INTERNATIONAL

Designation: ~~F2370 – 15~~ F2370 – 16

Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin[1]

This standard is issued under the fixed designation F2370; 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

The type of clothing worn by people directly affects the heat exchange between the human body and the environment. The heat transfer is both sensible (conduction, convection, and radiation) and latent (evaporation). The evaporative resistance of a clothing ensemble is dependent upon the designs and materials used in the component garments, the amount of body surface area covered by the clothing, the distribution of the layers over the body, looseness or tightness of fit, and the increased surface area for heat loss. Evaporative resistance measurements made on fabrics alone do not take these factors into account. Measurements of the resistance to evaporative heat loss provided by clothing can be used with thermal resistance values (Test Method F1291) to determine the comfort or stress of people in different environments.

1. Scope

1.1 This test method covers the determination of the evaporative resistance of clothing ensembles. It describes the measurement of the resistance to evaporative heat transfer from a heated sweating thermal manikin to a relatively calm environment. Information on measuring the local evaporative resistance values for individual garments and ensembles is provided in Annex A1.

1.1.1 This is a static test that provides a baseline clothing measurement on a standing manikin.

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

1.2 The evaporative resistance values obtained apply only to the particular ensembles evaluated and for the specified environmental conditions of each test, particularly with respect to air movement and sweating simulations.

1.3 Evaporative resistance values reported 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 establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

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

2.2 *ISO Standards:*[3]

~~ISO 9920~~ISO 9920:2007 Ergonomics of the Thermal Environment—Estimation of the Thermal Insulation and Evaporation Resistance of a Clothing Ensemble

3. Terminology

3.1 ~~*Definitions of Terms Specific to This Standard:*~~*Definitions:*

3.1.1 *clothing area factor* (f_{cl}), *n*—the ratio of the surface area of the clothed body to the surface area of the nude body.

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[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.

Current edition approved ~~Nov. 1, 2015~~Oct. 1, 2016. Published ~~December 2015~~October 2016. Originally approved in 2005. Last previous edition approved in ~~2010~~2015 as ~~F2370 - 10.~~F2370 - 15. DOI: ~~10.1520/F2370-15.~~10.1520/F2370-16.

[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.

3.1.2 *clothing ensemble, n*—a group of garments worn together on the body at the same time.

3.1.3 *evaporative resistance, n*—the resistance to evaporative heat transfer from the body to the environment.

3.1.3.1 *Discussion*—

The ~~evaporative resistance values can be used to compare different clothing ensembles as long as each test is conducted using the same experimental procedures and test conditions. The~~ following evaporative resistance values can be determined in this ~~method:~~test method when measured under isothermal condititions:

~~R_{ea} = evaporative resistance of the air layer on the surface of the nude manikin's sweating surface measured under isothermal conditions.~~
~~R_{et} = total evaporative resistance of the clothing and surface air layer around the manikin measured under isothermal conditions.~~
~~R_{ecl} = intrinsic evaporative resistance of the clothing measured under isothermal conditions.~~
~~AR_{ea} = apparent evaporative resistance of the air layer on the surface of the nude manikin's sweating surface measured under non-isothermal conditions.~~
~~AR_{et} = apparent total evaporative resistance of the clothing and surface air layer around the manikin measured under non-isothermal conditions.~~
~~AR_{ecl} = apparent intrinsic evaporative resistance of the clothing measured under non-isothermal conditions.~~

R_{ea} = evaporative resistance of the air layer on the surface of the sweating nude manikin.
R_{et} = total evaporative resistance of the clothing and surface air layer around the manikin.
R_{ecl} = intrinsic evaporative resistance of the clothing. When measurements are made under non-isothermal conditions, the following apparent evaporative resistance values can be determined.
AR_{ea} = apparent evaporative resistance of the air layer on the surface of the sweating nude manikin.
AR_{et} = apparent total evaporative resistance of the clothing and surface air layer around the manikin.
AR_{ecl} = apparent intrinsic evaporative resistance of the clothing.

