Designation: F1930 − 17

Standard Test Method for
Evaluation of Flame Resistant Clothing for Protection Against Fire Simulations Using an Instrumented Manikin[1]

This standard is issued under the fixed designation F1930; 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 is used to provide predicted human skin burn injury for single layer garments or protective clothing ensembles mounted on a stationary upright instrumented manikin which are then exposed in a laboratory to a simulated fire environment having controlled heat flux, flame distribution, and duration. The average exposure heat flux is 84 kW/m^2 (2 cal⁄s·cm^2), with durations up to 20 s.

1.2 The visual and physical changes to the single layer garment or protective clothing ensemble are recorded to aid in understanding the overall performance of the garment or protective clothing ensemble and how the predicted human skin burn injury results can be interpreted.

1.3 The skin burn injury prediction is based on a limited number of experiments where the forearms of human subjects were exposed to elevated thermal conditions. This forearm information for skin burn injury is applied uniformly to the entire body of the manikin, except the hands and feet. The hands and feet are not included in the skin burn injury prediction.

1.4 The measurements obtained and observations noted can only apply to the particular garment(s) or ensemble(s) tested using the specified heat flux, flame distribution, and duration.

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

1.6 This method is not a fire-test-response test method.

1.7 The values stated in SI units are to be regarded as standard. The values given in parentheses are mathematical conversions to inch-pound units or other units commonly used for thermal testing. If appropriate, round the non-SI units for convenience.

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 limitations prior to use.*

1.9 Fire testing is inherently hazardous. Adequate safeguards for personnel and property shall be employed in conducting these tests.

1.10 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D123 Terminology Relating to Textiles

D1835 Specification for Liquefied Petroleum (LP) Gases

D3776/D3776M Test Methods for Mass Per Unit Area (Weight) of Fabric

D5219 Terminology Relating to Body Dimensions for Apparel Sizing

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

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

E511 Test Method for Measuring Heat Flux Using a Copper-Constantan Circular Foil, Heat-Flux Transducer

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

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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.

E2683 Test Method for Measuring Heat Flux Using Flush-Mounted Insert Temperature-Gradient Gages
F1494 Terminology Relating to Protective Clothing

2.2 *AATCC Standards:*[3]
Test Method 135 Dimensional Changes of Fabrics after Home Laundering
Test Method 158 Dimensional Changes on Dry-Cleaning in Perchloroethylene: Machine Method

2.3 *Canadian Standards:*[4]
CAN/CGSB-4.2 No. 58-M90 Textile Test Methods Colorfastness and Dimensional Change in Domestic Laundering of Textiles
CAN/CGSB-3.14 M88 Liquefied Petroleum Gas (Propane)

2.4 *NFPA Standards:*[5]
NFPA 54 National Fuel Gas Code, 2009 Edition
NFPA 58 Liquefied Petroleum Gas Code 2008 Edition
NFPA 85 Boiler and Combustion Systems Hazards Code, 2007 Edition
NFPA 86 Standard for Ovens and Furnaces, 1999 Edition

3. Terminology

3.1 For definitions of terms used in this test method, use the following documents. For terms related to textiles refer to Terminology D123, for terms related to protective clothing refer to Terminology F1494, and for terms related to body dimensions refer to Terminology D5219.

3.2 *Definitions:*

3.2.1 *burn injury, n*—thermal damage which occurs to human skin at various depths and is a function of local temperature and time.

3.2.1.1 *Discussion*—Burn injury in human tissue occurs when the tissue is heated above a critical temperature (44 °C (317.15 K) or 111 °F). Thermal burn damage to human tissue depends on the magnitude of the temperature rise above the critical value and the duration that the temperature is above the critical value. Thus, damage can occur during both the heating and cooling phases of an exposure. The degree of burn injury (second or third degree) depends on the maximum depth within the skin layers to which tissue damage occurs. The first-degree burn injury is considered minor relative to second-degree and third-degree burn injuries. It is not included in the evaluation of test specimens in this test method (see Appendix X1).

3.2.2 *fire exposure, n*—in the fire testing of clothing, the fire exposure is a propane-air diffusion flame with a controlled heat flux and spatial distribution, engulfing the manikin for a controlled duration.

3.2.2.1 *Discussion*—The flames are generated by propane jet diffusion burners. Each burner produces a reddish-orange flame with accompanying black smoke (soot).

3.2.3 *flame distribution, n*—in the fire testing of clothing, a spatial distribution of incident flames from burners to provide a controlled heat flux over the surface area of the manikin.

3.2.4 *heat flux, n*—the heat flow rate through a surface of unit area perpendicular to the direction of heat flow (kW/m^2) (cal/s·cm^2).

3.2.4.1 *Discussion*—Two different heat fluxes are referred to in this test method: incident and absorbed. The incident heat flux refers to the energy striking the nude manikin, or the exterior of the test specimen when mounted on the manikin, during flame engulfment. The absorbed heat flux refers to only the portion of the incident heat flux which is absorbed by each thermal energy sensor based on its absorption characteristics. The incident heat flux is used in setting the required exposure conditions while the absorbed heat flux is used in calculating the predicted skin burn injury.

3.2.5 *instrumented manikin, n*—in the fire testing of clothing, a structure designed and constructed to represent an adult-size human and which is fitted with thermal energy (heat flux) sensors at its surface.

3.2.5.1 *Discussion*—The manikin is fabricated to specified dimensions from a high temperature-resistant material (see 6.1). The instrumented manikin used in fire testing of clothing is fitted with at least 100 thermal energy sensors, distributed over the manikin surface. The feet and hands are not normally fitted with sensors. If the feet and hands are equipped with sensors, it is up to the user to define a procedure to interpret the results.

3.2.6 *predicted second-degree burn injury, n*—a calculated second-degree burn injury to skin based on measurements made with a thermal energy sensor.

3.2.6.1 *Discussion*—For the purposes of this standard, predicted second-degree burn injury is defined by the burn injury model parameters (see Section 12 and Appendix X1). Some laboratories have unequally spaced sensors and assign an area to each sensor over which the same burn injury prediction is assumed to occur; others, with equally spaced sensors, have equal areas for each sensor.

3.2.7 *predicted third-degree burn injury, n*—a calculated third-degree burn injury to skin based on measurements made with a thermal energy sensor.

3.2.7.1 *Discussion*—For the purposes of this standard, predicted third-degree burn injury is defined by the burn injury model parameters (see Section 12 and Appendix X1). Some laboratories have unequally spaced sensors and assign an area to each sensor over which the same burn injury prediction is assumed to occur; others, with equally spaced sensors, have equal areas for each sensor.

3.2.8 *predicted total burn injury, n*—in the fire testing of clothing, the manikin surface area represented by all thermal energy sensors registering a predicted second-degree or predicted third-degree burn injury, expressed as a percentage (see 13.5).

3.2.9 *second-degree burn injury, n*—complete necrosis (living cell death) of the epidermis skin layer (see Appendix X1).

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[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 Standards Council of Canada, Suite 1200, 45 O'Conor St., Ottawa, Ontario, K1P 6N7.

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

3.2.10 *thermal energy sensor, n*—a device which produces an output suitable for calculating incident and absorbed heat fluxes.

3.2.10.1 *Discussion*—Types of sensors which have been used successfully include slug calorimeters, surface and buried temperature measurements, and circular foil heat flux gauges. Some types of sensors approximate the thermal inertia of human skin and some do not. The known sensors in current use have relatively small detection areas. An assumption is made for the purposes of this method that thermal energy measured in these small areas can be extrapolated to larger surrounding surface areas so that the overall manikin surface can be approximated by a minimum number of sensors. The resulting sensor-predicted burn injury applies to the extrapolated coverage area. Some laboratories assign different coverage areas to each sensor over which the same burn injury prediction is assumed to apply; others, with equally spaced sensors, have equal areas for each sensor (see 6.2.2.1).

3.2.11 *thermal protection, n*—the property that characterizes the overall performance of a garment or protective clothing ensemble relative to how it retards thermal energy that is sufficient to cause a predicted second-degree or predicted third-degree burn injury.

3.2.11.1 *Discussion*—Thermal protection of a garment or ensemble and the consequential predicted burn injury (second-degree and third-degree), is quantified from the response of the thermal energy sensors and use of a skin burn injury prediction model. In addition to the calculated results, the physical response and degradation of the garment or protective clothing ensemble is an observable phenomenon useful in understanding garment or protective clothing ensemble thermal protection.

3.2.12 *third-degree burn injury, n*—complete necrosis (living cell death) of the epidermis and dermis skin layers (see Appendix X1).

4. Summary of Test Method

4.1 This test method covers quantitative measurements and subjective observations that characterize the performance of single layer garments or protective clothing ensembles mounted on a stationary upright instrumented manikin. The conditioned test specimen is placed on the instrumented manikin at ambient atmospheric conditions and exposed to a propane-air diffusion flame with controlled heat flux, flame distribution, and duration. The average incident heat flux is 84 kW/m^2 (2 cal/s·cm^2) with durations up to 20 s.

4.2 The test procedure, data acquisition, calculation of results, and preparation of parts of the test report are performed with computer hardware and software programs. The complexity of the test method requires a high degree of technical expertise in the test setup and operation of the instrumented manikin and the associated data collection and analysis software.

4.3 Thermal energy transferred through and from the test specimen during and after the exposure is measured by thermal energy sensors located at the surface of the manikin. A computer-based data acquisition system is used to store the time varying output from the sensors over a preset time interval.

4.4 Computer software uses the stored data to calculate the incident heat flux and the absorbed heat flux and their variation with time for each sensor. The calculated absorbed heat flux and its variation with time is used to calculate the temperature within human skin and subcutaneous layers (adipose) as a function of time. The temperature history within the skin and subcutaneous layers (adipose) is used to predict the onset and severity of human skin burn injury. The computer software calculates the predicted second-degree and predicted third-degree burn injury and the total predicted burn injury resulting from the exposure.

