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

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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 intrinsic thermal resistance is from 0.002 to 0.5 $K \cdot m^2/W$ and for intrinsic evaporative resistance is from 0.0 to 1.0 $kPa \cdot m^2/W$.

1.3 The values in SI units shall be regarded as standard. No other units of measurement are included in this 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:*[2]

C177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus

D1518 Test Method for Thermal Resistance of Batting Systems Using a Hot Plate

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

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

F1291 Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin

F1494 Terminology Relating to Protective Clothing

F2370 Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin

2.2 *Other Standards:*

ISO 11092 Textiles–Physiological Effects–Measurement of Thermal and Water-Vapour Resistance Under Steady-State Conditions (Sweating Guarded-Hotplate Test)[3]

3. Terminology

3.1 *Definitions:*

3.1.1 *clo, n*—a unit of thermal resistance (insulation) equal to 0.155 $K \cdot m^2/W$.

3.1.1.1 *Discussion*—The value of the clo was selected as roughly the insulation value of typical indoor clothing, which should 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.

3.1.2 *evaporative resistance, n*—The resistance to the flow of moisture vapor from a saturated surface (high vapor pressure) to an environment with a lower vapor pressure.

3.1.2.1 *Discussion*— The evaporative resistance in units of $kPa \cdot m^2/W$ can be calculated for several different cases. 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

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

[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

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.

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

3.1.3.1 *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. The permeability index is calculated one of two ways.

i_m = permeability index calculated using the total thermal resistance and the total evaporative resistance of a material. The U.S. military uses this value in their databases on fabrics and clothing systems.

i_{mf} = permeability index calculated using the intrinsic thermal resistance and the intrinsic evaporative resistance of a material. ISO 11092 uses this value.

3.1.4 *thermal resistance, n*—the resistance to the flow of heat from a heated surface to a cooler environment.

3.1.4.1 *Discussion*—Thermal resistance in units of K•m²/W can be calculated for several different cases.

I_t = total insulation value of the test specimen and the air layer, expressed in clo units.

I_f = intrinsic thermal resistance of the fabric test specimen only, expressed in clo units.

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.

3.1.5 *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 metre.

3.1.5.1 *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 F1494.

4. Significance and Use

4.1 The thermal resistance and evaporative resistance provided by fabrics, films, coatings, foams, and leathers, including multi-layer assemblies, is of considerable importance in determining their 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, films, coatings, foams, and leathers, including multi-layer assemblies. 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 system for a given clothing application. While a possible indicator of clothing performance, measurements produced by the testing of fabrics have 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 and evaporative resistance of clothing systems can be measured with a heated manikin in an environmental chamber in accordance with Test Methods F1291 and F2370.

5. Interferences

5.1 Departures from the instructions of this test method 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 F1868 with the results.

6. Apparatus

6.1 *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 for testing Parts B and C. See Test Methods D1518, C177, and ISO 11092 for additional information on hot plates.

6.2 *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 test plate, guard, and bottom plate sections shall be controlled to measure the same temperature to within ±0.1°C of each other.

6.3 *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 metres). Overall accuracy of the power monitoring equipment must be within ±2 % of the reading for the average power for the test period.

6.4 *Temperature Sensors*—Temperature sensors shall 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.

6.5 *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 test chamber wall temperature shall be ±0.5°C of the air in the chamber. The relative humidity shall be maintained as specified in the individual procedure section.

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

6.6.1 *Relative Humidity Measuring Equipment*—Either a wet-and-dry bulb psychrometer, a dew point hygrometer, or other electronic humidity measuring device 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 %.

6.6.2 *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 in the air stream such that the air temperature sensor is not influenced by the plate temperature.

6.6.3 *Air Velocity Indicator*—Air velocity shall be measured with an accuracy of ±0.1 m/s using a hot wire anemometer. Air velocity is measured at a point 15 mm (nominal) from the plate surface or from the top of the test specimen surface to the bottom of the anemometer sensing element. The air velocity shall be measured at three positions located along a horizontal line perpendicular to the airflow, 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.

NOTE 1—The air velocity is to be measured 15 mm above the plate surface for bare plate measurements. The air velocity is to be measured 15 mm above the test specimen surface when testing fabric or systems. The 15 mm distance is to be the distance from the plate or test specimen to the anemometer sensing element (wire)—not to the bottom of the sensing element housing.

