Designation: F 1868 – 98

Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate[1]

This standard is issued under the fixed designation F 1868; 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.

INTRODUCTION

Clothing is often made of materials that impede the flow of heat and moisture from the skin to the environment. Consequently, people may suffer from heat stress or cold stress when wearing clothing in different environmental conditions. Therefore, it is important to quantify the thermal resistance and evaporative resistance of clothing materials and to consider these properties when selecting materials for different clothing applications.

1. Scope

1.1 This test method covers the measurement of the thermal resistance and the evaporative resistance, under steady-state conditions, of fabrics, films, coatings, foams, and leathers, including multi-layer assemblies, for use in clothing systems.

1.2 The range of this measurement technique for thermal resistance is from 0.002 to 0.2 K·m^2/W and for evaporative resistance is from 0.01 to 1.0 kPa·m^2/W.

1.3 The values in SI units shall be regarded as standard.

1.4 *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 consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus[2]

D 1518 Thermal Transmittance of Textile Materials[3]

E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods[4]

E 641 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method[4]

F 1291 Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin[5]

F 1494 Terminology Relating to Protective Clothing[5]

2.2 *Other Standards:*

ISO 11092 Textiles–Physiological Effects–Measurement of Thermal and Water-Vapour Resistance Under Steady-State Conditions (Sweating Guarded-Hotplate Test)[6]

NFPA 1971 Protective Clothing for Structural Fire Fighting[7]

NFPA 1977 Protective Clothing and Equipment for Wildland Fire Fighting[7]

3. Terminology

3.1 *Definitions:*

3.1.1 *clo, n-, n*—unit of thermal resistance defined as the insulation required to keep a resting man (producing heat at the rate of 58 W/m^2) comfortable in an environment at 21°C, air movement 0.1 m/s, or roughly the insulation value of typical indoor clothing.

3.1.1.1 *Discussion*—Numerically the clo is equal to 0.155 K·m^2/W.

3.1.2 *evaporative heat transmittance, n*—time rate of unidirectional evaporative heat transfer per unit area, in the steady state, between parallel planes, per unit difference of water vapor pressure of the planes.

3.1.2.1 *Discussion*—Evaporative heat transmittance is expressed as watts per square metre of test specimen per

---

[1] This test method is under the jurisdiction of ASTM Committee F-23 on Protective Clothing and is the direct responsibility of Subcommittee F23.60 on Human Factors.

Current edition approved June 10, 1998. Published August 1998.

[2] *Annual Book of ASTM Standards*, Vol 04.06.

[3] *Annual Book of ASTM Standards*, Vol 07.01.

[4] *Annual Book of ASTM Standards*, Vol 14.02.

[5] *Annual Book of ASTM Standards*, Vol 11.03.

[6] Available from American National Standards Institute, 11 West 42nd St, New York, NY 10036.

[7] Available from National Fire Protection Assoc., 1 Batterymarch Park, Quincy, MA 02269.

kilopascal of vapor pressure difference between the test plate and the environment (W/m^2·kPa). The evaporative heat transmittance may consist of both diffusive and convective components.

3.1.3 *evaporative resistance*, *n*—reciprocal of evaporative heat transmittance expressed in kilopascals, square metre of test specimen per watt.

3.1.3.1 *Discussion*—The evaporative resistance for several different cases is determined in this method:

R_{ef}^A = apparent total evaporative resistance of the fabric test specimen only, when evaluated non-isothermally. The term *apparent* is used as a modifier for total evaporative resistance to reflect the fact that condensation may occur within the specimen.

R_{et}^A = apparent total evaporative resistance of the fabric test specimen, liquid barrier, and surface air layer when evaluated non-isothermally. The term *apparent* is used as a modifier for total evaporative resistance to reflect the fact that condensation may occur within the specimen.

R_{ebp} = evaporative resistance of the air layer on the surface of the liquid barrier without a fabric test specimen (that is, bare plate). This property reflects the instrument constant and the resistance of the liquid barrier, and in conjunction with R_{et}, is used in the calculation of R_{ef}.

R_{ef} = intrinsic evaporative resistance of the fabric test specimen only. In the calculation of this value, the assumption is made that the boundary layers of the bare plate and the boundary layers of the fabric are equal.

R_{et} = total evaporative resistance of the fabric test specimen, the liquid barrier, and the surface air layer.

3.1.4 *permeability index (i_m)*,n-, *n*—the efficiency of evaporative heat transport in a clothing system.