4.5 The overall percentage of predicted second-degree, predicted third-degree, and predicted total burn injury is calculated by dividing the total number of sensors indicating each of these conditions by the total number of sensors on the manikin. Alternately, the overall percentages are calculated using sensor area weighted techniques for facilities with nonuniform sensor coverage. A reporting is also made of the above conditions where the areas that are not covered by the test specimen are excluded (see 13.5.1 and 13.5.2). This test method does not include the ~12 % of body surface area represented by the unsensored manikin feet and hands. No corrections are applied for their exclusion.

4.6 The visual and physical changes to the test specimen are recorded to aid in understanding overall performance and how the resulting burn injury results can be interpreted.

4.7 Identification of the test specimen, test conditions, comments and remarks about the test purpose, and response of the test specimen to the exposure are recorded and are included as part of the report.

4.8 The performance of the test specimen is indicated by the calculated burn injury area, expressed as a percentage, and subjective observations of material response to the test exposure.

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

5. Significance and Use

5.1 Use this test method to measure the thermal protection provided by different materials, garments, clothing ensembles, and systems when exposed to a specified fire (see 3.2.2, 3.2.3, 4.1, and 10.4).

5.1.1 This test method does not simulate high radiant exposures, for example, those found in electric arc flash exposures, some types of fire exposures where liquid or solid fuels are involved, nor exposure to nuclear explosions.

5.2 This test method provides a measurement of garment and clothing ensemble performance on a stationary upright manikin of specified dimensions. This test method is used to provide predicted skin burn injury for a specific garment or protective clothing ensemble when exposed to a laboratory simulation of a fire. It does not establish a pass/fail for material performance.

5.2.1 This test method is not intended to be a quality assurance test. The results do not constitute a material's performance specification.

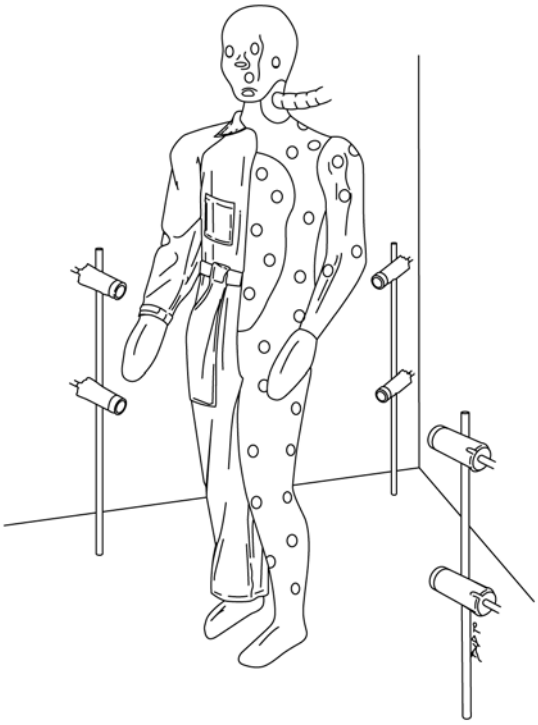
5.2.2 The effects of body position and movement are not addressed in this test method.

5.3 The measurement of the thermal protection provided by clothing is complex and dependent on the apparatus and techniques used. It is not practical in a test method of this scope to establish details sufficient to cover all contingencies. Departures from the instructions in this test method have the potential to lead to significantly different test results. Technical knowledge concerning the theory of heat transfer and testing practices is needed to evaluate if, and which departures from the instructions given in this test method are significant. Standardization of the test method reduces, but does not eliminate, the need for such technical knowledge. Report any departures along with the results.

6. Apparatus

6.1 *Instrumented Manikin*—An upright manikin with specified dimensions that represents an adult human form shall be used (see Fig. 1).

6.1.1 *Size and Shape*—The manikin shall be constructed with a head, neck, chest/back, abdomen/buttocks, arms, hands, legs, and feet. The manikin's dimensions shall correspond to those required for standard sizes of garments because deviations in fit will affect the results. A male manikin consisting of the sizes given in Table 1 has been found satisfactory to evaluate garments or protective ensembles. The sizes for a female manikin have not yet been set.



NOTE 1—Only six of eight burners are shown.

FIG. 1 Schematic of Instrumented Manikin and Burner Placement

6.1.2 The manikin shall be constructed of flame-resistant, thermally stable, nonmetallic materials which will not contribute fuel to the combustion process. A flame-resistant, thermally stable, glass fiber reinforced vinyl ester resin at least 3 mm (⅛ in.) thick has proven effective.

6.2 *Apparatus for Burn Injury Assessment:*

6.2.1 *Thermal Energy Sensors*—Each sensor shall have the capacity to measure the incident heat flux over a range from 0.0 to 165 kW/m^2 (0.0 to 4.0 cal/s·cm^2). This range permits the use of the sensors to set the exposure level by directly exposing the instrumented manikin to the controlled fire in a test without the test specimen and also have the capability to measure the heat transfer to the manikin when covered with a test specimen.

6.2.1.1 The sensors shall be constructed of a material with known thermal and physical characteristics that shall be used to indicate the time-varying heat flux received by the sensors. Types of sensors which have been used successfully include slug calorimeters, surface and buried temperature measurements, and circular foil heat flux gauges. Some types of sensors approximate the thermal inertia of human skin and some do not. The minimum response time for the sensors shall be <0.2 s.

(1) Discussion—Refer to Test Methods E457, E511, and E2683 for technical information on the different types of sensors.

6.2.1.2 The sensor surface shall have an absorptivity of at least 0.9. Coating the sensor with a thin layer of flat black high temperature paint with an absorptivity of at least 0.9[6] has been found effective.

6.2.2 *Manikin Thermal Energy Sensor Layout*—A minimum of 100 thermal energy sensors shall be used. The percentage distribution is given in Table 2. They shall be distributed as uniformly as possible within each area on the manikin.

6.2.2.1 *Discussion*—It is acceptable to have the sensor layout as one of uniform spacing or of nonuniform spacing. With uniform spacing each sensor is located in the center of an area, the areas being of uniform size over the surface of the manikin. The nonuniform spacing results in sensors being located in the center of an area, but the areas are not uniform over the surface of the manikin. With the nonuniform spacing, laboratories shall report area weighted values of predicted second-degree, predicted third-degree, and predicted total burn injury and the percentages as required in 13.5. Laboratories shall state the basis on which the calculations are made.

6.3 *Apparatus for Calibration of the Thermal Energy Sensors:*

6.3.1 *Energy Sources*—Pure radiant or a combination convective-radiant energy source has been found effective for these calibrations.

6.3.1.1 *Discussion*—Understanding the interaction between the energy source and the thermal energy sensor is critical to obtaining accurate calibrations. If the temperature of either the

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[6] Krylon # 1618 BBQ and Stove, Krylon #1316 Sandable Primer, and Krylon #1614 High Heat and Radiator paint have been found to be effective. See ASTM Study "Evaluation of Black Paint and Calorimeters used for Electric Arc Testing," ASTM contract #F18-103601, Kinectrics Report:8046-003-RC-0001-R00, August 22, 2000.

TABLE 1 Measurements for Male Manikin

Measurement Location	Centimetres	Inches
Height	180.3 ± 1.3	71 ± 0.5
Chest circumference at largest value (chest girth)	102.9 ± 1.9	40.5 ± 0.75
Center of base of rear neck to wrist measured across shoulder and along outside of arm (cervicale to wrist length)	79.4 ± 2.5	31.25 ± 1.0
Top of shoulder to wrist along arm (arm length).	61 ± 2.5	24 ± 1.0
Arm circumference at largest diameter between shoulder and elbow (upper-arm girth)	30.5 ± 0.6	12 ± 0.25
Waist circumference at narrowest position (waist girth)	85 ± 1.3	33.5 ± 0.5
Crotch to heel along the inside of the leg (crotch height minus ankle height)	86.4 ± 2.5	34 ± 1.0
Hips circumference at the largest dimension (hip girth)	101.6 ± 1.9	40 ± 0.75
Base of center of rear neck to waist (center back waist length)	42.5 ± 1.9	16.75 ± 0.75
Waist to base of heel (waist height)	115.6 ± 5.0	45.5 ± 2.0
Thigh circumference at largest dimension between crotch and knee (thigh girth)	58.4 ± 1.3	23 ± 0.5

TABLE 2 Percentage Area of Male Manikin Form Represented by Sensors

Body Area	Percent
Head	7
Trunk[A]	40
Arms	16
Thighs	22
Lower legs/Shanks	15
Hands/Feet	0
Total	100

[A] The trunk of the body includes the back, buttocks, chest, and pelvic areas.

source or the sensor changes during calibration, this will affect the energy transfer to the sensor and the resulting calibration.

6.3.2 *Calibration Heat Flux Sensor*—A traceable heat flux measuring device[7] used to confirm the output of the energy source used to calibrate the thermal energy sensors over a range of heat fluxes.

6.3.2.1 *Discussion*—Understanding the interaction between the energy source and the calibration heat flux sensor is critical to obtaining accurate calibrations. Different calibration heat flux sensor designs respond differently to different modes of heat transfer. For example, a thin foil or Gardon heat flux gauge responds well to pure radiant heat transfer, but not convection heat transfer. Schmidt-Boelter gauges respond well to both modes of heat transfer.

6.3.3 The calibrations determined in 10.2 for each thermal energy sensor shall be recorded and the most recent calibration results used to carry out the burn injury analysis.

6.4 *Data Acquisition Hardware*—A system shall be provided with the capability of acquiring and storing the results of the measurement from each sensor at least five times per second for the data acquisition period.

6.4.1 *Discussion*—The data acquisition rate of five readings per second from each sensor is the minimum necessary to obtain adequate data. Higher sampling rates are desirable during the flame exposure period. Laboratories sample up to ten samples per sensor during this period. The minimum rate of five samples per second per sensor is adequate after the flame exposure. The accuracy of the measurement system shall be less than 2 % of the reading or ±1.0 °C (±1.8 °F) for temperature measurements.

6.5 *Software Programs:*

6.5.1 *Logging of Recorded Data*—The software shall log the output from the thermal energy sensors in identifiable files for the preset time at or above the minimum specified data acquisition rate.

6.5.2 *Heat Flux Calculations*—The software shall convert the recorded thermal sensor outputs into a measured heat flux using a method appropriate for the thermal energy sensor design. This shall include accounting for the heat losses from the surface and sides of the sensor as appropriate.

