



Standard Test Method for Measuring the Heat Removal Rate of Personal Cooling Systems Using a Sweating Heated Manikin¹

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INTRODUCTION

Personal Cooling Systems (PCS) are used when wearers could be exposed to conditions that render the body's thermoregulatory system inadequate to maintain body core temperature within a safe range. The use of PCS can reduce the possibility of heat stress related physiological disorders and can also provide increased comfort, which in turn could also result in higher productivity. Cooling needs vary greatly depending on the level of activity, the external temperature and humidity, as well as the personal protective equipment worn. The PCS should be selected that is best suited for the specific application. Sweating heated manikins provide a convenient tool to assess the effectiveness of PCS as they can provide objective and repeatable results. These instruments can be used to quantify, in a reproducible manner, the cooling rate and cooling duration provided by the PCS while eliminating the variables associated with human physiology. Sweating heated manikins can be used for direct comparisons of PCS.

1. Scope

1.1 This test method covers the measurement of heat removal rate from a sweating heated manikin as well as the duration of cooling provided by a cooling garment, in order to assess the effectiveness of PCS.²

1.1.1 This test method requires the use of a sweating heated manikin. The sweating capability is essential, to take into account the potentially large fraction of heat dissipation associated with evaporative cooling.

1.2 The experimental values obtained for the cooling rates and cooling duration apply only to the particular PCS and additional clothing ensemble (standard outer garment, outer garment integrated to the PCS, or any other outer garment, as appropriate) as tested, and for the specified environmental conditions.

1.3 The values stated in this standard shall be SI units.

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.*

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

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² The present standard does not attempt to determine the thermal insulation and evaporative resistance of garments worn with the PCS, or these same properties for the PCS's themselves. Test Methods F 1291 and F 2370 are available for these measurements.

2. Referenced Documents

2.1 *ASTM Standards:*³

F 1291 Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin

F 1494 Terminology Relating to Protective Clothing

F 2370 Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin

3. Terminology

3.1 *Definitions:*

3.2 *clo, n*—unit of thermal resistance defined as the insulation required to keep a resting man (producing heat at the rate of 58 W/m²) comfortable in an environment at 21°C, air velocity 0.1 m/s, or roughly the insulation value of typical indoor clothing.

3.2.1 *Discussion*—Numerically, the clo is equal to 0.155 K·m²/W.

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

3.4 *garment, n*—a single item of clothing (for example, shirt).

3.5 *thermal insulation, n*—the resistance to dry heat transfer by way of conduction, convection, and radiation.

³ 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.

3.6 *total heat loss, n*—the amount of heat transferred through a clothing system by the combined dry and evaporative heat exchanges under specified conditions expressed in watts per square metre.

3.7 For definitions of terms related to protective clothing used in this test method, refer to Terminology F 1494.

4. Significance and Use

4.1 This test method can be used to quantify and compare the cooling provided by different Personal Cooling Systems (PCS's) worn with a standard outer garment or with any other specified one.

4.1.1 The test method is intended to allow garments based on various cooling technologies to be evaluated fairly and objectively, by taking into account convective and evaporative heat transfer.

4.1.2 A sweating thermal manikin accurately accounts for evaporative cooling, which represents the only active means of heat transfer occurring in humans. Utilizing a sweating thermal manikin will also permit the heat removal rate to be measured for all types of PCS.

4.2 The measurements of heat removal rates and duration of cooling provided by the PCS's depend on the apparatus and techniques used.

4.2.1 It is not practical in a test method of this scope to establish details sufficient to cover all contingencies.

4.2.2 Departures from the instructions in this test method will potentially lead to significantly different test results.

4.2.3 Technical knowledge concerning the theory of heat transfer, temperature, air motion measurement, evaporative cooling, and testing practices is needed to evaluate which departures from the instructions given in this test method are significant. Report any departures with the results.