3.1.4.1 *Discussion*—An i_m of zero indicates that the clothing system allows no evaporative heat transfer. An i_m of one indicates that the clothing system achieves the theoretical maximum evaporative heat transfer allowed by its insulation.

3.1.5 *thermal transmittance*, *n*—time rate of unidirectional heat transfer per unit area, in the steady state, between parallel planes, per unit difference of temperature of the planes. Thermal transmittance is also known as thermal conductance and the heat transfer coefficient.

3.1.5.1 *Discussion*—Thermal transmittance is expressed as watts per square metre of test specimen per kelvin difference between the test plate and the environment (W/m^2·K). The dry heat flux may consist of one or more conductive, convective, and radiant components.

3.1.6 *thermal resistance*, *n*—reciprocal of thermal transmittance, expressed in kelvin, square metre of test specimen per watt.

3.1.6.1 *Discussion*—Thermal resistance for several different cases is determined in this method:

R_{cbp} = thermal resistance of the air layer on the surface of the plate without a fabric test specimen (that is, bare plate). This property reflects the instrument constant and is used to standardize the plate, and in conjunction with R_{ct}, is used in the calculation of R_{cf}.

R_{cf} = intrinsic thermal resistance of the fabric test specimen only. In the calculation of this value, the assumption is made that the boundary layers of the bare plate and the boundary layers of the fabric test specimen are equal.

R_{ct} = total thermal resistance of the test specimen and the air layer.

3.1.7 *total clo*, *n*—clo plus the thermal resistance from the air boundary layer, (clo$_t$).

3.1.8 *total heat loss*, *n*—the amount of heat transferred through a material or a composite by the combined dry and evaporative heat exchanges under specified conditions expressed in watts per square meter,

3.1.8.1 *Discussion*—This single criterion for comparing fabric assemblies was developed as a special case by the National Fire Protection Assoc. The specific conditions used by NFPA are a 35°C fully sweating hot plate surface in a 25°C 65 % RH environment.

3.2 For definitions of other terms related to protective clothing used in this test method, refer to Terminology F 1494.

4. Significance and Use

4.1 The thermal resistance and evaporative resistance provided by a fabric, batting, or other type of material is of considerable importance in determining its suitability for use in fabricating protective clothing systems.

4.2 The thermal interchange between people and their environment is, however, an extremely complicated subject that involves many factors in addition to the steady-state resistance values of fabrics and battings. Therefore, thermal resistance values and evaporative resistance values measured on a hot plate may or may not indicate relative merit of a particular material or assembly for a given clothing application. While a possible indicator of clothing performance, measurements produced by the testing of fabrics has no proven correlation to the performance of clothing systems worn by people. Clothing weight, drape, tightness of fit, and so forth, can minimize or even neutralize the apparent differences between fabrics or fabric assemblies measured by this test method.

4.3 The thermal resistance of clothing systems can be measured with a heated manikin in an environmental chamber according to Test Method F 1291.[5]

4.4 Departures from the instructions of Test Method F 1868 may lead to significantly different test results. Technical knowledge concerning the theory of heat flow, temperature measurement, and testing practices is needed to evaluate which departures from the instructions are significant. Standardization of the method reduces, but does not eliminate the need for such technical knowledge. Report any departures from the instructions of Test Method F 1868 with the results.

5. Apparatus

5.1 *Hot Plate*—The guarded flat plate shall be composed of a test plate, guard section, and bottom plate, each electrically maintained at a constant temperature in the range of human skin temperature (33 to 36°C). The guard section shall be designed to prevent lateral loss of heat from the test plate. The guard section shall be wide enough to minimize heat loss and moisture transport through the edges of the test specimen under the conditions of the test. The bottom plate shall prevent downward loss of heat from the test plate and guard section. A system for feeding water to the surface of the test plate and guard section is also needed. See Test Methods D 1518, C 177, and ISO 11092 for information on hot plates.

5.2 *Temperature Control*—Separate independent temperature control is required for the three sections of the hot plate (test plate, guard section, and bottom plate). Temperature control may be achieved by independent adjustments to the voltage or current, or both, supplied to the heaters using solid state power supplies, solid-state relays (proportional time on), adjustable transformers, variable impedances, or intermittent heating cycles. The three sections of the plate shall be controlled to the same temperature to within ± 0.1°C.

5.3 *Power Measuring Instruments*—Power to the hot plate test section shall be measured to provide an accurate average over the period of the test. If time proportioning or phase proportioning is used for the power control, then devices that are capable of averaging over the control cycle are required. Integrating devices (watt-hour transducers) are preferred over instantaneous devices (watt meters). Overall accuracy of the power monitoring equipment must be within ± 2 % of the reading for the average power for the test period.