6.5.2.1 *Incident Heat Flux*—The incident heat flux at each sample point for each thermal energy sensor shall be calculated using the calibration characteristics determined in 10.2. These values shall be stored for use in calculating the average incident heat flux and its standard deviation for nude exposures as required in 10.4.

6.5.2.2 *Absorbed Heat Flux*—Using the absorption characteristics of the thermal energy sensors, calculate and store the absorbed heat flux for each sensor for each sample point.

6.5.3 *Burn Injury Calculations*—The computer software program used shall have the capability of using the calculated time-dependent absorbed heat flux files to calculate the temperatures within the skin and subcutaneous layers (adipose) as a function of depth and time, and calculating the time when a predicted second-degree or third-degree burn injury will occur for each sensor utilizing a skin burn injury model. The total predicted burn injury and the percentage predicted burn injury shall be calculated using only the sensors having a calculated second-degree and third-degree burn injury. The calculation requirements of this program are identified in Section 12.

6.5.3.1 *Discussion*—The computer software program shall, as a minimum, calculate the predicted skin burn injury at the epidermis/dermis interface and the dermis/subcutaneous (adipose) interface (see Section 12 and Appendix X1).

6.5.4 *Burn Injury Assessment*—The area-weighted sum of the sensors that received sufficient energy to result in a predicted second-degree burn shall be the predicted second-degree burn assessment. The area-weighted sum of the sensors that received sufficient energy to result in a predicted third-degree burn shall be the predicted third-degree burn assessment. The area-weighted sum of all sensors registering a second-degree or third-degree burn injury shall be the total predicted burn injury resulting from the exposure to the fire condition.

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[7] National Institute of Standards and Technology (NIST) or similar standards body.

6.5.4.1 *Discussion*—The calculated results report the burn injury assessment as a percentage (%) based on the total number of sensors (entire manikin) and the total covered by the test specimen only (see 13.5). For manikin systems that do not have a uniformly spaced sensor layout, the laboratory shall area weight the results.

6.5.5 *Additional Computer Software Requirements*—In addition to monitoring and controlling the operation of the fire, data acquisition systems, and carrying out the incident heat flux, absorbed heat flux, and skin burn injury calculations, the computer software shall be used to prepare some of the materials for the report, sensors calibrations, etc. Appendix X2 is a list of recommended safety, control, data acquisition, calculation, report preparation, and supporting programs.

6.6 *Exposure Chamber*—A ventilated, fire-resistant enclosure with viewing windows and access door(s) shall be provided to contain the manikin and exposure apparatus.

6.6.1 *Exposure Chamber Size*—The chamber size shall be sufficient to provide a uniform flame engulfment of the manikin and shall have sufficient space to allow safe movement around the manikin for dressing without accidentally jarring and displacing the burners. The minimum interior dimensions of the chamber shall be 2.1 by 2.1 by 2.4 m (7.0 by 7.0 by 8.0 ft). There is no maximum chamber size, but all chambers and burner systems shall meet the requirements in 4.1 and 10.4 in repeated exposures.

6.6.1.1 *Discussion*—There is no limitation on maximum size provided the operators are safely isolated from the chamber during and after the exposure when combustion products and toxic gases are likely to be present.

6.6.2 *Burner and Manikin Alignment*—Apparatus and procedures for checking the alignment of the burners and manikin position prior to each test shall be available.

6.6.3 *Chamber Temperature*—The chamber temperature prior to a test shall be between 15 and 30 °C (58 and 85 °F).

6.6.4 *Chamber Air Flow*—The chamber shall be isolated from air movement other than the natural air flow required for the combustion process so that the pilot flames, if fitted, and the exposure flames are not affected before and during the test exposure. The isolation from air movement shall continue during the data acquisition period after the exposure flames are extinguished. A forced-air exhaust system for rapid removal of combustion products after the data acquisition period shall be provided.

6.6.4.1 *Discussion*—The unaided air flow within the chamber shall be sufficient to permit the combustion process needed for the required heat flux during the exposure period and shall be controlled to provide a quiet atmosphere for the data acquisition period. Openings to the exterior of the test chamber shall be provided for the passive supply of adequate amounts of air for safe combustion of the fuel during the exposure. The forced air exhaust system for rapid removal of combustion products after the data acquisition period shall conform to NFPA 86 (1999), Section 5–4.1.2. Due to their nature, the products of combustion from diffusion flames contain toxic materials such as unburned fuel, carbon monoxide, and soot.

6.6.5 *Chamber Safety Devices*—The exposure chamber shall be equipped with sufficient safety devices, detectors, and suppression systems to provide safe operation of the test apparatus. Examples of these safety devices, detectors, and suppression systems include propane gas detectors, motion detectors, door closure detectors, hand-held fire extinguishers, and any other devices necessary to meet the requirements of local codes. A water deluge system and an interlocked "LEL/Exhaust" system have been found effective. LEL is the Lower Explosion Limit. For pure propane gas in air, the value is 2.1 % by volume (**1**).[8]

6.6.5.1 Additional information on safety devices is available from NFPA 54 and NFPA 85 or equivalent local standards.

6.7 *Fuel and Delivery System*—The chamber shall be equipped with fuel supply, delivery, and burner systems to provide reproducible fire exposures.

6.7.1 *Fuel*—The propane fuel used in the system shall be from a liquefied petroleum (LP) gas supply with sufficient purity and constancy to provide a uniform exposure.

6.7.1.1 *Discussion*—Fuels meeting the HD-5 specifications (See Specification D1835, CAN/CGSB 3.14 M88, or equivalent) have been found satisfactory. Liquefied petroleum (LP) gas is commonly referred to as propane fuel or propane gas. Propane gas are the words used in this standard to identify the LP gas.

6.7.2 *Delivery System*—A system of piping, pressure regulators, valves, and pressure sensors including a double block and bleed burner management scheme (see NFPA 58) or similar system consistent with local codes shall be provided to safely deliver gaseous propane to the ignition system and exposure burners. This delivery system shall be sufficient to provide an average heat flux of at least 84 kW/m^2 (2.0 cal/s·cm^2) for an exposure time of at least 8 s. Fuel delivery shall be controlled to provide known exposure duration within ±0.1 s of the set exposure time.

6.7.3 *Burner System*—The burner system shall consist of one ignition system for each exposure burner, and sufficient burners to provide the required range of heat fluxes with a flame distribution uniformity to meet the requirements in 10.4, 10.4.1, 10.4.2, and 10.4.3.

6.7.3.1 *Exposure Burners*—Large, induced combustion air, industrial style propane burners are positioned around the manikin to produce a uniform laboratory simulation of a fire. These burners produce a large fuel-rich, reddish-yellow flame. If necessary, enlarge the burner gas jet, or remove it, to yield a fuel-to-air mixture for a long luminous reddish-yellow flame that engulfs the manikin. A minimum of eight burners shall be used and positioned to yield the exposure level and uniformity as described in 10.4, 10.4.1, 10.4.2, and 10.4.3. A satisfactory exposure has been achieved with eight burners, one positioned at each quadrant of the manikin at the knee level, and one positioned at each quadrant at the upper thigh level (see Fig. 1). Variations in exposure chamber size and air flow detail might require use of additional burners to achieve the desired flame distribution. Some laboratories have found it necessary to use twelve burners with two each on six stands positioned at

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

approximately 60° intervals around the manikin to achieve the desired flame distribution.

6.7.3.2 *Ignition System*—Each exposure burner shall be equipped with a remotely operated ignition system positioned near the exit of the burner, but not in the direct path of the flames so as to interfere with the exposure flame pattern. The ignition system shall be interlocked to the burner gas supply valves to prevent premature or erroneous opening of these valves. Any electrical magnetic field generated by the ignition system shall be small enough so as not to interfere with the quality of the data acquisition and recording process. Standing pilot flames have been found to perform satisfactorily.

6.8 *Image Recording System*—A video system for recording a visual image of the manikin before, during, and after the flame exposure shall be provided. The front of the manikin shall be the primary record of the burn exposure, with a manikin rear record optional.

6.9 *Safety Check List*—A check list shall be included in the computer operating program to ensure that all safety features have been satisfied before the flame exposure can occur. This list shall include, but is not limited to, the following: confirm that the manikin has been properly dressed in the test specimen; confirm that no person is in the burn chamber; confirm that the chamber doors are closed and all safety requirements are met. The procedural safety checks shall be documented.

6.10 *Test Specimen Conditioning Area*—The area shall be maintained at 21 ± 2 °C (70 ± 5 °F) and 65 ± 5 % relative humidity. It shall be large enough to have good air circulation around the test specimens during conditioning.

6.10.1 *Discussion*—The permitted variation in the conditioning temperature and relative humidity is larger than other ASTM textile testing standards. This larger range was set to reflect present practice. Some manikin-fire laboratories are at isolated sites and do not have conditioning rooms that can meet the more stringent requirements.

7. Hazards

7.1 Procedural operating instructions shall be provided by the testing laboratory and strictly followed to ensure safe testing. These instructions shall include, but are not limited to; exhaust of the chamber prior to any test series; no personnel within the chamber when the ignition system is checked and activated; isolation of the chamber during the test to contain the combustion process and the resulting combustion products; ventilation of the chamber after the test exposure.

7.2 The exposure chamber shall be equipped with an approved fire suppression system.

7.3 Care shall be taken to prevent personnel contact with combustion products, smoke, and fumes resulting from the flame exposure. Exposure to gaseous products shall be prevented by adequate ventilation of the chamber. Appropriate personal protective equipment shall be worn when working in the exposure chamber, handling the exposed garments, and cleaning the manikin after the test exposure.

8. Types of Tests, Test Specimens, and Sampling

8.1 *Type of Tests*—This test method is useful for three types of evaluations: comparison of the materials of garment construction, garment design, and end-use garment specification. Each type of appraisal has different garment type and style requirements.

8.1.1 *Materials of Garment Construction Evaluation*—This evaluation requires garments of the standard garment design (see 8.2.1) and size (Table 3), constructed with the different materials.

8.1.2 *Garment Design Evaluation*—This evaluation requires garments constructed of the same material, of the standard size (Table 3), and with the different design characteristics of interest.