5. Apparatus

5.1 *Manikin*—A standing sweating manikin having the form, shape, and size of an adult male or female shall be used. The manikin shall be heated to a uniform, constant, 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 $1.8 \pm 0.3 \text{ m}^2$, and height shall be $170 \pm 10 \text{ cm}$. The manikin's dimensions shall correspond to those required for standard sizes of garments because deviations in fit will significantly affect the results.

5.1.2 *Sweat Generation*—The manikin must have the ability to evaporate water from its surface. Some examples of a sweating system include a cotton body suit saturated with water or water fed capillary body suit worn over a thermal manikin. Other technologies exist that deliver water to the manikin's surface with a valve delivery system.

5.1.2.1 *Sweating Surface Area*—The surface area from which water is evaporated must include the chest, back, abdomen, buttocks, arms and legs. Ideally, the manikin's head, hands, and feet should be sweating also.

5.1.3 *Surface Temperature*—The manikin shall be constructed so as to maintain a constant uniform temperature over

the nude body surface, with no local hot or cold spots. The skin temperature of the manikin shall be 35°C . Local deviations from the mean skin temperature shall not exceed $\pm 0.3^\circ\text{C}$. Temperature uniformity of the nude manikin shall be evaluated at least once annually using an infrared thermal imaging system or equivalent method. Repeat this procedure after repairs or alterations are completed that could affect temperature uniformity (for example, replacement of a heating element).

5.2 *Power-Measuring Instruments*—Record the time history of the power input to the manikin over the entire test period. Overall accuracy of the power monitoring equipment must be within $\pm 2 \%$ 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.

5.3 *Equipment for Measuring the Manikin's Skin Temperature*—Measure the mean skin temperature with point sensors or distributed temperature sensors.

5.3.1 *Point Sensors*—Point sensors may be thermocouples, resistance temperature devices (RTD's), thermistors, or equivalent sensors. They shall be no more than 2.0 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. The sensors shall be distributed so that each one represents the same surface area or are area-weighted when calculating the mean skin temperature for the body. 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 should be area-weighted when calculating the mean skin temperature. Distributed sensors must be small in diameter (that is, less than 1.0 mm) and firmly bonded to the manikin surface at all points.

5.4 *Controlled Environmental Chamber*—The manikin shall be placed in a chamber at least 2 by 2 by 2 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 $\pm 1.0^\circ\text{C}$, relative humidity $\pm 5 \%$, and air velocity $\pm 50 \%$ 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 $\pm 0.5^\circ\text{C}$, mean radiant temperature $\pm 0.5^\circ\text{C}$, relative humidity $\pm 5\%$, air velocity $\pm 20\%$ of the mean value for data averaged over 5 minutes. (See 5.4.5).

5.4.3 Relative Humidity Measuring Equipment—Any humidity-sensing device with an accuracy of $\pm 5\%$ relative humidity and a repeatability of $\pm 3\%$ 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 $\pm 0.15^\circ\text{C}$ is acceptable (for example, RTD, thermocouple, thermistor). The sensor shall have a time constant not exceeding 1 minute. 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 omni-directional anemometer with ± 0.05 m/s accuracy shall be used. Average measurements for a minimum of 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.

5.5 Calibration—Calibrate the sweating heated manikin in accordance with Test Method **F 2370**.

6. Sampling, Test Specimens, and Test Units

6.1 Personal Cooling System—It is sufficient to test only one sample personal cooling system, with replicate measurements made on that single sample.

6.1.1 Size and Fit—Select the size of the PCS garment that best fits the manikin. Base fit on the manufacturer's designed specifications for fitting the garment to an actual human body. It is expected that certain PCS ensembles will not fit properly due to the rigidity and set position of sweating thermal manikins. State the size of each PCS used and any fit discrepancies in the report.

6.2 Specimen Preparation—Test the PCS in the as-received condition or after dry cleaning or laundering in accordance with the manufacturer's instructions.