5.4 *Temperature Sensors*—Temperature sensors may be thermistors, thermocouples, resistance temperature devices (RTDs), or equivalent sensors. The test plate, guard section, and bottom plate shall each contain one or more temperature sensors that are mounted flush with the hot plate surface and in such a manner that they measure the surface temperature within ± 0.1°C.

5.5 *Controlled Atmosphere Chamber*—The hot plate shall be housed in an environmental chamber that can be maintained at selected temperatures between 20 and 35°C. The walls of the test chamber shall not be highly reflective, and the wall temperature shall be ± 0.5°C of the air in the chamber. The relative humidity shall be maintained at selected levels between 40 and 65 %.

5.6 *Measuring Environmental Parameters*—The air temperature, relative humidity, and air velocity shall be measured as follows:

5.6.1 *Relative Humidity Measuring Equipment*—Either a wet-and-dry bulb psychrometer or a dew point hygrometer shall be used to measure the relative humidity and calculate the dew point temperature inside the chamber. The relative humidity sensing devices shall have an overall accuracy of at least ± 4 %.

5.6.2 *Air Temperature Sensors*—Shielded air temperature sensors shall be used. Any sensor with an overall accuracy of ± 0.1°C is acceptable. The sensor shall have a time constant not exceeding 1 min. The sensor(s) is suspended with the measuring point exposed to air inside the chamber at a point just prior to the air passing over the hot plate.

5.6.3 *Air Velocity Indicator*—Any calibrated means of measuring air velocity with an accuracy of ± 0.1 m/s is acceptable (for example, anemometer). Air flow speed is measured 15 mm above the plate surface. The air flow velocity shall be measured at three positions located along a horizontal line perpendicular to the air flow, including a point at the center of the plate and at points at the centers of the guard section on both sides of the plate. Spatial variations in air velocity shall not exceed ±10 % of the mean value.

5.6.4 *Temporal Variations*—Temporal variations shall not exceed the following air temperature ± 0.1°C, relative humidity ± 4 %, and air velocity ± 10 % of the mean value for data averaged over 5 min.

6. Materials

6.1 *Water*—For the evaporative resistance measurements in Parts B, C, and E, distilled water shall be used to wet the test plate surface.

6.2 *Liquid Barrier*—For the evaporative resistance measurements in Parts B, C, and E, a liquid barrier shall be used to cover the test plate so that water does not contact the test specimen. The permeability index of the liquid barrier shall be greater than 0.7, where $i_m = .061\ (R_{cbp}/R_{ebp})$. Examples include untreated cellophane film, microporous polytetraflouroethylene film, and so forth.

6.3 *Calibration Fabrics*[8]—A calibration fabric is required for the calibration in Part C. Sources for the calibration fabric are given in Footnote 8.

7. Sampling and Preparation of Test Specimens

7.1 *Sampling*—Test three specimens from each laboratory sampling unit.

7.2 *Specimen Preparation*—Use test specimens large enough to cover the surface of the hot plate test section and the guard section *completely*. Remove any undesirable wrinkles from the test specimens. Possible techniques for removing wrinkles include smoothing, free-hanging, pressing, steaming, ironing, and so forth.

7.3 *Conditioning*—Allow the test specimens to come into equilibrium with the atmosphere of the testing chamber by conditioning them in the chamber for a least 4 h.

8. Part A - Thermal Resistance

8.1 *Test Conditions*:

8.1.1 *Temperature of the Test Plate, Guard Section, and Bottom Plate*—Maintain the temperature of these sections at 35 ± 0.5°C and without fluctuating more than± 0.1°C during a test.

8.1.2 *Air Temperature*—Maintain the air temperature of the air flowing over the plate at 20 ± 0.5°C without fluctuating more than ± 0.1°C during a test.

8.1.3 *Relative Humidity*—Maintain the relative humidity of the air flowing over the plate at 65 ± 4 % and without fluctuating more than ± 4 % during a test. The dew point temperature corresponding to 65 % RH at 20°C is 13°C.

8.1.4 *Air Velocity*—Maintain the air velocity at a mean value of 1 ± 0.1 m/s and without fluctuating more than ±0.1 m/s over the duration of the test measurement.

8.2 *Procedures*:

[8] Information on laboratories with sweating hot plates, liquid barriers, and calibration fabrics can be obtained from The Center for Research on Textile Protection and Comfort, NCSU, Raleigh, NC 27695 and The Institute for Environmental Research, KSU, Manhattan, KS 66506.