6.6.4 *Air Temperature Variations*—Air temperature variations during testing shall not exceed ±0.1°C

6.6.5 *Relative Humidity Variations*—Relative humidity variations during testing shall not exceed ±4 %.

6.6.6 *Air Velocity Variations*—Air velocity variations shall not exceed ±10 % of the mean value for data averaged over 5 min.

7. Materials

7.1 *Water*—For the evaporative resistance measurements in Parts B and C distilled, de-ionized, or reverse osmosis-treated water shall be used to wet the test plate surface.

7.2 *Liquid Barrier*—For the evaporative resistance measurements in Parts B and C, 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 = 0.060 (R_{cbp}/R_{ebp}). Examples include untreated cellophane film and microporous polytetraflouroethylene film.

7.3 *Verification Fabrics*[4]—A verification fabric is required for the verification in Part C. The verification fabric is 7.5 oz/yd^2, plain weave, yellow color with a fiber blend of 93 % meta-aramid, 5 % para-aramid, and 2 % anti-static with a durable water-repellent finish. Sources for the verification fabric are given in Footnote 4.

8. Sampling and Preparation of Test Specimens

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

8.2 *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.

8.3 *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.

9. Procedure Part A—Thermal Resistance (R_{ct} and R_{ct}; I_t and I_f)

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 and without fluctuating more than ±0.1°C during a test.

[4] Verification fabrics are available from TestFabrics at Testfabrics.com.

9.1.2 *Air Temperature*—Maintain the air temperature of the air flowing over the plate between 4 and 25°C without fluctuating more than ±0.1°C during a test.

9.1.2.1 Select an air temperature that will generate a power level in the middle range of the instrument while maintaining the plate temperature at 35°C. Thicker materials will need to be tested at lower temperatures.

9.1.3 *Relative Humidity*—Maintain the relative humidity of the air flowing over the plate between 20 and 80 % without fluctuating more than ±4 % during a test.

9.1.3.1 The relative humidity has little or no effect on fabric insulation under steady-state conditions. Under transient conditions, the absorption of moisture from the air will generate heat in the fabric, and the desorption of moisture will produce a cooling effect.

9.1.4 *Air Velocity*—Maintain the air velocity between 0.5 and 1.0 m/s without fluctuating more than ±0.1 m/s over the duration of the test measurement.

9.1.4.1 The method described in Test Method D1518 does not specify air velocity over the hot plate, and ISO 11092 specifies an air temperature of 20ºC, a relative humidity of 65 %, and an air velocity of 1.0 m/s.

9.2 *Procedures:*

9.2.1 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.

9.2.2 Measure the total thermal resistance, (R_{ct}), by placing a fabric or fabric system 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. Still air trapped between clothing layers can contribute to the insulation of the fabric system when worn on the body.

NOTE 2—Fabrics and fabric systems thicker than 0.5 cm should be tested on plates with a large guard section (for example, 12.7 cm) to prevent lateral heat loss through the edges of the fabric. If a large guard is not used, a lower insulation value will be measured.

9.2.3 After the fabric or fabric system reaches steady-state conditions, record measurements for power input and the conditions given in 9.1 (with the exception of air velocity) every 1 min for a minimum test period of 30 min to determine the total thermal resistance of the fabric plus the air layer, (R_{ct}).

9.3 *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} = total resistance to dry heat transfer provided by the fabric system and air layer (K·m^2/W),
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).

9.3.1 Average the data from three specimens for the dry thermal resistance tests to determine the average R_{ct} for the laboratory sampling unit.

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

9.3.3 To convert the insulation values measured in SI units to clo units, multiply by 6.45. R_{ct} is often designated as I_t and R_f is designated as I_f when insulation is expressed in clo units.

10. Procedure Part B—Evaporative Resistance (R_{et} and R_{ef}) and Permeability Index (i_m and i_{mf})

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 *Isothermal Conditions*—The air temperature is the same as the plate temperature, so no dry heat exchange is occurring between the plate and the environment. This is the preferred condition for measuring evaporative resistance.

10.1.2.1 *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.