Total evaporative resistance values are measured directly with a manikin. Intrinsic clothing evaporative resistance values are determined by subtracting the air layer resistance around the clothed manikin from the total evaporative resistance value for the ensemble.

3.1.4 *total thermal resistance* (R_t) —the total ~~resistance to dry heat loss from the manikin that includes the resistance provided by the ensemble and the~~thermal resistance (insulation) of the clothing and surface air layer around the ~~clothed manikin.~~manikin.

4. Significance and Use

4.1 This test method can be used to quantify and compare the evaporative resistance provided by different clothing systems. The evaporative resistance values for ensembles measured under isothermal conditions can be used in models that predict the physiological responses of people in different environmental conditions. Garment evaporative resistance values can be compared as well (see Annex A1).

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

5. Apparatus[4]

5.1 *Manikin*—A standing manikin shall be used that is formed in the shape and size of an adult male or female and heated to a constant average surface temperature.

5.1.1 *Size and Shape*—The manikin shall be constructed to simulate the body of a human being; that is, it shall consist of a head, chest/back, abdomen/buttocks, arms, hands (preferably with fingers extended to allow gloves to be worn), legs, and feet. Total surface area shall be 1.8 ± 0.3 m^2, and height shall be 170 ± 10 cm. The manikin's dimensions shall correspond to those required for standard sizes of garments because deviations in fit will affect the results.

5.1.2 *Sweat Generation*—The manikin must have the ability to evaporate water from its surface. ~~Sweating~~ The sweating system can be a water-fed capillary body suit worn over a thermal manikin. Sweating can also be simulated by supplying water to and

[4] Information on laboratories with sweating manikins can be obtained from the Textile Protection and Comfort Center, North Carolina State University, Raleigh, NC 27695 or from the Institute for Environmental Research, Kansas State University, Manhattan, KS 66506.

maintaining it at the inner surface of a waterproof, but moisture-permeable fabric skin. ~~Other technologies exist that deliver water to the manikin's surface with a valve delivery system.~~

5.1.2.1 *Sweating Surface Area*—The entire surface of the manikin shall be heated and sweating including the head, chest, back, abdomen, buttocks, arms, hands, legs, and feet.

5.1.3 *Surface Temperature*—The manikin shall be constructed so as to maintain a uniform temperature distribution over the nude body surface, with no local hot or cold spots. The mean surface (skin) temperature of the manikin shall be 35°C. Local deviations from the mean surface temperature shall not exceed ±0.5°C. Temperature uniformity of the nude manikin shall be evaluated at least once annually using an infrared thermal imaging system or equivalent method. This procedure shall also be repeated after repairs or alterations are completed that could affect temperature uniformity, for example, replacement of a heating element.

5.2 ~~*Methods of Measuring Evaporative Resistance*—~~*Power-Measuring Instruments*—~~The evaporative resistance of a clothing system~~ Power to the manikin shall be measured ~~by measuring the power consumption of the manikin (Option 1 in~~so as to give an average over the period of a test. If time proportioning or phase proportioning is used for power control, then devices that are capable of averaging over the control cycle are required. ~~8.6) or by measuring the evaporation rate of the liquid exiting the garment (Option 2 in~~Integrating devices (watt-hour meters) 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 ~~8.6).~~test period. Since there are a variety of devices and techniques used for power measurement, no specified calibration procedures shall be given. However, an appropriate power calibration procedure is to be developed and documented.

~~5.2.1 *Power-Measuring Instruments*—If power consumption method (Option 1) is used to calculate evaporative resistance, the power to the manikin shall be measured so as to give an average over the period of a test. If time proportioning or phase proportioning is used for power control, then devices that are capable of averaging over the control cycle are required. Integrating devices (watt-hour meters) 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. Since there are a variety of devices and techniques used for power measurement, no specified calibration procedures shall be given. However, an appropriate power calibration procedure is to be developed and documented.~~

~~5.2.2 *Equipment for Measuring Evaporative Water Loss*—If the rate of evaporation method (Option 2) is used to calculate evaporative heat loss, the mass loss due to evaporation shall be measured by a set of balances to give an accurate average over the period of a test. One balance shall be used to measure the amount of water being fed to the manikin while the other measures the weight change of the manikin. Both balances shall be calibrated yearly and have a resolution to the nearest gram.~~

