which consists of the skin, the subcutaneous tissue (adipose) below the skin, hair, nails and assorted glands. The skin consists of two layers. Starting from the outer surface the layers are identified as epidermis and dermis. The outer layer is relatively inert and acts as a protective layer against penetration by gases and fluids. The interface of the epidermis and dermis layers is where most of the cell growth occurs. This layer is sometimes called the basal layer. Cell growth also occurs in deeper layers. The dermis layer consists of blood vessels, connective tissue, lymph vessels, sweat glands, receptors and hair shafts.

X1.1.2 The subcutaneous layer (adipose) is not normally considered to be part of the skin. This fatty tissue is important in that it attaches the skin to underlying bone and muscle as well as supplying it with blood vessels and nerves. It also plays and important role in the thermal regulation of the internal body temperature as it acts as an insulator.

X1.1.3 If the skin layers experience elevated temperatures, such as occur with long exposure to sunlight or short exposure to high temperature fluids or flames, damage in the form of discoloration, cell destruction, or charring occur.

X1.2 Moritz and Henriques (**8**) were the first to quantify skin burn injury of pigs and humans due to heating with hot fluids. They discovered that destruction of the skin cell growing layer located at the epidermis/dermis interface in human skin begins when the temperature of the skin surface rises above 44°C (317.15 K). In a later paper, Henriques (**7**) showed that the rate of cell destruction could be modeled by a first order chemical reaction rate equation (see Eq X1.1).

X1.3 The estimation of second-degree skin burn injury used in this test method (F1930) is based on later work by Stoll and Greene (**5**), Weaver and Stoll (**6**) and Stoll and Chianta (**9**). These investigations were conducted on the forearms of human volunteers using an apparatus that would heat a small (~ 17 mm diameter) circular area using a lamp. The temperature of the surface of the skin was measured simultaneously with the heating using an optical technique. Through trial and error the investigators determined the amount of energy required to just cause a blister to form within up to 24 hours after the exposure. The presence of a blister was taken as an indication that second-degree burn injury occurred. The initial skin surface temperature was very close to 32.5°C for all tests.

X1.4 Stoll and Greene (**5**) found that destruction of the growing layer located at the epidermis/dermis interface in human skin not only begins when the temperature of this layer rises above 44°C (317.15 K), it continues as long as the temperature of the layer is above this value. This meant that the cooling phase contributes to the overall skin burn injury and needs to be included in the prediction method. Moritz and Henriques (**8**) did not consider the cooling phase in their analysis. Stoll and coworkers found that the destruction rate could be closely modeled by a first order chemical reaction rate equation as suggested by Henriques (**7**), that is:

$$d\Omega/dt = Pe^{-\Delta E/RT} \qquad (X1.1)$$

where:

Ω = quantitative measure of burn damage at the basal layer or at any depth in the dermis,
P = frequency factor, s^{-1}
e = natural exponential=2.7183,
ΔE = the activation energy for skin, J/mol
R = the universal gas constant, 8314.5J/mol • K,
T = the absolute temperature at the basal layer or at any depth in the dermis, K,
t = total time for which T is above 44°C (317.15 K)

X1.5 The total burn damage is found by integrating Equation A1 over the total time interval that the basal layer is above 44°C (317.15 K), that is, during both heating and cooling phases. This results in the following equation:

$$\Omega = \int_0^t Pe^{-\Delta E/RT} dt \qquad (X1.2)$$

X1.6 Henriques (**7**) found that if Ω is less than, or equal to 0.53 no damage will occur at the basal layer. If Ω is greater than 0.53 and less than 1.0, first-degree burns (reddening) will occur, where as if $\Omega \geq 1.0$, second-degree burns (blistering) will result. This damage criterion can be applied to any depth of skin provided the appropriate values of P and ΔE are used. For this test method a second-degree burn injury is defined as an $\Omega \geq 1.0$ at the epidermis/dermis interface or deeper, and a third-degree burn injury as an $\Omega \geq 1.0$ at the dermis/subcutaneous tissue (adipose) interface or deeper.

X1.7 Morse, Tickner, and Brown (**10**) examined the various values of P and ΔE available in the literature and suggest that the criteria developed by Weaver and Stoll (**6**) be used in the epidermal layer and that of Takata, Rouse and Stanley (**11**) be used in the dermal and subcutaneous layers (adipose). The values of P and ΔE developed by Weaver and Stoll (**6**) for the epidermis layer are:

for 44°C ≤ T ≤ 50°C	$P = 2.185 \times 10^{124}\ s^{-1}$ and $\Delta E/R$ = 93 534.9 K
for T > 50°C	P = 1.823 × 1051 s–1 and $\Delta E/R$ = 39 109.8 K

while those of Takata, Rouse and Stanley (**11**) for the dermis and deeper layers are:

for 44°C ≤ T ≤ 50°C	$P = 4.322 \times 10^{64}\ s^{-1}$ and $\Delta E/R$ = 50 000 K
for T > 50°C	$P = 9.389 \times 10^{104}\ s^{-1}$ and $\Delta E/R$ = 80 000 K

X1.8 The data used by Weaver and Stoll (**6**) to calculate the values of P and ΔE in X1.6 came from the experiments of Stoll and Greene (**5**). Only five different exposure heat fluxes were used in the experiments. This limited number of data points was extended to higher exposure heat fluxes and shorter exposure times by numerical calculation by Weaver and Stoll (**6**). This extended data set is presented in Table 2. The extended data base was used to calculate the values of P and ΔE.