8.1.3 *End-Use Garment Specification*—This specification requires garments of the standard size (Table 3), constructed with the material and design representing the anticipated end-use.

8.2 *Test Specimen*—A specimen is a garment (for example, a single layer coverall) or protective clothing ensemble.

8.2.1 *Discussion*—Garment or ensemble fit on the manikin (the amount of ease) can be an important issue, especially for lightweight specimens. Increasing the ease adds to the thickness of the insulating layer of air between the garment and the manikin surface. Experiments suggest that for a single-layer coverall, increasing the coverall by one size above the nominal value for the manikin reduces the skin burn injury prediction by about 5 %. When using a manikin with the dimensions given in Table 1, size 42R coveralls (Table 3) have been found satisfactory.

8.2.2 *Standard Garment Design*—The standard garment shall be a long-sleeved coverall, with a full-length metal slide fastener in the front and without pockets or pant cuffs. A full-length fabric cover on the interior of the slide fastener shall be provided to cover the slide fastener, and slide fastener tape to prevent direct contact of the slide fastener with any manikin sensors. The garment seams shall be sewn with nonmelting, noncombustible thread. The test specimens shall meet the size requirements of Table 3. Use the digitized pattern available from ASTM headquarters to create a more reproducible standard garment consistent with the dimensions in Table 3.

8.2.2.1 The standard garment shall have a 150 by 150 mm (6 by 6 in.) swatch attached inside to a seam. This swatch shall be used for measuring the area density using Option C of Test Methods D3776/D3776M. The swatch shall be cut from the same lot of material used to make the outer layer of the test specimen.

TABLE 3 Standard Coverall Size Requirements

Measurement Location	Centimetres	Inches
Chest	125 ± 4.0	49.0 ± 1.5
Waist	105 ± 2.5	41.5 ± 1.0
Sleeve	86 ± 2.5	34.0 ± 1.0
Trunk	190 ± 5.0	74.75 ± 2.0
Inseam	72 ± 2.5	28.5 ± 1.0
Seat	130 ± 4.0	51.0 ± 1.5
Thigh	79 ± 2.5	31.0 ± 1.0

8.2.3 Garment styles that deviate from the type or dimensions outlined in Table 3 can be used, but shall be described in detail in the test report (see 8.2.1).

8.3 *Laboratory Sample*—Garments or ensembles meeting the purpose of the evaluation requirements of 8.1.1, 8.1.2, or 8.1.3 shall be the laboratory sampling unit.

8.3.1 Test a minimum of three specimens from the laboratory sampling unit. A greater number of specimens can be used to improve precision of test results.

9. Preparation of Test Specimen and Cutting Samples for Area Density Measurements

9.1 *Laundering*—Launder each garment one wash and dry cycle prior to conditioning unless designated not to be laundered.

9.1.1 For garments that are designated on the flame resistant garment label to be washed, use the AATCC or CAN/CGSB procedure identified in 9.1.4.

9.1.2 For garments that are designated on the flame resistant garment label to be dry cleaned, use the AATCC procedure identified in 9.1.5.

9.1.3 For garments that are designated on the flame resistant garment label to be either washed or dry cleaned, specimens shall be tested after one cycle of washing and drying as specified in 9.1.4, or after one cycle of dry cleaning as specified in 9.1.5.

9.1.4 Use laundry conditions of AATCC Test Method 135, (1, V, A, iii) or CAN/CGSB-4.2 No. 58-M90.

9.1.5 Use dry cleaning procedures of Sections 9.2 and 9.3 of AATCC Test Method 158.

9.2 *Conditioning*—Condition each specimen for at least 24 h in an environment controlled to 21 ± 2 °C (70 ± 5 °F) and 65 ± 5 % relative humidity (see 6.10 and 6.10.1). Each specimen shall be tested within 30 min of removal from the conditioning area. If the specimen cannot be tested within 30 min, seal it in a manner that restricts moisture loss or gain until immediately prior to testing. Test such garments within 20 min after removal from the bag. Garments shall not remain isolated for longer than 4 h prior to testing.

9.3 Standard garments come with an attached swatch from which samples shall be taken for making area density measurements (8.2.2.1). With nonstandard garments, cut samples for area density measurements from behind pockets or inside collars before exposure on the manikin. **Warning—**Cut samples only from locations that are not directly over a sensor.

10. Calibration and Preparation of Apparatus

10.1 *Calibration Principles*—The thermal energy sensors and the burn injury calculation routine are calibrated using energy sources of known characteristics. Pure radiant and combined convection and radiation sources have been found effective. A traceable calibration heat flux sensor shall be used when setting the energy levels for these calibrations. Sensor calibrations shall be completed before the required flame exposure conditions for specimen testing are set.

10.1.1 Thermal energy sensors are used to measure the fire exposure intensity and the thermal energy transferred to, and absorbed by, the manikin during a nude exposure and during specimen testing. Calibrate each sensor against a suitable NIST (or other recognized standards body) traceable reference (6.3.2). Calibrate to the exposure and heat transfer conditions experienced during nude test setup and during specimen testing, typically over a range of 3 to 100 kW/m^2 (0.07 to 2.5 cal⁄s·cm^2).

10.2 *Calibration of Thermal Energy Sensor*—Using the calibration energy source, generate a calibration curve for each thermal energy sensor by exposing the sensor over the range of 3 to 100 kW/m^2 (0.07 to 2.5 cal/s·cm^2). It is recommended that a minimum of two different heat flux levels be used for this calibration, one representative of nude exposure conditions and the other representative of conditions under a test specimen. Measure the heat fluxes produced by the calibration energy source with the calibration heat flux sensor (6.3.2).

10.2.1 Check the response of the thermal energy sensor to the different exposure energies. The ideal response is linear. If the response is linear but not within 5 % of the known calibration exposure heat flux, include a correction factor in the heat flux calculations. If the response is not linear, and not within 5 % of the known calibration exposure heat flux, determine a correction factor curve for each sensor for use in the heat flux calculations.

10.2.2 Calibrate each sensor prior to startup of a new manikin, whenever a sensor is repaired or replaced, and whenever the results appear to have shifted or to differ from the expected values.

10.3 *Confirmation of Burn Injury Prediction*—In addition to individual sensor calibration, check the thermal energy sensor—data acquisition—burn injury prediction model as a unit. Expose a randomly selected sensor to a known constant heat flux with a duration which will result in a second-degree burn injury being calculated by the manikin burn injury computer program that meets the requirements in Section 12. Table 4 lists a range of absorbed heat fluxes and durations to be used and the required agreement. Use any exposure conditions that will result in absorbed energies within the range listed, accounting for sensor surface heat absorption characteristics (for example, absorptivity). Precise matching to a heat flux is not required. If interpolation is required, account for the highly nonlinear behavior of the relationship, or calculate the exposure duration using the manikin burn injury prediction computer code. If the calibration falls outside the recommended values in Table 4, identify the reason and correct.

TABLE 4 Manikin Sensor – Burn Injury Prediction – *In situ* Calibration Parameters

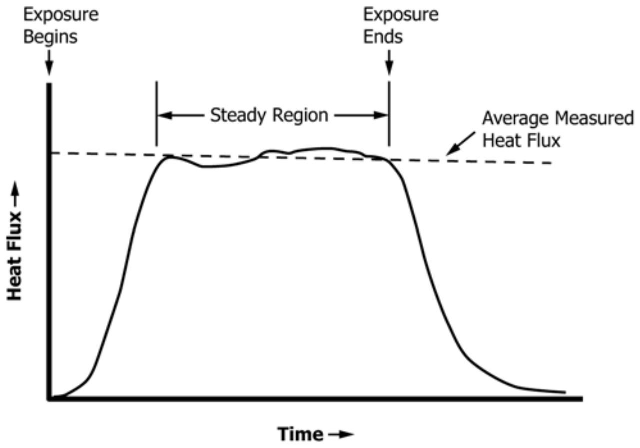
Absorbed Heat Flux – W ⁄m^2	Absorbed Heat Flux – cal ⁄s•cm^2	Recommended Minimum Continuous Heating Time – Sec	Range of Values of Required Times for Omega Equal to 1.0
4000	0.096	40	33.0 – 34.1
6000	0.143	25	19.4 – 20.0
8000	0.191	20	13.2 – 13.7
10 000	0.239	15	9.7 – 10.0
12 000	0.287	10	7.5 – 7.8
14 000	0.335	10	6.0 – 6.2
16 000	0.382	10	4.9 – 5.1

10.3.1 *Discussion*—The parameters in Table 4 cover the range of absorbed heat fluxes used by Stoll and Greene (**2**) in their experiments. The time values listed in Table 4 do not match the average values determined in the experiments conducted by Stoll and Greene that are presented in Section 12. Stoll and Greene used constant intensity fixed duration exposures that resulted in the injury occurring some time after the exposure was terminated as the skin layers cooled. It is the total time that the growing cells are above 44 °C that is important in producing cell damage and blistering of the skin (second degree burn injury). Here the heating is continuous to the end point. With continuous heating the onset of a second degree burn injury will occur at a time later than the exposure time used by Stoll and Greene because no cool down period is included and the final omega value will be greater than 1.0.

10.4 *Setting the Incident Heat Flux*—Using the procedure described in Section 11, expose the nude manikin to the test fire for 4 s or for the test duration if less than 4 s. Confirm that the average calculated incident heat flux is 84 kW⁄m^2 ± 5 % and its standard deviation is not greater than 21 kW⁄m^2 (0.5 cal⁄s·cm^2) using the procedure in 10.4.2. If the calculated average heat flux or standard deviation is not within these specifications, determine the cause and correct before proceeding with specimen testing. The calculated average is the average exposure heat flux level for the test conditions, and the standard deviation is a measure of the exposure uniformity.

10.4.1 *Discussion*—Exposing a nude manikin for more than 4 s will result in surface temperatures high enough to cause deterioration of the shell of the manikin and some sensor designs.