~~5.2.2.1 *Measuring Water Dripping from the Manikin*—A pan large enough to retain all water drippings from the manikin during steady-state measurements, must be utilized if the rate of evaporation method (Option 2) is used to calculate the evaporative resistance of a clothing system. The captured water shall be measured at the end of the test with a calibrated balance having a resolution to the nearest gram. Water loss from dripping is subtracted out of the evaporation rate used to calculate evaporative resistance.~~

~~*Discussion*—If evaporation from the collection pan is a concern, place a highly absorbent material (example: diaper lining) in the pan to collect and retain all liquid that has dripped from the manikin.~~

5.3 *Equipment for Measuring the Manikin's Surface (Skin) Temperature*—The mean surface temperature shall be measured with point sensors or distributed temperature sensors.

5.3.1 *Point Sensors*—Point sensors shall be thermocouples, resistance temperature devices (RTD's), thermistors, or equivalent sensors. They shall be no more than 2 mm thick and shall be well-bonded, both mechanically and thermally, to the manikin's surface. Lead wires shall be bonded to the surface or pass through the interior of the manikin, or both. Each sensor temperature shall be area-weighted when calculating the mean surface temperature for the body. ~~A~~ If point sensors are used, a minimum of 15 point sensors are required. At least one sensor shall be placed on the head, chest, back, abdomen, buttocks, and both the right and left upper arm, lower arm, hand, thigh, calf, and foot. These sensors must be placed in the same position for each test and the placement of the sensors shall be given in the report.

5.3.2 *Distributed Sensors*—If distributed sensors are used (for example, resistance wire), then the sensors must be distributed over the surface so that all areas are equally weighted. If several such sensors are used to measure the temperature of different parts of the body, then their respective temperatures shall be area-weighted when calculating the mean surface (skin) temperature. Distributed sensors shall be less than 1 mm in diameter and firmly attached to the manikin surface at all points.

5.4 *Controlled Environmental Chamber*—The manikin shall be placed in a chamber at least 1.5 by 1.5 by 2.5 m in dimension that can provide uniform conditions, both spatially and temporally.

5.4.1 *Spatial Variations*—Spatial variations shall not exceed the following: air temperature ±1°C, relative humidity ±5 %, and air velocity ±50 % of the mean value. In addition, the mean radiant temperature shall not be more than 1.0°C different from the mean air temperature. The spatial uniformity shall be verified at least annually or after any significant modifications are made to the chamber. Spatial uniformity shall be verified by recording values for the conditions stated above at heights of 0.1, 0.6, 1.1, 1.4, and 1.7 m above the floor at the location occupied by the manikin. Sensing devices specified below shall be used when measuring the environmental conditions.

5.4.2 *Temporal Variations*—Temporal variations shall not exceed the following: air temperature ±0.5°C, mean radiant temperature ±0.5°C, relative humidity ±5 %, air velocity ±20 % of the mean value for data averaged over 5 min. (see 5.4.5).

5.4.3 *Relative Humidity Measuring Equipment*—Any humidity sensing device with an accuracy of ±5 % relative humidity and a repeatability of ±3 % is acceptable (for example, wet bulb/dry bulb, dew point hygrometer). Only one location needs to be monitored during a test to ensure that the temporal uniformity requirements are met.

5.4.4 *Air Temperature Sensors*—Shielded air temperature sensors shall be used. Any sensor with an overall accuracy of ±0.15°C is acceptable (for example, RTD, thermocouple, thermistor). The sensor shall have a time constant not exceeding 1 min. The sensor(s) shall be 0.5 m ~~from~~ in front of the manikin. If a single sensor is used, it shall be 1.0 m above the floor. If multiple sensors are used, they shall be spaced at equal height intervals and their readings averaged.

5.4.5 *Air Velocity Indicator*—An omni-directional anemometer with ±0.05 m/s accuracy shall be used. Measurements shall be averaged for at least 1 min at each location. If it is demonstrated that velocity does not vary temporally by more than ±0.05 m/s, then it is not necessary to monitor air velocity during a test. However, the value of the mean air velocity must be reported. If air velocity is monitored, then measurement location requirements are the same as for temperature.