8.2.1 Measure the bare plate thermal resistance, (R_{cbp}), in the same manner as that for R_{ct} except that the test plate shall not be covered with a test specimen. Average the data from three bare plate tests to determine the bare plate thermal resistance.

8.2.2 Measure the total thermal resistance, (R_{ct}), by placing a fabric or fabric assembly on the test plate. Place the test specimen on the test plate with the side normally facing the human body towards the test plate. In the case of multiple layers, arrange the specimens on the plate as on the human body. Eliminate bubbles and wrinkles within the test specimen and air gaps between the specimen and the plate or between specimen layers by smoothing without compressing. This smoothing of bubbles and wrinkles is one reason that the results from this test may not represent the performance of actual clothing worn by people. In many cases, trapped air in clothing can override any fabric effects.

8.2.3 After the fabric or fabric assembly reaches steady-state conditions, record measurements for power input and the conditions given in 8.1 (with the exception of air velocity) at least every 3 min for a minimum test period of 30 min to determine the total thermal resistance of the fabric plus the air layer, (R_{ct}).

8.3 *Calculations*—Calculate the total resistance to dry heat transfer, (R_{ct}), for a fabric system, including the surface air layer resistance using Eq. 1.

$$R_{ct} = (T_s - T_a)\,A/H_c \tag{1}$$

where:

R_{ct} = resistance to dry heat transfer provided by the fabric system and air layer (K·m²/W),
A = area of the plate test section (m²),
T_s = surface temperature of the plate (°C),
T_a = air temperature (°C), and
H_c = power input (W).

8.3.1 Average the data from three specimens for the dry heat transfer tests to determine the average R_{ct} for the laboratory sampling unit.

8.3.2 Determine the resistance to dry heat transfer provided by the fabric alone, R_{cf}, by subtracting the average thermal resistance value measured for the air layer, R_{cpb} (that is, bare plate test) from the average thermal resistance value measured for the total fabric system, R_{ct}.

9. Part B - Isothermal Evaporative Resistance (ISO 11092)

9.1 *Test Conditions*:

9.1.1 *Temperature of the Test Plate, Guard Section, and Bottom Plate*—Maintain the temperature of these sections at 35 ± 0.5°C without fluctuating more than ±0.1°C during a test.

9.1.2 *Air Temperature*—Maintain the air temperature of the air flowing over the plate at 35 ± 0.5°C and without fluctuating more than ±0.1°C during a test.

9.1.3 *Relative Humidity*—Maintain the relative humidity of the air flowing over the plate at 40 ± 4 % and without fluctuating more than ± 4 % during a test. The dew point temperature corresponding to 40 % RH at 35°C is 19°C.

9.1.4 *Air Velocity*—The air velocity shall have a mean value of 1 ±0.1 m/s and without fluctuating more than ±0.1 m/s over the duration of the test measurement.

9.2 *Procedures*:

9.2.1 Feed distilled water to the surface of the test plate and guard section.

9.2.2 Cover the test plate and guard section with a liquid barrier that prevents wetting of the fabric specimens by liquid water. Adhere the liquid barrier closely to the test plate and guard section with no wrinkles or air bubbles present.

9.2.3 Measure the bare plate evaporative resistance, (R_{ebp}), in the same manner as that for R_{et}, except that the test plate and liquid barrier shall not be covered with a test specimen. Average the data from three bare plate tests to determine the bare plate evaporative resistance.

9.2.4 Measure the total evaporative resistance, (R_{et}), by placing a fabric or fabric assembly on the test plate. Place the test specimen on the test plate with the side normally facing the human body towards the test plate. In the case of multiple layers, arrange the specimens on the plate as on the human body. Eliminate bubbles and wrinkles within the test specimen and air gaps between the specimen and the plate or between specimen layers by smoothing without compressing. This smoothing of bubbles and wrinkles is one reason that the results from this test may not represent the performance of actual clothing worn by people. In many cases, trapped air in clothing can override any fabric effects.

9.2.5 After the fabric or fabric assembly reaches equilibrium conditions, record measurements for power input and the conditions given in 9.1 (with the exception of air velocity) at least every 3 min for a minimum test period of 30 min to determine the total evaporative resistance of the fabric plus the air layer, (R_{et}).

9.3 *Calculations*—Calculate the total resistance to evaporative heat transfer, (R_{et}), provided by the liquid barrier, fabric, and surface air layer using Eq 2.

$$R_{et} = (P_s - P_a)\,A/H_E \tag{2}$$

where:

R_{et} = resistance to evaporative heat transfer provided by the fabric system and air layer (kPa·m²/W
A = area of the plate test section (m²),
P_s = water vapor pressure at the plate surface (kPa),
P_a = the water vapor pressure in the air (kPa), and
H_E = power input (W).