10.4.2 The average value of all sensors shall be determined, taking into account the sensor calibrations and characteristics. The average heat flux value reported is the average of the averages for each of the sensors for the steady region of the exposure duration (see Fig. 2). The incident heat flux values calculated for each sensor at each time step shall be placed in a file for future use in estimating the temperature history within the skin and subcutaneous layers (adipose) for the burn injury calculation.



(Exposure begins – Burner gas valve opens)
(Exposure ends – Burner gas valve closes)

FIG. 2 Average Heat Flux Determination for a Nude Exposure

10.4.3 *Confirmation of Heat Flux Distribution*—The burners shall be positioned so that the average incident heat flux calculated for the back and buttocks area, chest and pelvic area, arms, thighs and shanks (lower legs) is each within ±15 % of the average incident heat flux required in 4.1 or 10.4.

10.4.4 Expose the nude manikin to the flames before testing a set of specimens and repeat the nude exposure at the conclusion of the testing of the set. If the average exposure heat flux for the test conditions differs by more than 5 % between the before and after measurements, report this and give consideration to repeating the sequence of specimen tests. As a minimum, check the nude manikin exposure level at the beginning and at the end of the work day as required in 13.4.1. A control charting method shall be used (see Annex A1).

10.4.5 *Confirmation of Steady Fuel Flow*—Providing a steady fuel delivery rate during the testing is essential for maintaining the required heat flux. The fuel flow rate can be monitored directly by using an appropriate flow meter such as a turbine meter or indirectly by monitoring fuel pressure. With any fire exposure longer than 4 s, ensure that the fuel flow rate does not fall by more than 10 % during the exposure.

10.4.6 *Measurement of the Exposure Duration*—The duration of the fire exposure shall be controlled by the internal clock of the computer control system. The measured duration of the exposure (Fig. 2) shall be the specified value ±0.1 s or ±5 %, whichever is smaller.

10.4.7 The average heat flux calculated in 10.4.2 shall be the specified test condition ±5 %. If not, adjust the fuel flow rate by modifying the gas pressure or flow at the burner heads. Repeat the calibration run(s) until the specified value is obtained. Repeat nude calibrations shall only be conducted when the average temperature of all sensors is less than 34 °C (93 °F) and no single sensor temperature exceeds 38 °C (100 °F) in order to eliminate the effect of any elevated internal temperature or temperature gradients on the calculation of the heat flux.

10.4.7.1 *Discussion*—Depending on the sensor design, it is possible that internal temperature gradients are present when this criterion is met. Individual laboratories shall have a thorough understanding of their sensors' characteristics and how elevated internal temperatures affect results.

10.5 *Defective Sensor Replacement*—Damaged or inoperative sensors shall be repaired or replaced when % or more of the total number of thermal energy sensors no longer function properly and the nonfunctional thermal energy sensors are located under the test specimen. Repaired or replaced sensors shall be calibrated.

10.6 *Laboratory Precision Analysis*—It is recommended that each laboratory determine the precision and bias of its equipment and test procedure. One laboratory found testing 30 identical garments under the same test exposure conditions to be effective. Report the laboratory precision with test results.

11. Procedure

11.1 *Preparation of Apparatus*—Exposing the instrumented manikin to the short duration fire in a safe manner and evaluating the test specimen requires a startup and exposure sequence that is specific to the test apparatus. Some of the steps listed require manual execution; others are initiated by the computer program, depending upon the individual apparatus. Perform the steps as specified in the apparatus operating procedure. Some of the steps that shall be included are:

11.1.1 *Burn Chamber Purging*—Ventilate the chamber or a period of time sufficient to remove a volume of air at least ten times the volume of the chamber. The degree of ventilating the chamber shall at a minimum comply with NFPA 86. This purge is intended to remove any fuel that would form an explosive atmosphere if any had leaked from the supply lines.

11.1.2 *Gas Line Charging*—The following procedure or a comparable procedure shall be used for gas line charging. Close the supply line vent valves and open the valves to the fuel supply to charge the system with propane gas pressure up to, but not into, the chamber. If pilot flames are used as the ignition source, charge and initiate them first before charging the header in the exposure chamber for the main burners. High and low pressure sensors shall be used on the main at the operating burner header as safety interlock devices to address equipment failures during the charging process. Set the high and low pressure detectors as close to the operating pressure as feasible to provide system shutdown with a gas supply failure. In a double block and bleed burner management system (chamber piping arrangement), a mass flow sensor shall be used to detect failure of the main burner bleed valve(s) prior to main burner ignition.

11.2 *Dress the Manikin*—Dress the manikin in the test specimen. Cut the test specimen if necessary to provide a large enough opening for dressing around the obstruction of the data cables. If cutting is required, repair the cut in the test specimen with a nonflammable closure, such as metal staples, as close as possible to proper fit. Try to avoid placement of metal closure directly over a sensor. Arrange the test specimen on the manikin in the same way it is expected to be used by the end-user/wearer or as specified by the test number. Note in the test report how the manikin is dressed. Use the same fit and placement of the test specimen for each test to minimize variability in the test results.

11.3 *Record the Test Attributes*—Record the information that relates to the test, including: purpose of test, test series, test specimen identification, layering, fit on the manikin, test specimen style number or pattern description, test conditions, test remarks, exposure duration, data acquisition time, persons observing the test, and any other information relevant to the test series. As a minimum, provide the information listed in Section 13.

11.4 *Burner Alignment*—Verify that burner alignment is correct as established in 10.4.3.

11.5 *Manikin Alignment*—Verify that the manikin is spatially positioned and aligned in the exposure chamber via a centering or alignment device as established in 6.6.2.

11.6 *Set Test Parameters*—Enter into the burner management control system the specified exposure time and data acquisition time.

11.6.1 The minimum data acquisition time shall be 60 s for all exposures with test specimens. Shorter data acquisition times with nude burn calibrations are possible subject to the characteristics of a particular laboratory/manikin/sensor combination. The data acquisition time shall be long enough to ensure that the thermal energy stored in the test specimen is no longer contributing to burn injury. Confirm that the acquisition time is sufficient by inspecting the calculated burn injury versus time information to determine that the total burn injury of all of the sensors has leveled off and is not continuing to rise at the end of the data acquisition time. If the amount of burn injury is not constant for the last 10 s of acquisition time, increase the acquisition time to achieve this requirement.

11.7 *Confirm Safe Operation Conditions*—Follow the safe operating procedure developed by the laboratory to ensure that all of the safety requirements have been met and that it is safe to proceed with the fire exposure.

11.8 *Ignition System Check*—When all of the safety requirements are met, and no personnel are in the exposure chamber, check the operation of the ignition system.

11.8.1 If pilot lights are used, light the pilot flames and confirm that all of the pilot flames on the burners that will be used in the test exposure are actually lit. (**Warning—**Visually confirm, from outside the exposure chamber, the presence of each pilot flame in addition to the panel light, UV detection system, or computer indication.) The test exposure shall be initiated only when all of the safety requirements are met, the pilot flames are ignited and visually confirmed, and the final valve in the gas supply line is opened.

11.8.2 If a spark ignition is used, activate the system and visually confirm that a spark is present at each igniter.

11.9 *Chamber Temperature*—Record the chamber temperature.

11.10 *Start Image Recording System*—Start the video recording system used to visually document each test.

11.11 *Expose the Test Specimen*—Initiate the test exposure by pressing the appropriate computer key. The computer program will start the data acquisition, open the burner gas supply solenoid valves for the time of the exposure, and stop the data acquisition at the end of the specified time.

11.12 *Acquire the Heat Transfer Data*—Collect the data from all installed thermal energy sensors. Note that data collection during and after the fire exposure shall be done in a still air environment.

11.13 *Record Test Specimen Response Remarks*—Record the observed effects of the exposure on the test specimen. These remarks include, but are not limited to, the following: occurrence of after-flame (time, intensity, and location), ignition, melting, smoke generation, unexpected garment or material failures (for example, formation of holes, sleeves falling off, button or slide closure failure, etc.), material shrinkage, and charring or observed degradation. These remarks become a permanent part of the test record.

11.14 *Initiate Test Report Preparation*—Initiate the computer program to perform the calculations to determine the predicted burn injury for each thermal energy sensor, the total predicted burn injury, the percentage that is predicted second-degree and predicted third-degree injury, and to prepare the test report. Perform these operations immediately or, if warranted, delay them for later processing.

11.15 *Initiate Forced-Air Exhaust System*—Start the forced-air exhaust system to remove the combustion products resulting from the fire exposure. Run the system long enough to ensure a safe working environment in the exposure chamber prior to entering.

11.15.1 *Discussion*—The operating time for the exhaust system to produce a safe working environment is laboratory and test specimen specific. Refer to NFPA 85 and NFPA 86 for guidance.

11.16 *Prepare for the Next Test Exposure*—Carefully remove the exposed specimen from the manikin. Wipe the manikin and sensor surfaces with a damp cloth to remove residue from the test specimen exposure. The manikin and sensors shall be inspected to ensure that they are free of any decomposition materials, and if a deposit is present, carefully clean the manikin and sensors with soap and water or a petroleum solvent. Use the gentlest method that is effective in cleaning the sensor. If required, repaint the surface of the sensor and dry the paint. Ensure that the manikin and sensors are dry, and if necessary, dry them, for example with the ventilating fan(s), before conducting the next test. Visually inspect the sensors for damage, for example, cracks or discontinuities in the sensor surface.

11.17 *Sensor Replacement*—Repair or replace damaged or inoperative sensors. Calibrate repaired or replaced sensors before using (see 10.2, 10.2.1, and 10.2.2).

11.18 *Sensor Temperatures*—Before starting the next exposure, ensure that the average temperature of all the sensors located under the test specimen is 32 ± 2 °C (90 ± 4 °F) and no single sensor exceeds 38 °C (100 °F) with the exception noted in 11.19. See also 10.4.7 and its discussion in 10.4.7.1.

11.19 The most common tests are ones where the test specimens do not provide any covering for the head. In these cases the nude head always shows a predicted second-degree burn injury or higher. Cooling the sensors in the head to the requirement in 11.18 is unnecessary in this case as the same predicted burn injury is always obtained. The cooling procedure lengthens the time between tests, adding to the cost. When setting the exposure conditions in 10.4, the requirement of 11.18 shall be met.