6. ~~Sampling, Test Specimens,~~ Sampling and Test ~~Units~~Specimens

6.1 *Sampling*—It is desirable to test three identical ensembles to reflect sample variability. However, if only one ensemble is available (that is often the case with prototype garments), replicate measurements shall be made on one ensemble.

6.1.1 If only one ensemble is available, the garments must be removed from the manikin after each test, dried, and conditioned as specified in 6.4 before retesting.

6.2 *Specimen Size and Fit*—Select the size of garments that will fit the manikin appropriately (that is, the way the manufacturer designed them to be worn on the human body during their intended end use). For example, some knitted garments are designed to fit the body relatively tightly. Others are designed to fit loosely to accommodate a wider range of body dimensions or to allow other garments to be worn underneath. In a stationary manikin test, large air layers in the clothing system will contribute to a higher evaporative resistance value than small air layers. Therefore, garments that do not have the appropriate fit on the manikin (that is, too tight or too loose), will cause errors in measurement.

6.2.1 When manikin measurements are used to compare materials used in certain garments, those garments must be made from the same pattern so that design and fit variables are held constant. In addition, they must be tested with the same companion garments in the ensemble (for example, underwear, footwear, and so forth).

6.2.2 When manikin measurements are used to compare a variety of garments, the same size garments of a given type shall be tested as indicated by the size label in the garments (for example, large). However, if it is determined that the fit of a garment is inappropriate, ~~another size may be used and stated~~ it is acceptable to use another size and state it in the report.

6.3 *Specimen Preparation*—Garments shall be tested in the as-received condition or after dry cleaning or laundering in accordance with the manufacturer's instructions. The cleaning procedures and number of processings shall be stated in the report.

6.4 *Conditioning*—Allow the clothing components to come to equilibrium with the atmosphere in the test chamber by conditioning them in the chamber for at least 12 hours.

7. Calibration of Sweating Manikin

7.1 *Calibration*—Calibrate the sweating manikin using the isothermal procedures in Section 8.

7.1.1 The intrinsic clothing evaporative resistance of the calibration ensemble (R_{ecl}) is 0.016 (kPa·m^2/W), assuming the f_{cl} value is 1.22.

7.2 *Calibration Clothing Ensemble*—The garments required for use in this calibration ensemble are:

7.2.1 *Protective Nomex III Shirt*—203 g/m^2 (6.0 oz/yd^2) plain weave Nomex IIIA button up long sleeve shirt (Bulwark #SND6NV), with two chest pockets.[5] The shirttail shall hang over the trousers, and the top button shall remain unbuttoned.

7.2.2 *Protective Nomex III Pants*—203 g/m^2 (6.0 oz/yd^2) plain weave Nomex IIIA pants (Bulwark #PNW3NV), with two side pockets and two back pockets.[5]

7.2.3 *Men's Underwear Briefs*—180 g/m^2 (5.3 oz/yd^2) ± 10 %, 100 % cotton jersey knit; jockey style that fits snugly at the waist and legs.

7.2.4 *Men's T-Shirt*—140 g/m^2 (4.1 oz/yd^2) ± 10 %, 100 % cotton jersey knit, short-sleeve, crew neck T-shirt.

7.2.5 *Men's Socks*—Basic knit sock that covers foot and extends up the calf no more than 25.4 cm (10 in.) from the bottom of the heel. Each individual sock must be composed of at least 75 % cotton and shall weigh 33 ± 5 ~~g each.~~g.

7.2.6 *Athletic Shoes*—Fabric/soft leather and soft sole.

7.2.7 The size of the calibration garments shall be selected based on the measurements of the manikin. The garments shall fit the manikin properly as described in 6.2.

[5] The sole source of supply for the Nomex IIIA shirt and pants known to the committee at this time is Bulwark Protective Apparel, 545 Marriott Drive, Nashville, TN 37214; Phone: 800-667-0700. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.