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Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin¹

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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 insulation provided by 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. Insulation measurements made on fabrics alone do not take these factors into account. Measurements of the resistance to dry heat loss provided by clothing can be used to determine the thermal comfort or stress of people in a variety of environments (see Practice F2732, ASHRAE 55-2013, and ISO 7730:2005). However, the moisture permeability of clothing is more important in environmental conditions where heat balance can only be achieved by the evaporation of sweat.

1. Scope

1.1 This test method covers the determination of the insulation value of clothing ensembles. It describes the measurement of the resistance to dry heat transfer from a heated manikin to a relatively calm, cool environment. Information on measuring the local thermal 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 insulation values obtained apply only to the particular ensembles evaluated and for the specified environmental conditions of each test, particularly with respect to air movement.

1.3 The values stated in either clo or SI units are to be regarded separately as standard. Each system shall be used independently of the other. The thermal resistance units, clo or SI, shall be identified clearly and consistency of units shall be maintained throughout reporting process.

1.4 The evaporative resistance of a clothing ensemble can be measured in accordance with Test Method F2370.

1.5 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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.

1.6 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

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

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

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

F2732 Practice for Determining the Temperature Ratings for Cold Weather Protective Clothing

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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.

2.2 *ASHRAE Standards*:³

ASHRAE 55-2013 Thermal Environmental Conditions for Human Occupancy

2.3 *ISO Standards*:⁴

ISO 7730:2005 Moderate Thermal Environments—Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort

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*:

3.1.1 *clo*, *n*—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 person (producing heat at the rate of 58 W/m²) comfortable in an environment at 21 °C, air movement 0.1 m/s. When clo was developed, typical indoor clothing consisted of a three-piece suit and light underclothes.

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

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

3.1.4 *thermal insulation*, *n*—the resistance to dry heat transfer via conduction, convection, and radiation.

3.1.4.1 *Discussion*—The following insulation values are determined in this method:

R_a = thermal resistance (insulation) of the air layer on the surface of the nude manikin,

R_t = total thermal resistance (insulation) of the clothing ensemble and surface air layer around the manikin, and

R_{cl} = intrinsic thermal resistance (insulation) of the clothing ensemble.

R_a , R_t , and R_{cl} are typically used for SI units, while I_a , I_t , and I_{cl} are typically used with clo units.

Total insulation values are measured directly with a manikin. Intrinsic clothing insulation values are determined by subtracting the air layer resistance around the clothed manikin from the total insulation value for the ensemble. Intrinsic clothing insulation values are used in several thermal comfort and clothing standards (see 2.1, 2.2, and 2.3).

4. Significance and Use

4.1 This test method can be used to quantify and compare the insulation provided by different clothing systems. For example, variations in the design and fabric used in component garments can be evaluated. The effects of garment layering,

closure, and fit can be measured for clothing ensembles. The insulation values for ensembles can be used in models that predict the physiological responses of people in different environmental conditions. Garment insulation values can be compared as well (see Annex A1).

4.2 The measurement of the insulation provided by clothing is complex and dependent on 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, temperature 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.

4.3 Report the insulation values in SI units or clo units as standard procedure. Conversion factors to other units are given in Test Method D1518.

5. Apparatus⁵

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 skin 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 m², 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 *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 skin 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 *Power-Measuring Instruments*—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

³ Available from American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE), 1791 Tullie Circle, NE, Atlanta, GA 30329, <http://www.ashrae.org>.

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

⁵ Information on laboratories with thermal manikins can be obtained from the Institute for Environmental Research, Kansas State University, Manhattan, KS 66506.

for power measurement, no specified calibration procedures shall be given. However, an appropriate power calibration procedure is to be developed and documented.

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 (RTDs), 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 skin temperature for the body. If point sensors are used, a minimum of 17 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 must 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 ± 1.0 °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 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 omnidirectional 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. The value of the mean air velocity must be reported, however. If air velocity is monitored, then measurement location requirements are the same as for temperature.

6. Sampling and Test 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.

6.2 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 insulation value than small air layers. Therefore, garments that do not have the appropriate fit on the manikin (that is, are 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, 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 h.