11.20 *Test Remaining Specimens*—Test the remaining specimens at the same exposure conditions.

12. Skin Burn Injury Prediction

12.1 *Determination of Manikin Sensor Heat Flux Values:*

12.1.1 Convert the recorded thermal energy sensor responses at each time step into their respective time-dependent absorbed heat flux values in kW/m^2 ($cal/s{\cdot}cm^2$) using the method appropriate for the sensor.

12.1.1.1 *Discussion*—Different laboratories use different sensor technologies in their manikins. Each requires a different method to convert the measured responses into respective absorbed heat flux values.

12.2 *Determination of the Predicted Skin and Subcutaneous Fat (Adipose) Internal Temperature Field:*

12.2.1 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 differential equation (Fourier's Field Equation):

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

where:

$\rho Cp(x)$ = volumetric heat capacity, $J/m^3{\cdot}K$ ($cal/cm^3{\cdot}K$),
t = time, s,
x = depth from skin surface, m [cm],
$T(x,t)$ = temperature at depth x, time t, K, and
$k(x)$ = thermal conductivity, W/m·K (cal/s·cm·K).

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

12.2.2 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 5. Each of the three layers shall be constant thickness, lying parallel to the surface.

12.2.2.1 *Discussion*—The property values stated in Table 5 are representative of *in vivo* (living) values for the forearms of the test subjects who participated in the experiments by Stoll and Greene (**2**). They are average values. The thermal conductivity of each of the layers is known to vary with temperature due to the generalized thermophysical characteristics of the layer components (simplified composition: water, protein, and fat). Appendix X1 outlines a method for taking the temperature variation of the thermal conductivity into account when the skin layers are treated as having the simplified composition: water, protein, and fat.

12.2.2.2 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).

(1) Discussion—Equally spaced depth intervals (Δx), denoted as "nodes" or "meshes," are recommended for highest accuracy in all numerical models. A value for Δx of 15×10^{-6} m has been found effective. Sparse or unstructured meshes are not recommended for use in the finite difference method.

TABLE 5 Physical Properties for Skin Burn Injury Model

Parameter	Epidermis	Dermis	Subcutaneous Tissue
Thickness of layer (m) (μm)	75×10^{-6} (75)	1125×10^{-6} (1125)	3885×10^{-6} (3885)
Thermal conductivity k (W/m·K) (cal/s·cm·K)	0.6280 (0.0015)	0.5820 (0.001391)	0.2930 (0.0007)
Volumetric heat capacity ρCP ($J/m^3{\cdot}K$) ($cal/cm^3{\cdot}K$)	4.40×10^6 (1.05)	4.184×10^6 (1.00)	2.60×10^6 (0.62)

12.2.3 Use the following initial and boundary conditions:

12.2.3.1 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).

(1) Discussion—Pennes (**3**) measured the temperature distributions in the forearms of volunteers. For the overall thickness of the skin and subcutaneous layers (adipose) listed in Table 5, the measured rise was 1 K (1 °C). The skin surface temperature of the volunteers in the experiments by Stoll and Greene (**2**) was kept very near to 305.65 K (32.5 °C).

12.2.3.2 The absorbed heat flux is applied only at the skin surface and it is assumed that heat conduction is the only mode of heat transfer in the skin and subcutaneous layers (adipose). This calculation excludes any thermal radiation components that could penetrate the skin.

(1) 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 5 are back calculated from the experimental results of Stoll and Greene (**2**) and numerical extensions by Weaver and Stoll (**4**). The values account to a large degree for the blood flow in the test subjects.

12.2.3.3 The absorbed heat flux at the skin surface at time *t* = 0 (start of the exposure) is zero (0).

12.2.3.4 The absorbed heat flux values at the skin surface at all times $t > 0$ are the time dependent absorbed heat flux values determined in 12.1.1. No corrections are made for radiant heat losses or emissivity/absorptivity differences between the sensors and the skin surface used in the model.

12.2.4 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).

12.3 *Determination of the Predicted Skin Burn Injury:*

12.3.1 The Damage Integral Model of Henriques (**5**), Eq 2, is used to predict skin burn injury parameter 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).

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

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,
ΔE = activation energy, dependent on depth and temperature, J/kmol,
R = universal gas constant, 8314.5 J/mol · K, and
T = temperature at specified depth (in kelvin) K.

12.3.2 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.

12.3.3 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).

12.3.4 A second-degree burn injury occurs when the value of $\Omega \geq 1.0$ for depths $\geq 75 \times 10^{-6}$ m and $< 1200 \times 10^{-6}$ m.

12.3.5 A third-degree burn injury occurs when the value of $\Omega \geq 1.0$ for depths $\geq 1200 \times 10^{-6}$ m.

12.3.6 For the second-degree and third-degree burn injury predictions, the temperature dependent values for P and ΔE/R are listed in Table 6.

12.4 *Skin Burn Injury Test Cases:*

12.4.1 The calculation method used in 12.2 and 12.3 shall meet the validation requirements identified in Table 7.

12.4.2 When validating the skin burn injury model, use the layer thickness, thermal conductivity, and volumetric heat capacity values specified in Table 5 or if using the variable thermal conductivity method, those in Table X1.2, and the boundary and initial conditions of 12.2.3 with the exception that the exposure heat fluxes in 12.2.3.4 become the constant valued ones listed in Table 7. 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 (44 °C) during the cooling phase. For these test cases 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 listed in Table 5 or Table X1.2 are permitted providing the validation requirements specified in Table 7 are met with one set of values for all twelve test cases.

12.4.2.1 *Discussion*—The adiabatic boundary condition during cooling is selected because of the lack of detail in the published documents on the orientation of the forearms and the proximity of surrounding equipment used to conduct the

TABLE 6 Constants for Calculation of Omega Using Eq 2

Skin Injury	Temperature Range	P	ΔE/R
Second-degree (**4**)	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)	1.823×10^{51} s^{-1}	39 109.8 K
Third-degree (**6**)	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

TABLE 7 Skin Model Validation Data Set[A]

Absorbed Exposure Heat Flux (constant for the exposure)		Exposure Duration[B]	Required Size of Time Step
W/m^2	(cal/s·cm^2)	s	s
3935	(0.094)	35.9	0.01
5900	(0.141)	21.09	0.01
11 800	(0.282)	8.30	0.01
15 730	(0.376)	5.55	0.01
23 600	(0.564)	3.00	0.01
31 465	(0.752)	1.95	0.01t
39 350	(0.940)	1.41	0.01
47 195	(1.128)	1.08	0.01
55 060	(1.316)	0.862	0.001
62 925	(1.504)	0.713	0.001
70 795	(1.692)	0.603	0.001
78 660	(1.880)	0.522	0.001

[A] Skin models using the absorbed heat flux and exposure times in Table 7 shall result in values of 1 ± 0.10 for all test cases at the epidermis/dermis interface at the time when the interface temperature has cooled to or below 317.15 K (44 °C). The skin layer properties listed in Table 5 and the calculation constants in Table 6 shall be used for these calculations. In addition, the time when Ω = 1 shall never be less than the exposure duration listed. This latter requirement is to keep the prediction consistent with the observations of Stoll and Greene **(2)**. Note that the parameter, Ω, is a cumulative value and having epidermis/dermis interface temperatures lower than 317.15 K (44 °C) does not produce negative values that are subtracted.

[B] The exposure durations are based on the values given in Stoll and Chianta **(7)**. These values were obtained using curve fitting routines and as such are slightly different from those published.

experiments. Furthermore, the data gathered from the thermal energy sensors when conducting this test method takes into account convection and radiation heat losses inherently through the calculation of the net energy absorbed by the thermal energy sensors. Therefore this adiabatic assumption only applies to the model validation data set and not the entire test method.

13. Report

13.1 State that the specimens were tested as directed in Test Method F1930, noting any deviations.

13.1.1 Describe the test specimens including for each: garment type, size, fabric weight (see 8.2.2.1 and 9.3), fiber type, color, and nonstandard or special garment features and design characteristics.

13.2 Report the information in 13.3 – 13.6.

13.3 *Type of Test*—Material of construction evaluation, garment design evaluation, or end-use garment evaluation.

13.4 *Exposure Conditions*—The information that describes the exposure conditions, including:

13.4.1 The average of the exposure heat flux and the standard deviation of the average heat flux from all sensors determined from the nude exposures taken before and after each test series.

13.4.2 The nominal heat flux, the duration of the exposure, and the duration of the data acquisition time for each test.

13.4.3 The temperature in the exposure chamber at the beginning of each test.

13.4.4 The temperature and relative humidity in the room where the garments were held prior to testing.

13.4.5 Any other information relating to the exposure conditions shall be included to assist in interpretation of the test specimen results.

13.5 *Calculated Results*—For all garment evaluation and specification test reports, include results of the computer program. Base the predicted burn injury, expressed as a percentage, on the total area of the manikin containing sensors (see 13.5.1) and on the total area of the manikin covered by the test specimen (see 13.5.2). The hands and feet are not included in either total area evaluation.

13.5.1 Total area of manikin containing sensors.

13.5.1.1 Predicted second-degree burn injury (%).

13.5.1.2 Predicted third-degree burn injury (%).

13.5.1.3 Total predicted burn injury (sum of second- and third-degree burn injury) (%), and associated variation statistic.

13.5.1.4 State if the results are area weighted or not.

13.5.2 Total area (%) of manikin covered by the test specimen.

13.5.2.1 Predicted second-degree burn injury (%).

13.5.2.2 Predicted third-degree burn injury (%).

13.5.2.3 Total predicted burn injury (sum of second- and third-degree burn injury) (%) and associated variation statistic.

13.5.2.4 State if the results are area weighted or not.

13.5.3 Other calculated information used in assessing performance.

13.5.3.1 Diagram of the cumulative second-degree burn injury (%) and cumulative third-degree burn injury (%) as a function of time for the entire data acquisition period. The area used in determining the percentage shall be stated on the diagram (see 13.5.1 and 13.5.2).