P_s and P_a are determined from water vapor saturation tables using T_s and T_a, respectively.

9.3.1 If the conditions of the test varied so that isothermal conditions were not maintained, then modify Eq 2 by subtracting H_c (rearranging Eq 1) from H_E.

9.3.2 Average the data from three specimens for the evaporative transfer tests to determine the mean R_{et} for the laboratory sample.

9.3.3 Determine the resistance to evaporative heat transfer provided by the specimen alone, R_{ef}, by subtracting the mean evaporative resistance value measured for the air layer and liquid barrier, R_{ebp} (that is, bare plate covered with the liquid barrier only), from the mean total evaporative resistance measured for the specimen, R_{et}.

10. Part C - Total Heat Loss in a Standard Environment

10.1 *Test Conditions*:

10.1.1 *Temperature of the Test Plate, Guard Section and Bottom Plate*—Maintain the temperature of these sections at 35 ± 0.5°C without fluctuating more than ± 0.1°C during a test.

10.1.2 *Air Temperature*—Maintain the air flowing over the test plate at 25°C ± 0.5°C without fluctuating more than ±0.1°C during a test.

10.1.3 *Relative Humidity*—Maintain the relative humidity of the air flowing over the plate at 65 ± 4 % and without fluctuating more than ± 4 % during a test. The dew point temperature corresponding to 65 % RH at 25°C is 18°C.

10.1.4 *Air Velocity*—Adjust the air velocity to meet the calibration requirements. Maintain the same air velocity for all calibrations and tests, and without fluctuating more than ±0.1 m/s over the duration of the test measurement.

10.2 *Procedures*:

10.2.1 Measure the bare plate thermal resistance, including the air layer and any apparatus contribution (R_{cbp}) in the same manner as that for R_{ct} except that the test plate shall not be covered with a test specimen. The bare plate thermal resistance shall be an average of at least three measurements with nothing mounted on the test plate.

10.2.2 For thermal resistance measurements, calibrate the apparatus as follows:

10.2.2.1 Place one layer of calibration fabric on the test plate and measure the total thermal resistance (R_{ct}).

10.2.2.2 Place two layers of calibration fabric on the test plate and measure the total thermal resistance (R_{ct}).

10.2.2.3 Place three layers of calibration fabric on the test plate and measure the total thermal resistance (R_{ct}).

10.2.2.4 Place four layers of calibration fabric on the test plate and measure the total thermal resistance (R_{ct}).

10.2.2.5 The apparatus shall meet the following constraints:

(a) (*a*) A graph of total thermal resistance versus number of layers of calibration fabric shall be linear for the bare plate value, one, two, three and four layers.

(b) (*b*) The slope of the linear regression shall be $0.0206 K·m^2/W$ ± 10 %.

(c) (*c*) No individual data measurement shall be outside ± 10 % of the value predicted by the linear regression.

(d) (*d*) The intrinsic thermal resistance of four layers of calibration fabric shall be $0.082 K·m^2/W$ ± 10 %.

10.2.2.6 If the apparatus cannot meet any one of these constraints, no specimens shall be tested until the apparatus is adjusted to meet these constraints.

10.2.2.7 Calibrate the apparatus, at least, whenever it is modified or repaired. Maintain the apparatus calibration according to good laboratory practice.

10.2.3 Place the fabric or fabrics to be tested on the hot plate surface and measure the total thermal resistance (R_{ct}). Place the test specimen on the test plate with the side normally facing the human body towards the test plate. In the case of multiple layers, arrange the specimens on the plate as on the human body. Eliminate bubbles and wrinkles within the test specimen and air gaps between the specimen and the plate or between specimen layers by smoothing without compressing. This smoothing of bubbles and wrinkles is one reason that the results from this test may not represent the performance of actual clothing worn by people. In many cases, trapped air in clothing can override any fabric effects.

10.2.3.1 Measurement of thermal resistance shall be done when equilibrium is reached.

10.2.3.2 Data used to calculate the thermal resistance shall be collected at lease every 5 min.

10.2.3.3 Equilibrium shall be a rate of change of less than 3 % per hour of the calculated thermal resistance over a period not less than 30 min.

10.2.3.4 The standard deviation of calculated thermal resistance shall be less than 1 %.

10.2.4 After testing all specimens for thermal resistance, perform the following procedures before the evaporative measurements are made.