X1.9 The values of P and ΔE calculated by Takata, Rouse and Stanley (**11**) were from experiments on anesthetized pigs.

X1.10 To predict the severity and extent of damage that results from a fire exposure, it is necessary to know the temperature history of the skin layers. The temperature in the skin layers is calculated using a transient, one dimensional variable property heat transfer model, subject to a set of initial conditions and the heat flux and its variation that occurs at the surface of the manikin. The thermal energy sensors fitted in the surface of the manikin are used to generate data from which the heat flux at the surface of the skin at each sensor location and its variation with time can be calculated. This information is then used to predict the temperature history of the skin and subcutaneous layers and the extent of skin damage for each sensor location. Details on how to carry out the calculations are included in a series of technical reports from the University of Alberta (**12**), (**13**), (**14**).

X1.11 *Skin Physical Properties*—The physical properties of human skin to be used in the skin heat transfer model for temperature predictions are given in Table X1.1. The values listed for in vivo (living) thicknesses of the layers come from several sources in the physiological literature. Stoll and Greene (**5**) did not measure the layer thicknesses of their human volunteers. The values of thermal conductivity and volumetric heat capacity were obtained using numerical optimization techniques to back calculate these values to meet the requirements of 11.2.2.

X1.12 The initial temperature distribution through the three layers shall have a linear temperature rise of 1°C, with the skin surface temperature set to 32.5°C. The back side of the subcutaneous (adipose) shall be fixed at 33.5°C for all time. This internal temperature gradient was measured by Pennes (**4**) in the forearms of volunteers over the same total thickness of skin and subcutaneous tissue.

X1.13 The thermal conductivity of each of the layers is known to vary with temperature due to the generalized thermo-physical characteristics of the layer components (simplified composition: water, protein and fat). Cooper and Trezek (**15**) and Knox et. al. (**16**) have developed relationships for estimating the thermo-physical properties of the skin and sub cutaneous (adipose) layers based on the percent water, protein and fat in each layer. Accounting for the variation of the thermal conductivity of the water component in each of the three layers can produce good agreement with the requirements of Table X1.2. While the composition of the tissue in the arms of the subjects in the experiments by Stoll and her coworkers is not known, back calculations to fit the measurements suggest that the following values provide a good fit.

TABLE X1.1 Physical Properties for Burn Model

Parameter	Epidermis	Dermis	Subcutaneous Tissue
Thickness of layer (m)	75×10^{-6}	1125×10^{-6}	3885×10^{-6}
Thermal conductivity, k (W/m • K)	0.6280	0.5902	0.2930
Volumetric heat capacity, Cp (J/m3 •K)	4.40×10^{6}	4.186×10^{6}	2.60×10^{6}

TABLE X1.2 Physical Properties for Variable Property Burn Model

Parameter	Epidermis	Dermis	Subcutaneous Tissue
Thickness of layer (m)	75×10^{-6}	1125×10^{-6}	3885×10^{-6}
Thermal conductivity, k (W/m • K)	0.6155	0.5976	0.3659
Volumetric heat capacity, Cp (J/m^3 • K)	4.158×10^{6}	4.017×10^{6}	2.285×10^{6}
Water fraction (% mass)	80	70	20

X2. SUBJECTIVE VISUAL EXAMINATION AND EVALUATION OF THE EXPOSED SPECIMEN

X2.1 Except for the subjective observation on ignition, the exposed specimen may be evaluated on each side of the specimen.

X2.1.1 The surface of the specimen exposed to the heat source shall be identified as the front side.

X2.1.2 The surface facing the heat sensor shall be identified as the back side.

X2.1.3 For visual examination, lay the exposed specimen parallel on a flat surface with proper illumination.

X2.2 Subjective ratings may 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.

X2.3 Rate each specimen after exposure using the following subjective terms:

X2.3.1 *Break-open:*
X2.3.1.1 No break-open.
X2.3.1.2 Break-open characteristic (size of hole)

X2.3.2 *Melting:*
X2.3.2.1 No melting observed
X2.3.2.2 Melting observed

X2.3.3 *Dripping:*
X2.3.3.1 No dripping observed
X2.3.3.2 Dripping observed

X2.3.4 *Charring:*
X2.3.4.1 1 = no charring.
X2.3.4.2 2 = slight specimen scorching/discoloration.
X2.3.4.3 3 = slight specimen charring evident.
X2.3.4.4 4 = significant specimen chars and embrittlement.
X2.3.4.5 5 = severe charring, specimen embrittles and has cracks or holes, or both.

X2.3.5 *Embrittlement:*
X2.3.5.1 1 = no embrittlement.
X2.3.5.2 2 = slight, specimen starts to harden.
X2.3.5.3 3 = moderate, small hardened areas.
X2.3.5.4 4 = significant, specimen completely embrittles.
X2.3.5.5 5 = heavy specimen embrittlement or cracks or holes, or both.

X2.3.6 *Shrinkage:*
X2.3.6.1 No shrinkage.
X2.3.6.2 % observed shrinkage.

X2.3.7 *Sticking:*
X2.3.7.1 No sticking.

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