13.5.3.2 Diagram of the manikin showing location and burn injury levels as second- and third-degree areas.

(1) Discussion—Although not required, it is common to add color-coding information to the manikin diagram. Multiple colors have been used by several laboratories to increase the clarity of the resulting exposure results. Different colors have been used to denote sensors not covered by the test specimen, sensors that are under the test specimen, sensors registering a predicted second-degree burn injury, sensors registering a predicted third-degree burn injury, and sensors that failed during testing.

13.6 *Subjective and Recorded Observations*—Document the results of the exposure on the test specimen in narrative form. Support the observations with the video image recorded in 11.10 and, if necessary, a still photographic record. These observations shall include, but are not limited to:

13.6.1 Intensity, location, and duration of after flame or ignition.

13.6.2 Amount of smoke generated (for example, light, medium, or heavy).

13.6.3 Physical stability of the test garment: shrinkage, char formation, melting, generation of holes, sleeves falling off, etc.

13.7 Laboratories have the option of reporting the following information.

13.7.1 Tables of individual and summary sensor results showing Sensor Number, Sensor Location, Time to achieve a Second-Degree Burn (s), Time to achieve a Third-Degree Burn (s), Energy Absorbed at Time of Second Degree Burn (J/m^2, cal/cm^2), Total Energy Absorbed During the Data Acquisition Period (J/m^2, cal/cm^2), the Depth of Damage (that is, location where $\Omega = 1.0$ (μm)), and Degree of Burn as a numerical value (2 or 3). (See X1.6.)

14. Precision and Bias[9]

14.1 The precision of this test method is based on an interlaboratory study of this test method, which was conducted in 2000/2002. Eight laboratories were asked to report triplicate results, for flame resistance under four unique conditions, obtained using three different materials. Every "test result" reported represents an individual determination. Practice E691 was followed for the design and analysis of the data.

14.1.1 *Repeatability Limit (r)*—Two test results obtained within one laboratory shall be judged not equivalent if they differ by more than the *r* value for that material; *r* is the interval representing the critical difference between two test results for the same material, obtained by the same operator using the same equipment on the same day in the same laboratory.

14.1.1.1 Repeatability limits are listed in Tables 8-10.

14.1.2 *Reproducibility Limit (R)*—Two test results shall be judged not equivalent if they differ by more than the *R* value for that material; *R* is the interval representing the critical difference between two test results for the same material, obtained by different operators using different equipment in different laboratories.

14.1.2.1 Reproducibility limits are listed in Tables 8-10.

TABLE 8 Material A (Percentage of Body Receiving Second Degree Burn Injury or Worse)

Condition	Average^A	Repeatability Standard Deviation	Reproducibility Standard Deviation	Repeatability Limit	Reproducibility Limit
	$\bar{x}$	S_r	S_R	r	R
1	11.1	2.6	3.8	7.1	10.7
2	67.9	7.0	15.9	19.6	44.5
3	53.5	6.6	18.8	18.6	52.7
4	82.4	3.3	6.2	9.3	17.4

^{A}The average of the laboratories' calculated averages.

TABLE 9 Material B (Percentage of Body Receiving Second Degree Burn Injury or Worse)

Condition	Average^A	Repeatability Standard Deviation	Reproducibility Standard Deviation	Repeatability Limit	Reproducibility Limit
	$\bar{x}$	S_r	S_R	r	R
1	29.7	5.3	12.0	15.0	33.7
2	63.0	2.9	12.9	8.0	36.1
3	43.6	3.3	7.0	9.2	19.7
4	54.4	3.5	6.2	9.8	17.3

^{A}The average of the laboratories' calculated averages.

TABLE 10 Material C (Percentage of Body Receiving Second Degree Burn Injury or Worse)

Condition	Average^A	Repeatability Standard Deviation	Reproducibility Standard Deviation	Repeatability Limit	Reproducibility Limit
	$\bar{x}$	S_r	S_R	r	R
1	33.6	3.8	7.5	10.6	20.9
2	64.0	2.3	8.1	6.5	22.7
3	48.6	3.9	7.1	10.8	20.0
4	62.6	1.8	5.1	5.0	14.3

^{A}The average of the laboratories' calculated averages.

14.1.3 The above terms (repeatability limit and reproducibility limit) are used as specified in Practice E177.

14.1.4 Any judgment in accordance with statement 14.1.1 would have an approximate 95 % probability of being correct.

14.2 *Bias*—At the time of the study, there was no accepted reference material suitable for determining the bias for this test method, therefore no statement on bias is being made.

14.3 This precision statement was determined through the statistical examination of 273 results from eight laboratories, on three materials, tested under four different conditions. These materials and conditions were described as:

Material A: Flame retardant treated cotton at a nominal fabric basis weight of 305 g/m^2 (9 oz/yd^2);

Material B: Para-aramid /pbi (60 % ⁄40 %) at a nominal fabric basis weight of 153 g/m^2 (4.5 oz/yd^2);

Material C: Meta-aramid/para-aramid/carbon at a nominal fabric basis weight of 203 g/m^2 (6.0 oz/yd^2);

Condition 1: 3 s at 84 kW/m^2 (2 cal/s·cm^2) with a manikin dressed only in the test coverall;

Condition 2: 4 s at 84 kW/m^2 (2 cal/s·cm^2) with a manikin dressed only in the test coverall;

Condition 3: 4 s at 84 kW/m^2 (2 cal/s·cm^2) with a manikin dressed in 100 % cotton T-shirt and briefs under test coverall.

Condition 4: 5 s at 84 kW/m^2 (2 cal/s·cm^2) with a manikin dressed in 100 % cotton T-shirt and briefs under test coverall.

15. Keywords

15.1 fire, flash; flame testing; flammability, textile; manikin, instrumented flammability testing; protective clothing; thermal testing

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[9] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:F23-1009. Contact ASTM Customer Service at service@astm.org.

ANNEXES

(Mandatory Information)

A1. CONTROL CHARTING

A1.1 The primary output parameter from this test method is the severity of the predicted skin burn injury and the surface area of the manikin so affected. Control charting of this prediction shall be done. The necessary steps are mentioned in the test method. The required sequence is listed below.

A1.1.1 Calibrate the sensors as required in 10.2.

A1.1.2 Confirm the prediction of the sensor, data acquisition, and burn model as a unit as described in 10.3

A1.1.3 Confirm the exposure conditions as required in 10.4.

A1.1.4 As a minimum check on repeatability, carry out 10.4.4.

A1.2 A supplementary control-charting program is also recommended. The use of a control garment is one possibility. In it a test garment from a large lot is exposed to establish standard conditions at the beginning of each day (after the nude exposure calibration required in 10.4) and the burn injury results plotted on an Individual Moving Range chart. A laboratory instituting this test method shall establish a process for taking corrective action based on the results of this daily standard garment test.

A2. COMPUTER CODE ACCURACY TEST CASES – TEMPERATURE

A2.1 The two test cases are based on the closed form solution of heat conduction into a semi infinite solid, initially at a uniform temperature and suddenly exposed to a constant heat flux at its surface. The analytical solution is available in any textbook on heat transfer.

A2.1.1 For the two cases listed below, set the initial temperature of the tissue layers to 30 °C everywhere. Keep the base temperature at 5085 µm at 30 °C for all time steps in the calculations.

A2.2 Case One

A2.2.1 Absorbed heat flux at skin surface = 2 kW/m^2.

A2.2.2 Thermal conductivity of all three tissue layers, k = 0.1 W/m K.

A2.2.3 Volumetric heat capacity of all three layers, $\rho Cp = 4 \times 10^6$ J/m^3 K.

A2.2.4 Calculate the temperature at 0 µm, 75 µm, and 1200 µm depths at 60 s after the exposure begins. Use any time step equal to or smaller than 0.1 s.

A2.3 Case Two

A2.3.1 Absorbed heat flux at skin surface = 20 kW/m^2.

A2.3.2 Thermal conductivity of all three tissue layers, k = 0.6 W/m K.

A2.3.3 Volumetric heat capacity of all three layers, $\rho Cp = 4 \times 10^6$ J/m^3 K.

A2.3.4 Calculate the temperature at 0 µm, 75 µm, and 1200 µm depths at 6 s after the exposure begins. Use any time step equal to or smaller than 0.1 s.

A2.4 The temperature and temperature rise at each of the three locations as calculated from the closed form solution for the two cases are listed in Tables A2.1 and A2.2.

A2.5 The required match is to predict the temperature rise at the three locations for the two cases with a maximum error of 0.2 %.

TABLE A2.1 Case One

	Q = 2 kW/m^2	Calculation Time = 60 s	Temp at 0 µm °C	Temp at 75 µm °C	Temp at 1200 µm °C
Closed Form Solution	k = 0.1 W/mK	$\rho Cp = 4 \times 10^6$ J/m^3 K	57.64	56.17	40.02
Temperature Rise			27.64	26.17	10.02

TABLE A2.2 Case Two

	Q = 20 kW/m^2	Calculation Time = 6 s	Temp at 0 µm °C	Temp at 75 µm °C	Temp at 1200 µm °C
Closed Form Solution	k = 0.6 W/mK	ρCp = 4 × 10^6 J/m^3 K	65.68	63.24	39.07
Temperature Rise			35.68	33.24	9.07

APPENDIXES

(Nonmandatory Information)

X1. SKIN BURN INJURY MODEL

X1.1 The parameter used in evaluating the performance of garments or ensembles 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 epidermis, or outer layer, is relatively inert and acts as a protective layer against penetration by gases and fluids. The outside layer of the epidermis is constantly wearing off. It is replenished with new cells. 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 dermis layers. The dermis layer consists of blood vessels, connective tissue, lymph vessels, sweat glands, receptors, and hair shafts.

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 an important role in the thermal regulation of the internal body temperature as it acts as an insulator.

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. The observation time for damage to occur in their experiments was 24 to 48 h after the heating was terminated. They discovered that destruction of the skin cell growing layer located at the epidermis/dermis interface and deeper layers in human skin begins when the temperature of the skin surface rises above 44 °C (317.15 K). In a later paper, Henriques (**5**) showed that the rate of cell destruction could be modeled by a first order chemical reaction rate equation (Eq X1.1).