10.2.4.1 Feed distilled water to the test plate so that water uniformly wets the test plate and guard section surface.

10.2.4.2 Cover the test plate and guard section with the liquid barrier to prevent wetting of the test specimen by the liquid water. Adhere the liquid barrier closely to the test plate and guard section with no wrinkles or air bubbles present.

10.2.4.3 Make no adjustments to the apparatus or test conditions. These parameters shall be the same for all the thermal and evaporative resistance measurements.

10.2.5 Measure the bare plate evaporative resistance, including the air layer, the liquid barrier, and any apparatus contribution (R_{ebp}). In the same manner as that for (R_{et}) except that the test plate and liquid barrier shall not be covered with a test specimen. The bare plate evaporative resistance shall be an average of at least three measurements with only the liquid barrier mounted on the test plate. For this measurement, the local environmental climate shall be permitted to increase above 25°C, if necessary, to maintain test plate temperature at 35°C, or the plate temperature shall be permitted to decrease below 35°C, if necessary, due to limited energy available to the test plate.

10.2.6 For evaporative resistance measurements, calibrate the apparatus as follows:

10.2.6.1 Place one layer of calibration fabric on the test plate and measure the apparent total evaporative resistance (R_{et}^A).

10.2.6.2 Place two layers of calibration fabric on the test plate and measure the apparent total evaporative resistance (R_{et}^A).

10.2.6.3 Place three layers of calibration fabric on the test plate and measure the apparent total evaporative resistance (R_{et}^A).

10.2.6.4 Place four layers of calibration fabric on the test plate and measure the apparent total evaporative resistance (R_{et}^A).

10.2.6.5 The apparatus shall meet the following constraints:

(a) (*a*) A graph of apparent total evaporative resistance (R_{et}^A) versus number of layers of calibration fabric shall be linear for the bare plate value, one, two, three and four layers.

(b) (*b*) The slope of the linear regression shall be .005 $kPa·m^2/W$ ± 10 %.

(c) (*c*) No individual data measurement shall be outside ± 10 % of the value predicted by the linear regression.

(d) (*d*) The apparent intrinsic evaporative resistance ($R_{ef}{}^A$) of four layers of calibration fabric shall be 0.020 kPa·m²/W ±10 %.

10.2.6.6 If the apparatus cannot meet any one of these constraints, no specimens shall be tested until the apparatus is adjusted to meet these constraints.

10.2.7 Measure the apparent total evaporative resistance ($R_{et}{}^A$) by placing the fabric or fabrics to be tested on the hot plate surface. Place the test specimen on the test plate with the side normally facing the human body towards the test plate. In the case of multiple layers, arrange the specimens on the plate as on the human body. Eliminate bubbles and wrinkles within the test specimen and air gaps between the specimen and the plate or between specimen layers by smoothing without compressing. This smoothing of bubbles and wrinkles is one reason that the results from this test may not represent the performance of actual clothing worn by people. In many cases, trapped air in clothing can override any fabric effects.

10.2.7.1 Measure the apparent total evaporative resistance when equilibrium is reached.

10.2.7.2 Collect data used to calculate apparent total evaporative resistance at least every 5 min.

10.2.7.3 Equilibrium shall be a rate of change of less than 3 % per hour of the calculated apparent total evaporative resistance over a period not less than 30 min.

10.2.7.4 The standard deviation of calculated total evaporative resistance shall be less than 1 %.

10.2.7.5 If data collection cannot be completed within 4 h after placing the specimen on the test plate, remove the specimen from the test plate and allow to dry at least 24 h at 20 ± 5°C before retesting. Subsequent data reporting shall state that drying was required. If the retest of the specimen still cannot be completed within 4 h, report that the specimen cannot be tested by this procedure.

10.3 *Calculations*:

10.3.1 Calculate the total thermal resistance of the specimen using Eq 1.

10.3.2 Determine the average intrinsic thermal resistance of the sample alone (R_{cf}) by subtracting the average bare plate resistance (R_{cbp}) from the average total thermal resistance (R_{ct}) of the specimens tested.

10.3.3 Calculate the apparent total evaporative resistance of the specimen using Eq 3.

$$R_{et}{}^A = [(P_s - P_a)A] / [H_E - (T_s - T_a)A/R_{ct}] \tag{3}$$

where:

$R_{et}{}^A$ = apparent total evaporative resistance of the specimen and surface air layer (kPa·m²/W),
P_s = water vapor pressure at the test plate surface (kPa),
P_a = water vapor pressure in the air flowing over the specimen (kPa),
A = area of the test plate (m²),
H_E = power input (W),
T_s = temperature at the test plate surface (°C),
T_a = temperature in the air flowing over the specimen (°C), and
R_{ct} = total thermal resistance of the specimen and surface air layer (K·m²/W).