10.1.2.2 *Air Velocity*—Maintain the air velocity between 0.5 and 1 m/s without fluctuating more than ±0.1 m/s over the duration of the test measurement. The air velocity should be the same for the dry thermal resistance test and the evaporative resistance test if both are being conducted on a fabric system.

10.1.2.3 *Relative Humidity*—The relative humidity shall be 40 ± 4 % during a test.

10.1.3 *Non-Isothermal Conditions*—The materials are tested under environmental conditions that simulate actual conditions of use. The same environmental conditions are used for the insulation test (Part A) and the non-isothermal sweating hot plate test. The air temperature is lower than the plate's temperature, so dry heat loss is occurring simultaneously with evaporative heat loss, and condensation may develop between the plate and the fabric, or between fabric layers, or both. The evaporative resistance determined under non-isothermal conditions shall be referred to as the apparent evaporative resistance value. The apparent evaporative resistance values for materials shall only be compared to those of other materials measured under the same environmental conditions.

10.1.3.1 State the air temperature, air velocity, and relative humidity used in the non-isothermal tests. (See Part C for the non-isothermal protocol used to evaluate materials used in NFPA protective clothing.)

NOTE 3—*ISO 11092 Test Conditions*—The environmental conditions specified in the ISO standard are an air temperature of 35°C (isothermal), a relative humidity of 40 %, and an air velocity of 1.0 m/s.

10.2 *Procedures:*

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

10.2.2 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.

10.2.3 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.

10.2.4 Measure the total evaporative resistance, (R_{et}), by placing a fabric or fabric system 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.

NOTE 4—In order to obtain consistent results, it is important that the sample remain flat against the plate. This will minimize the occurrence of unwanted air layers. Some fabrics and fabric systems have a tendency to ripple, swell, curl, or otherwise not lie flat during testing. The following protocol may be used in order to minimize the effect of this behavior.
1) Begin sweating hot plate test as normal, after approximately 20 minutes evaluate sample for flatness.
2) If necessary use the hand to eliminate bubbles, wrinkles, curls, etc., by smoothing the sample without compressing or stretching it. If tape or other device was used to secure the sample at the leading edge, remove prior to smoothing. After smoothing, re-secure the sample leading edge.
3) Place a metal bar, magnet, water vapor impermeable adhesive tape, or other retaining mechanism on each remaining edge of the sample. Care should be taken in the choice of the method to retain the sample. The retaining method should allow for possible additional movement of the sample during testing. Metal bars have shown to be suitable for this purpose. Appropriate metal bars are approximately 0.3-g per mm of length, 12-mm wide, 3-mm thick, and sufficient length to correspond with sample. Bars are to be replaced should they show signs of corrosion or wear.
4) Check the sample for smoothness and continue with testing. Should the sample not remain flat, repeat Steps 2-4.

10.2.5 After the fabric or fabric system reaches equilibrium conditions, record measurements for power input and the conditions given in 10.1 (with the exception of air velocity) every 1 min for a minimum test period of 30 min to determine the total evaporative resistance of the fabric plus the air layer, (R_{et}).

10.3 *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.

10.3.1 If the conditions of the test varied so that isothermal conditions were not maintained, or if non-isothermal conditions were used, then modify Eq 2 by subtracting H_c from H_E (see Eq 5 in Part C).

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

10.3.3 Determine the resistance to evaporative heat transfer provided by the specimen alone, R_{ef}, by subtracting the 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}.

NOTE 5—ISO 11092 defines the resistance to evaporative heat transfer provided by the fabric alone as R_{et} where "t" means "textile". In this standard and others, "t" means "total". The R_{et} values are also given in Pa units in ISO 11092. Therefore, for example, if the intrinsic thermal resistance of a fabric, R_{ef} = 0.0132 kPa · m²/W in this standard, then it would be R_{et} = 13.2 Pa · m²/W in the ISO standard.

10.4 Calculate the permeability index for a fabric system including the surface air layer using Eq 3.

$$i_m = 0.060\, R_{ct}/R_{et} \tag{3}$$

where:

i_m = permeability index (dimensionless),
R_{ct} = total insulation value determined in accordance with Part A, (K•m ²/W), and
R_{et} = total evaporative resistance determined in accordance with Part B, (kPa•m²/W).