X1.3 The estimation of second-degree skin burn injury used in this test method is based on later work by Stoll and Greene (**2**), Weaver and Stoll (**4**), and Stoll and Chianta (**7**). These investigations were conducted on the forearms of human volunteers using an apparatus that would heat a small (~18 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 h 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 (**2**) found that destruction of the growing layer located at the epidermis/dermis interface and deeper layers 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 (**5**), that is:

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

where:

Ω = a 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, 8314.5 J/mol · K,
T = the absolute temperature at the basal layer or at any depth in the dermis, K, and
t = total time for which T is above 44 °C (317.15 K).

X1.5 The total burn damage is found by integrating Eq X1.1 over the total time interval that the basal layer is above 44 °C (317.15 K), that is, during both the heating and cooling phases. This results in the following equation:

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

X1.6 With the assumption that the skin surface temperature and the epidermal/dermal interface temperature are essentially equal in long duration heating, Henriques (**5**) found that if Ω is less than or equal to 0.53, no damage will occur in the epidermis or deeper layers. If Ω is greater than 0.53 and less than 1.0, first-degree burns (reddening) will occur in the epidermis only, where as if $\Omega \geq 1.0$, second-degree burns (complete epidermal necrosis or blistering) will result. This damage criteria can be applied to any depth of skin provided the appropriate values of P and ΔE are used and the temperature history of the layer is known. 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. First-degree burn injury is not normally calculated or reported.

X1.7 Morse, Tickner, and Brown (**9**) examined the various values of P and ΔE available in the literature and suggested that the criteria developed by Weaver and Stoll (**4**) be used in the epidermal layer and that of Takata (**6**) be used in the dermal and subcutaneous layers (adipose). The values of P and ΔE developed by Weaver and Stoll (**4**) 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	$P = 1.823 \times 10^{51}\ s^{-1}$ and $\Delta E/R = 39\,109.8$ K

while those of Takata 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 (**4**) to calculate the values of P and ΔE in X1.7 came from the experiments of Stoll and Greene (**2**). 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 (**4**). This extended data set is presented in Table 7. The extended data base was used by Weaver and Stoll (**4**) to calculate the values of P and ΔE.

X1.9 The values of P and ΔE calculated by Takata (**6**) were from experiments on anesthetized pigs exposed to hot combustion gases.

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 as discussed in Section 12. 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 (**10-12**).

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 (**2**) 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 from the Stoll and Greene (**2**) experiments in order to meet the requirements of 12.4.

X1.12 The initial temperature distribution through the three layers is represented by a linear temperature rise of 1 ºC, with the skin surface temperature set to 32.5 ºC. The back side of the subcutaneous (adipose) is fixed at 33.5 ºC for all time. This internal temperature gradient was measured by Pennes (**3**) in the forearms of volunteers over the same total thickness of skin and subcutaneous tissue.

X1.13 The thermal properties of all parameters in each of the layers is known to vary with temperature due to the generalized thermophysical characteristics of the layer components (simplified composition: water, protein, and fat). Cooper and Trezek (**13**) and Knox et al. (**14**) have developed relationships for estimating the temperature variation of the thermal conductivity of the skin and subcutaneous (adipose) layers based on the percent water, protein, and fat in each layer. Accounting for the variation of the thermal conductivity of the components in each of the three layers can produce good agreement with the requirements of Table 7. 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 thermal conductivity values listed in Table X1.2 provide a good fit to Table 7 when they are used as the initial values. The calculation of the thermal conductivity, k, at other depths and temperatures different from 32.5 °C is outlined below.

X1.13.1 The skin model parameters: volumetric heat capacity, ρCp, in J/m^3 and temperature-dependent thermal conductivity, k, in W/mK, shall be calculated for each skin layer, x, according to the following equations, adopted from Cooper and Trezek (**13**) and Knox et al (**14**).

X1.13.2 Layers: 1 = epidermis; 2 = dermis; 3 = subcutaneous.

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	0.5820	0.2930
Volumetric heat capacity, ρCp (J/m^3·K)	4.40×10^6	4.184×10^6	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, ρCp (J/m³·K)	4.158×10^{6}	4.017×10^{6}	2.285×10^{6}
Water fraction (% mass)	80	70	20
Fat fraction (% mass)	6	12	72
Protein fraction (% mass)	14	18	8

X1.13.3 For any layer (where Wx is the mass fraction of material, w - water, f - fat, p - protein), calculate the values:

$$\text{density}, \rho = \left(\frac{W_w}{\rho_w} + \frac{W_f}{\rho_f} + \frac{W_p}{\rho_p} \right)^{-1}$$

$$C_p, \qquad C_p = W_w{*}C_{pw} + W_f{*}C_{pf} + W_p{*}C_{pp}$$

$$k, k = \rho \cdot \left| \frac{k_w \cdot W_w}{\rho_w} + \frac{k_f \cdot W_f}{\rho_f} + \frac{k_p \cdot W_p}{\rho_p} \right|$$

X1.13.4 By using the following parameters:

X1.13.4.1 Temperature: tempK = temperature + 273.15, being temperature in °C.

X1.13.4.2 Water thermophysical values: $\rho_w = 1.0$ being the density of water, g/cm^3; $C_{pw} = 1.0$ being the heat capacity of water, cal/g°C; k_w = (–0.2758 + 4.6120E-03 * tempK - 5.5391E-06 * tempK * tempK) / 418.40 being the temperature dependent thermal conductivity, cal/cm s °C.

X1.13.4.3 Fat thermophysical values: $\rho_f = 0.87$ being the density of fat, g/cm$^{3;}$ $C_{pf} = 0.44$ being the heat capacity of fat, cal/g°C; $k_f = 5.42 \times 10^{-4} + 3.6 \times 10^{-6} \times$ temperature - $4.0 \times 10^{-9} \times$ temperature × temperature being the temperature dependent thermal conductivity, cal/cm s °C.

X1.13.4.4 Protein thermophysical values: $\rho_p = 1.54$ being the density of protein, g/cm^3; $C_{ppp} = 0.91$ being the heat capacity of protein, cal/g°C; $k_p = 2.0 \times 10^{-3} + 2.5 \times 10^{-6} \times$ temperature × temperature being temperature dependent thermal conductivity, cal/cm s °C.

X1.13.4.5 Mass fractions for each of the layers: for layer = 1 (mass fractions for epidermis layer): $W_w = 0.80$ being the mass fraction of water; $W_f = 0.3{*}(1–W_w)$ being the mass fraction of fat, 30 % (ex water); $W_p = 0.7{*}(1–W_w)$ being the mass fraction of protein, 70 % (ex water). For layer = 2 (mass fractions for dermis layer): $W_w = 0.7$ being the mass fraction of water; $W_f = 0.40{*}(1–W_w)$ being the mass fraction of fat, 40 % (ex water); $W_p = 0.60{*}(1–W_w)$ being the mass fraction of protein, 60 % (ex water). For layer = 3 (mass fractions for subcutaneous layer): $W_w = 0.2$ being the mass fraction of water; $W_f = 0.9{*}(1–W_w)$ being the mass fraction of fat, 90 % (ex water); $W_p = 0.1{*}(1–W_w)$ being the fat mass fraction of protein, 10 % (ex water).

X1.13.4.6 For obtaining the values of the volumetric heat capacity $\rho \times C_p$ in the SI units (J/m^3 K), multiply the above obtained values for $\rho \times C_p$ by 4 184 000.

X1.13.4.7 For obtaining the values of the thermal conductivity k in the SI units (W/m K), multiply the above obtained values for k by 418.40.

X2. ELEMENTS OF COMPUTER SOFTWARE PROGRAM

X2.1 The sections and elements of a computer software program that are recommended for inclusion, but not limited to, are given in X2.1.1 – X2.1.6.

X2.1.1 *Monitor Status of Apparatus and Then Control the Process as Required:*

X2.1.1.1 Temperature of Sensors.

X2.1.1.2 Position of fuel supply line and vent valves.

X2.1.1.3 Position of fuel supply pressure sensors.

X2.1.1.4 Exposure burner ignition system.

X2.1.1.5 Exposure burner pilot light sensors (if fitted).

X2.1.1.6 Ventilation flow sensor.

X2.1.1.7 Keyboard queries and commands.

X2.1.1.8 Safety devices, such as propane sensors, chamber door, and so forth.

X2.1.2 *Process Control:*

X2.1.2.1 Chamber air purge—ventilation fans.

X2.1.2.2 Fuel line charging.

X2.1.2.3 Test burner ignition system.

X2.1.2.4 Exposure burner pilot ignition and detection (if fitted).

X2.1.2.5 Exposure burner fuel solenoid control.

X2.1.2.6 Data acquisition.

X2.1.2.7 Exhaust fan control.

X2.1.2.8 Emergency shutdown.

X2.1.3 *Data Acquisition:*

X2.1.3.1 Record sensor temperatures or output signal at least twice per second and create a table of sensor response versus time for each sensor for the duration of the data acquisition period.

X2.1.3.2 Record time that the exposure burner fuel solenoids are open-exposure duration.

X2.1.3.3 Garment identification field comments.

X2.1.3.4 Exposure conditions field comments.

X2.1.3.5 Exposure remarks field comments.

X2.1.3.6 Garment reaction remarks field comments.

X2.1.3.7 Garment after-flame intensity and duration.

X2.1.4 *Calculations:*

X2.1.4.1 Calculate heat flux at manikin surface from sensor response readings.

X2.1.4.2 Calculate tissue temperature from manikin surface heat flux calculations or measurements.

X2.1.4.3 Calculate burn injury from tissue temperature calculations.

X2.1.4.4 Summarize results in detailed data table.

X2.1.5 *Report Preparation*—Summarize and create a test report that includes, but is not limited to, the requirements of Section 13 of test method and the following as needed: (*1*) Contents of remarks fields, and (*2*) detailed tables including heat flux, time to second- and third-degree burns, sensor temperatures, and calculated skin temperatures versus time for each sensor.

X2.1.6 *Supporting Programs:*

X2.1.6.1 Sensor calibration exposure and data collection.

X2.1.6.2 Sensor calibration factor calculation.

X2.1.6.3 Manual exposure of manikin using auxiliary heat source.

X2.1.6.4 Burn injury and sensor response diagnostics.

X2.1.6.5 Manikin diagram with sensor areas.

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