10.3.4 Determine the average apparent intrinsic evaporative resistance of the sample alone ($R_{ef}{}^A$) by subtracting the average bare plate evaporative resistance (R_{ebp}) from the average apparent total evaporative resistance ($R_{et}{}^A$) of the specimens tested.

10.3.5 Determine the average intrinsic thermal resistance (R_{cf}) of each specimen by averaging all values obtained over the equilibrium period (minimum of six). Determine the average intrinsic thermal resistance (R_{cf}) of the laboratory sample by averaging the values for all specimens. If the results for any of the three individual specimens vary more than 10 % from the average of all three, then repeat the test on the specimen(s) lying outside the ± 10 % limit. If the retest produces a value(s) within the ± 10 % limit, then use the new value(s) instead. If the retest remains outside the ± 10 % limit, then test an additional three specimens.

10.3.6 Determine the average apparent intrinsic evaporative resistance ($R_{ef}{}^A$) of each specimen by averaging all values obtained over the equilibrium period (minimum of six). Determine the average apparent intrinsic evaporative resistance ($R_{ef}{}^A$) of the laboratory sample by averaging the values for all specimens. If the results for any of the three individual specimens vary more than 10 % from the average of all three, then repeat the test on the specimen(s) lying outside the ±10 % limit. If the retest produces a value(s) within the ± 10 % limit, then use the new value(s) instead. If the retest remains outside the ± 10 % limit, then test an additional three specimens.

10.3.7 Calculate the total heat loss of the laboratory sampling unit using Eq. 4.

$$Q_t = \frac{10°C}{R_{cf} + .04} + \frac{3.57\ kPa}{R_{ef}{}^A + .0035} \tag{4}$$

where:

Q_t = total heat loss (W/m²),
R_{cf} = average intrinsic thermal resistance of the laboratory sample determined in 10.3.5 (K·m²/W), and
$R_{ef}{}^A$ = average apparent intrinsic evaporative resistance of the laboratory sample determined in 10.3.6 (kPa·m²/W).

11. Part D - Insulation Value (I)

11.1 *Test Conditions*:

11.1.1 *Temperature of the Test Plate, Guard Section, and Bottom Plate*—Maintain the temperature of these sections at 35 ± 0.5°C and without fluctuating more than± 0.1°C during a test.

11.1.2 *Air Temperature*—Maintain the air temperature of the air flowing over the plate at 20 ± 0.5°C and without fluctuating more than ± 0.1°C during a test.

11.1.3 *Relative Humidity*—Maintain the relative humidity of the air flowing over the plate at 50 ± 4 % and without fluctuating more than ± 4 % during a test. The dew point temperature corresponding to 50 % RH at 20°C is 9°C.

11.1.4 *Air Velocity*—Maintain the air velocity at a mean value of 1 ±0.1 m/s and without fluctuating more than ±0.1 m/s over the duration of the test measurement.

11.2 *Procedures*:

11.2.1 Measure the insulation value (clo_t) by placing a fabric or fabric assembly on the test plate. Place the test specimen on the test plate with the side normally facing the human body towards the test plate. In the case of multiple layer, arrange the specimens on the plate as on the human body. Eliminate bubbles and wrinkles within the test specimen and air gaps between the specimen and the plate or between specimen layers by smoothing without compressing. This smoothing of bubbles and wrinkles is one reason that the results from this test may not represent the performance of actual clothing worn by people. In many cases, trapped air in clothing can override any fabric effects.

11.2.2 After the test specimen reaches steady-state conditions, record measurements for power input and the conditions given in 11.1 (with the exception of air velocity) at least every 3 min for a minimum test period of 30 min to determine the insulation value.

11.3 *Calculations*:

11.3.1 Calculate the insulation value for a fabric system including the surface air layer using Eq 5.

$$I = (T_s - T_a)A/.155 \cdot H_c \tag{5}$$

where:

I = insulation value, (clo_t),
A = area of the plate test section (m^2),
T_s = surface temperature of the plate (°C),
T_a = air temperature (°C), and
H_c = power input (W).

11.3.2 Average the insulation values for three test specimens to determine the insulation value for the laboratory sampling unit.

12. Part E - Permeability Index (i_m)

12.1 *Test Conditions*:

12.1.1 *Temperature of the Test Plate, Guard Section, and Bottom Plate*—Maintain the temperature of these sections at 35 ± 0.5°C and without fluctuating more than ± 0.1°C during a test.