10.5 Calculate the permeability index for a fabric system alone using Eq 4.

$$i_m = 0.060\, R_{cf}/R_{ef} \tag{4}$$

where:

i_m = permeability index (dimensionless),
R_{cf} = intrinsic insulation value determined in accordance with Part A, (K•m²/W), and
R_{ef} = intrinsic evaporative resistance determined in accordance with Part B, (kPa•m²/W).

11. Procedure Part C—Total Heat Loss in a Standard Environment

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 without fluctuating more than ±0.1°C during a test.

11.1.2 *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.

11.1.3 *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.

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

11.2 *Procedures:*

11.2.1 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.

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

11.2.2.1 Place one layer of verification fabric on the test plate and measure the total thermal resistance (R_{ct}), using Eq 1.

11.2.2.2 Place two layers of verification fabric on the test plate and measure the total thermal resistance (R_{ct}), using Eq 1.

11.2.2.3 Place three layers of verification fabric on the test plate and measure the total thermal resistance (R_{ct}), using Eq 1.

11.2.2.4 Place four layers of verification fabric on the test plate and measure the total thermal resistance (R_{ct}), using Eq 1.

11.2.2.5 The apparatus shall meet the following constraints:

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

(b) The slope of the linear regression shall be 0.0195 $K \cdot m^2/W \pm 10\ \%$.

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

(d) The intrinsic thermal resistance of four layers of verification fabric shall be 0.078 $K \cdot m^2/W \pm 10\ \%$.

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

11.2.2.7 Calibrate the apparatus, at least, whenever it is modified or repaired. Maintain the apparatus ~~calibration~~ in accordance with good laboratory practice.

11.2.3 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.

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

11.2.3.2 Data used to calculate the thermal resistance shall be collected at least every 5 min.

11.2.3.3 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.

11.2.3.4 The coefficient of variation of calculated thermal resistance shall be less than 10 %.

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

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

11.2.4.2 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.

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

11.2.5 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.

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

11.2.6.1 Place one layer of verification fabric on the test plate and measure the apparent total evaporative resistance ($R_{et}{}^{A}$), using Eq 3.

11.2.6.2 Place two layers of verification fabric on the test plate and measure the apparent total evaporative resistance ($R_{et}{}^{A}$), using Eq 3.

11.2.6.3 Place three layers of verification fabric on the test plate and measure the apparent total evaporative resistance ($R_{et}{}^{A}$), using Eq 3.

11.2.6.4 Place four layers of verification fabric on the test plate and measure the apparent total evaporative resistance ($R_{et}{}^{A}$), using Eq 3.

11.2.6.5 The apparatus shall meet the following constraints:

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

(2) The slope of the linear regression shall be 0.0043 $kPa \cdot m^2/W \pm 10\ \%$.

(3) No individual data measurement shall be outside $\pm 10\ \%$ of the value predicted by the linear regression.

(4) The apparent intrinsic evaporative resistance ($R_{ef}{}^{A}$) of four layers of verification fabric shall be 0.0172 $kPa \cdot m^2/W \pm 10\ \%$.

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

11.2.7 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.

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

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

11.2.7.3 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.

11.2.7.4 The coefficient of variation of calculated total evaporative resistance shall be less than 10 %.

11.2.7.5 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, 65 ± 5 % relative humidity 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.

11.3 *Calculations:*

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

11.3.2 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.

11.3.3 Calculate the apparent total evaporative resistance of the specimen using Eq 5.

$$R_{et}{}^{A} = [(P_s - P_a)A]/[H_T - (T_s - T_a)A/R_{ct}] \tag{5}$$

where:

$R_{et}{}^{A}$ = apparent total evaporative resistance of the specimen and surface air layer (kPa·m^2/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 (m^2),
H_T = 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·m^2/W).

11.3.4 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.

11.3.5 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.

11.3.6 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.

11.3.7 Calculate the total heat loss of the laboratory sampling unit using Eq 6.

$$Q_t = \frac{10°C}{R_{cf} + .04} + \frac{3.57\ kPa}{R_{ef}{}^{A} + .0035} \tag{6}$$

where:

Q_t = total heat loss (W/m^2),
R_{cf} = average intrinsic thermal resistance of the laboratory sample determined in 10.3.5 (K·m^2/W), and
$R_{ef}{}^{A}$ = average apparent intrinsic evaporative resistance of the laboratory sample determined in 11.3.6 (kPa·m^2/W).