7. Calibration of Manikin

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

7.1.1 The intrinsic clothing insulation value of the calibration ensemble (R_{cl}) is $0.122 \text{ } ^\circ\text{C}\cdot\text{m}^2/\text{W}$ or (I_{cl}) 0.79 clo , 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.⁶ The shirt tail 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.⁶

7.2.3 *Men's Underwear Briefs*— 180 g/m^2 (5.3 oz/yd^2) $\pm 10 \%$, 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) $\pm 10 \%$, 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 $33 \pm 5 \text{ g}$.

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.

8. Test Procedure

8.1 *Environmental Test Conditions*—The test conditions given below shall be standard for all tests.

8.1.1 *Air Temperature*—The air temperature shall be at least $12 \text{ } ^\circ\text{C}$ lower than the manikin's mean temperature (that is, $23 \text{ } ^\circ\text{C}$) during a test. When ensembles with high insulation values are tested (for example, cold weather clothing), the air temperature shall be lowered so that a minimum average heat flux of 20 W/m^2 from the manikin's segments is maintained.

8.1.2 *Air Velocity*—The air velocity shall be $0.4 \pm 0.1 \text{ m/s}$ during a test.

8.1.3 *Relative Humidity*—Select a level between 30 and 80% relative humidity $\pm 5 \%$, preferably 50% . The relative humidity has no effect on measurements of insulation under steady-state conditions.

8.1.4 If it is necessary to test the clothing ensembles in different environmental conditions (air temperature, air velocity, or relative humidity), the conditions must be clearly defined and reported.

8.2 *Mean Surface (Skin) Temperature of Manikin*—The manikin's surface temperature shall be maintained at $35 \pm 0.5 \text{ } ^\circ\text{C}$ for all tests. The mean surface temperature shall not be allowed to drift more than $\pm 0.2 \text{ } ^\circ\text{C}$ during a 30 min test.

8.3 Dress the standing manikin in the garments to be tested. Record a description of the garments and the dressing procedure.

⁶ The sole source of supply of 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.

dures. For example: Is the shirt tail tucked in the pants or is it left hanging out? Are all fasteners closed? Position the manikin so that it is hanging with its arms at its sides and its feet above the floor. Take a photograph of the ensemble on the manikin for the report (optional).

8.3.1 Bring the dressed manikin to $35 \pm 0.5 \text{ } ^\circ\text{C}$ and allow the system to reach steady-state (that is, the mean surface temperature of the manikin and the power input remain constant $\pm 3 \%$).

8.3.2 After the manikin system reaches equilibrium conditions, record the manikin's surface temperatures, the air temperature, and the power to the manikin's body segments every 1 min . The average of these measurements taken over a period of 30 min will be sufficient to determine the insulation value.

8.4 *Replication of Tests*—Three independent replications of the clothing test shall be conducted. If only one set of garments is being tested, remove them and put them back on the manikin for another test. In this way, normal variations in dressing and instrumentation will be taken into account.

8.5 *Nude Test*—Measure the insulation (R_a) provided by the air layer surrounding the nude manikin by conducting a test in the same environmental conditions used for the clothing tests. However, if a low temperature is being used to test cold weather clothing, it is feasible that the nude manikin's skin temperature will not be able to reach the $35 \text{ } ^\circ\text{C}$ set point. In this case, a higher air temperature is acceptable for the nude test. The nude manikin shall be tested at the beginning of each series of clothing tests.

9. Calculations

9.1 The parallel method of calculating the total thermal resistance (insulation) of the clothing ensemble shall be used. First the total thermal resistance for each single zone is calculated using Eq 1:

$$R_i = (T_i - T_a)A_i / H_i \quad (1)$$

where:

R_i = total thermal resistance (insulation) of the clothing and surface air layer around the manikin ($^\circ\text{C}\cdot\text{m}^2/\text{W}$),

A_i = surface area of a single zone of the manikin (m^2),

T_i = surface temperature of a single zone of the manikin ($^\circ\text{C}$),

T_a = air temperature ($^\circ\text{C}$), and

H_i = power required to heat a single zone of the manikin (W).

9.2 Then calculate the parallel weighted average for the multi-zone sections of the manikin using Eq 2:

$$R_t = A_{tot} / \Sigma(A_i / R_i) \quad (2)$$

where:

R_t = total thermal resistance of the clothing on the manikin zone grouping ($^\circ\text{C}\cdot\text{m}^2/\text{W}$), and

A_{tot} = total surface area of manikin zone grouping (m^2).

9.3 Determine the average total insulation value (R_t) of the sample by averaging the values from the three replications of the test. If the results for any of the three replications vary more