12.1.2 *Air Temperature*—Maintain the air temperature of the air flowing over the plate at 35 ± 0.5°C and without fluctuating more than ± 0.1°C during a test.

12.1.3 *Relative Humidity*—Maintain the relative humidity of the air flowing over the plate at 50 ± 4 % and without fluctuating more than ± 4 % during a test. The dew point temperature corresponding to 50 % RH at 35°C is 23°C.

12.1.4 *Air Velocity*—Maintain the air velocity at a mean value of 1 ±0.1 m/s and without fluctuating more than ±0.1 m/s over the duration of the test measurement.

12.2 *Procedures*:

12.2.1 Feed distilled water to the surface of the test plate and guard section.

12.2.2 Cover the test plate and guard section with a liquid barrier that prevents wetting of the fabric specimens by liquid water. Adhere the liquid barrier closely to the test plate and guard section with no wrinkles or air bubbles present.

12.2.3 Measure the permeability index, (i_m), by placing a fabric or fabric assembly on the test plate. Place the test specimen on the test plate with the side normally facing the human body towards the test plate. In the case of multiple layers, arrange the specimens on the plate as on the human body. Eliminate bubbles and wrinkles within the test specimen and air gaps between the specimen and the plate or between specimen layers by smoothing without compressing. This smoothing of bubbles and wrinkles is one reason that the results from this test may not represent the performance of actual clothing worn by people. In many cases, trapped air in clothing can override any fabric effects.

12.2.4 After the test specimen reaches steady-state conditions, record measurements for power input and the conditions given in 12.1 (with the exception of air velocity) at least every 3 min for a minimum test period of 30 min to determine the permeability index.

12.3 *Calculations*:

12.3.1 Calculate the permeability index for a fabric system including the surface air layer using Eq 6.

$$i_m = .0094 I[P_s - P_a) A/H_E] \tag{6}$$

where:

i_m = permeability index (dimensionless),
I = insulation value determined according to Section 11 (clo_t),
P_s = water vapor pressure at the plate surface (kPa),
P_a = water vapor pressure in the air (kPa),
A = area of the test plate (m^2),
H_E = power input (W), and

P_s and P_a are determined from water vapor saturation tables using T_s and T_a, respectively.

12.3.2 Average the permeability index results for three test specimens to determine the permeability index for the laboratory sampling unit.

13. Report

13.1 State that the specimens were tested as directed in Test Method F 1868, Part A, B, C, D, or E, as appropriate.

13.2 Report the weight, thickness, material, and construction of the fabric tested, and the order and orientation of the specimen on the hot plate if a fabric assembly was tested.

13.3 Report any techniques how, when, and how often used to remove undesirable wrinkles.

13.4 Report the results according to Part A, B, C, D, or E, as appropriate.

13.5 Report any modification to the test.

13.6 Report the impingement angle, geometry, and velocity of the airflow.

14. Precision and Bias

14.1 *Interlaboratory Test Program*—The information given below is based on data obtained in the NFPA Committee on Protective Clothing for Structural Fire Fighting[9] in 1989. Four laboratories tested four three-layer composites representing a range of available structural fire fighting protective clothing ensembles. Each laboratory tested three specimens of each composite according to Section 10 of this test method. The design of the experiment is similar to that of Practice E 691.

14.2 The terms repeatability limit and reproducibility limit in Table 1 are used as specified in Practice E 177.

[9] Gohlke, D. J. "History of the Development of the Total Heat Loss Test Method", Performance of Protective Clothing: 6th Vol, ASTM STP 1273, Jeffrey O. Stull and Arthur D. Schwope, eds., ASTM, 1997.

TABLE 1 Total Heat Loss (W/m^2)–Precision Statistics

Material	Average Total Heat Loss (W/m^2)	Repeatability Standard Deviation (W/m^2)	Reproducability Standard Deviation (W/m^2)	Repeatability Limit (W/m^2)	Reproducability Limit (W/m^2)
A	259	6.5	18.1	18.1	50.7
B	202	8.3	23.7	23.3	66.4
C	114	3.5	8.8	9.8	24.6
D	130	4.8	11.3	13.4	31.6

14.3 *Bias*—Because there is no accepted reference material suitable for determining the bias for the procedure in this test method for measuring thermal and evaporative resistance, no statement on bias is being made.

15. Keywords

15.1 evaporative resistance; I; insulation; permeability index; thermal resistance; total heat loss