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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 intrinsic thermal resistance is from 0.002 to 0.5 K·m²/W and for intrinsic evaporative resistance is from 0.0 to 1.0 kPa·m²/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.*

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

2. Referenced Documents

2.1 ASTM Standards:²

¹ This test method is under the jurisdiction of ASTM Committee F23 on Personal Protective Clothing and Equipment and is the direct responsibility of Subcommittee F23.60 on Human Factors.

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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.

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·m²/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/m²) 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 Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

3.1.2.1 *Discussion*— The evaporative resistance in units of $\text{kPa}\cdot\text{m}^2/\text{W}$ 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 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_{er} , 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_{er} = 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 $\text{K}\cdot\text{m}^2/\text{W}$ 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_{er} , 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 one position perpendicular to the airflow, at the center of the plate.

6.6.3.1 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.

6.6.3.2 At a minimum, annually verify that air velocity spatial variation does not exceed ± 10 % of the mean value. Measurements of 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.

6.6.3.3 The additional two anemometers needed for spatial variation must meet the same requirements as defined in section **6.6.3** and shall be permitted to be external anemometers or integral anemometers to the system.

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 polytetrafluoroethylene film.

7.3 Verification Fabrics⁴—A verification fabric is required for the verification in Part C. The verification fabric is 7.5 oz/yd², 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.

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

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_{cf} ; 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.

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 20 °C, 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 1—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.

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

where:

R_{ct} = total 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 (°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