12. Report

12.1 State that the specimens were tested as directed in Test Method F1868, Part A, B, or C, as appropriate.

12.2 Report the weight, thickness, composition, and construction of the fabric tested, and the order and orientation of the specimen on the hot plate if a fabric system was tested.

12.3 Report any techniques used to restrain fabrics during testing.

12.4 Report the results in accordance with Part A, B, or C, as appropriate.

12.5 Report any modification to the test.

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

13. Precision and Bias[5]

13.1 *Interlaboratory Test Program*—An interlaboratory study of Parts A-E of this standard was conducted in 2001 in accordance with Practice E691. Samples of three fabric systems were tested in each of six laboratories under different environmental conditions. Three replications were conducted. One lab's data were omitted from the statistical analysis because they deviated significantly from the others.

13.2 The terms repeatability limit and reproducibility limit in Tables 1-3 are used as specified in Practice E177. The tables were calculated using the relationship: limit = 2.8 × standard deviation.

13.3 *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.

14. Keywords

14.1 evaporative resistance; insulation; permeability index; thermal resistance; total heat loss

[5] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:F23-1005.

TABLE 1 Thermal Resistance Precision Statistics

Fabric and Part of Standard	Test Conditions	Mean Insulation Value (R_{cf}) (°C · m²/W)	95 % Repeatability Limit (Within a Lab) (r)	95 % Reproducibility Limit (Between Labs) (R)
Fabric 1 Part C (NFPA)	T_a = 25°C RH = 65 %	0.171	0.024	0.053
Fabric 2 Part C (NFPA)	T_a = 25°C RH = 65 %	0.130	0.013	0.047
Fabric 1 Part A	T_a = 20°C RH = 50 %	0.174	0.027	0.061
Fabric 3 Part A	T_a = 20°C RH = 50 %	0.008	0.003	0.010
Fabric 1 Part A	T_a = 20°C RH = 65 %	0.170	0.021	0.054
Fabric 3 Part A	T_a = 20°C RH = 65 %	0.009	0.004	0.013

TABLE 2 Evaporative Resistance Precision Statistics

Fabric and Part of Standard	Test Conditions	Mean Evaporative Resistance (R_{ef}) (kPa · m²/W)	95 % Repeatability Limit (Within a Lab) (r)	95 % Reproducibility Limit (Between Labs) (R)
Fabric 1 Part C (NFPA)	T_a = 25°C RH = 65 %	0.0321	0.0041	0.0042
Fabric 2 Part C (NFPA)	T_a = 25°C RH = 65 %	0.0168	0.0024	0.0024
Fabric 1 Part B	T_a = 35°C RH = 50 %	0.0610	0.0075	0.0202
Fabric 3 Part B	T_a = 35°C RH = 40 %	0.0197	0.0038	0.0047

TABLE 3 Total Heat Loss Precision Statistics

Fabric and Part of Standard	Test Conditions	Mean Total Heat Loss (Q_t) (W / m²)	95 % Repeatability Limit (Within a Lab) (r)	95 % Reproducibility Limit (Between Labs) (R)
Fabric 1 Part C (NFPA)	T_a = 25°C RH = 65 %	148.2	11.90	17.25
Fabric 2 Part C (NFPA)	T_a = 25°C RH = 65 %	236.0	24.48	30.64

APPENDIX

(Nonmandatory Information)

X1. END PRODUCT STANDARDS THAT REFERENCE THIS TEST METHOD

X1.1 Various end product standards for protective clothing refer to this test method. Among them are:
1) NFPA 1951, Standard on Protective Ensembles for Technical Rescue Operations[6]
2) NFPA 1971, Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting[6]
3) NFPA 1977, Standard on Protective Clothing and Equipment for Wildland Fire Fighting[6]
4) NFPA 1994, Standard on Protective Ensembles for First Responders to CBRN Terrorism Incidents[6]
5) NFPA 1999, Standard on Protective Clothing for Emergency Medical Protective Operations[6]

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