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Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate¹

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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 thermal resistance is from 0.002 to 0.2 $\text{K}\cdot\text{m}^2/\text{W}$ and for evaporative resistance is from 0.01 to 1.0 $\text{kPa}\cdot\text{m}^2/\text{W}$.

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:²

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

D 1518 Thermal Transmittance of Textile Materials

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

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

F 1291 Test Method for Measuring the Thermal Insulation

of Clothing Using a Heated Manikin

F 1494 Terminology Relating to Protective Clothing

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

NFPA 1971 Protective Clothing for Structural Fire Fighting⁴

NFPA 1977 Protective Clothing and Equipment for Wildland Fire Fighting⁴

3. Terminology

3.1 Definitions:

3.1.1 *clo, 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 $0.155 \text{ K}\cdot\text{m}^2/\text{W}$.

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

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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.

⁴ Available from National Fire Protection Assoc., 1 Batterymarch Park, Quincy, MA 02269.

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*—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 ($W/m^2 \cdot K$). 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:

I_t = total insulation value of the test specimen and the air layer, 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.

3.1.7 *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,

3.1.7.1 *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 in accordance with Test Method F 1291.

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 $\pm 0.1^\circ\text{C}$.

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 $\pm 2\%$ 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 $\pm 0.1^\circ\text{C}$.

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 $\pm 0.5^\circ\text{C}$ 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 $\pm 4\%$.

5.6.2 *Air Temperature Sensors*—Shielded air temperature sensors shall be used. Any sensor with an overall accuracy of $\pm 0.1^\circ\text{C}$ 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 $\pm 10\%$ of the mean value.

5.6.4 *Temporal Variations*—Temporal variations shall not exceed the following air temperature $\pm 0.1^\circ\text{C}$, relative humidity $\pm 4\%$, and air velocity $\pm 10\%$ 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 polytetrafluoroethylene film, and so forth.

6.3 *Calibration Fabrics*⁵—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 $35 \pm 0.5^\circ\text{C}$ and without fluctuating more than $\pm 0.1^\circ\text{C}$ during a test.

8.1.2 *Air Temperature*—Maintain the air temperature of the air flowing over the plate at $20 \pm 0.5^\circ\text{C}$ without fluctuating more than $\pm 0.1^\circ\text{C}$ during a test.

8.1.3 *Relative Humidity*—Maintain the relative humidity of the air flowing over the plate at $65 \pm 4\%$ and without fluctuating more than $\pm 4\%$ 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:

8.2.1 Measure the bare plate thermal resistance, (R_{cbp}), in the same manner as that for R_{ct} except that the test plate shall

⁵ 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.

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.

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

where:

R_{ct} = resistance to dry heat transfer provided by the fabric system and air layer ($\text{K}\cdot\text{m}^2/\text{W}$),
 A = area of the plate test section (m^2),
 T_s = surface temperature of the plate ($^{\circ}\text{C}$),
 T_a = air temperature ($^{\circ}\text{C}$), and
 H_c = power input (W).

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

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 $35 \pm 0.5^{\circ}\text{C}$ without fluctuating more than $\pm 0.1^{\circ}\text{C}$ during a test.

9.1.2 *Air Temperature*—Maintain the air temperature of the air flowing over the plate at $35 \pm 0.5^{\circ}\text{C}$ and without fluctuating more than $\pm 0.1^{\circ}\text{C}$ during a test.

9.1.3 *Relative Humidity*—Maintain the relative humidity of the air flowing over the plate at $40 \pm 4\%$ and without fluctuating more than $\pm 4\%$ 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.

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

where:

R_{et} = resistance to evaporative heat transfer provided by the fabric system and air layer ($\text{kPa}\cdot\text{m}^2/\text{W}$)
 A = area of the plate test section (m^2),
 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 resistance 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} .

9.3.3.1 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