7. Procedure

7.1 Environmental Test Conditions—The following isothermal conditions shall be considered standard.

7.1.1 Air Velocity—The air velocity shall be 0.4 ± 0.1 m/s or less during a test (that is, still air conditions).

7.1.2 Relative Humidity—The relative humidity shall be $40 \pm 5\%$ during a test.

7.1.3 Air Temperature—The air temperature shall be $35 \pm 0.5^\circ\text{C}$ during a test.

7.2 Mean Skin Temperature of Manikin—The manikin's outermost sweating surface temperature shall be $35 \pm 0.5^\circ\text{C}$

for all tests. The mean skin temperature shall not be allowed to drift more than $\pm 0.1^\circ\text{C}$ during a 2-hour test.

7.3 Sweating—The manikin surface must have water available for evaporation throughout the test period. The amount of water on the surface should be the supplied or added to the surface of the manikin in the same manner as was used to generate the evaporative resistance value during calibration (see 5.5).

7.3.1 Manikins without sweating heads, hands or feet cannot be used to evaluate PCS that provide cooling to these areas. These manikins can only evaluate PCS that provide cooling to the arms, legs, torso chest and back.

7.3.2 Areas that do not have a sweating surface must be heated to properly simulate heat production in a human body.

7.4 Saturate the manikin's sweating surface with water. Water added to the manikin's sweating surface must be heated to $35 \pm 0.5^\circ\text{C}$ before being delivered to the manikin.

7.4.1 Discussion—Saturation can usually be detected visually however, if needed an IR camera can insure that the surface is completely saturated.

7.5 Baseline Test—First, carry out a baseline test without cooling. Perform this test with the PCS ensemble placed on the manikin, but turned off, if possible, so that no cooling is provided. In the case where the PCS cannot be turned off (for example, ice vest, or phase change material), carry out the baseline test with the PCS in equilibrium with the atmosphere in the test chamber by previously conditioning it in the chamber for at least 12 hours.

7.5.1 Dress the standing manikin in the garment(s) to be tested, together with light shorts and a t-shirt (shorts and t-shirt directly on the skin), and the outer garment (either coveralls having a clo value of 1, or any other specified outer garment). Record a description of the garment(s) and the dressing procedures. Position the manikin so that it is standing with its arms hanging straight at its sides. Follow the manufacturer's instructions as to the sequence of clothing (for example, PCS or t-shirt closer to the skin).

7.5.2 The baseline test involves determining the power input to the manikin when wearing the turned off PCS (or without the PCS, if it cannot be turned off), needed to maintain the skin temperature at $35^\circ\text{C} \pm 0.5^\circ\text{C}$. The sweating mechanism shall be switched on (see sections 7.3 and 7.4). The baseline power is determined once steady-state condition is achieved (mean skin temperature and power input to the manikin constant within $\pm 3\%$).

7.6 PCS Performance Test—For the test with the PCS, dress the mannequin with the shorts, t-shirt and the outer garment. At first, only don the PCS if it can be turned off. Position the manikin so that it is standing with its arms hanging straight at its sides.

7.6.1 Bring the manikin to its prescribed skin temperature ($35^\circ\text{C} \pm 0.5^\circ\text{C}$) with the PCS switched off, or without the PCS, if it cannot be turned off. The sweating mechanism must be on (see 7.3 and 7.4). Once the temperature is stabilized, switch on, or put on the PCS. If it is necessary to turn off the manikin and instrumentation during the donning procedure, the manikin power must not be switched off for more than 5 minutes.

7.6.2 As soon as the PCS is on (or donned) and the manikin is powered, start recording the manikin's skin temperature, the air temperature, and the power input to the manikin, at least every 1 minute, or continuously over the test period. At the time data recording starts, it is possible that the manikin skin temperature is below the target temperature ($35^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$). It is assumed that this drop in temperature is mainly due to the action of the PCS, as compared to other losses to the environment. Take measurements until the effective cooling rate (power input to the manikin, minus the baseline cooling rate obtained in 7.5.2) has decreased to 50 W, or up to a maximum of 2 hours. Steady state may be reached for PCS's with "infinite" cooling source (such as vapor compression cooling). Otherwise, the cooling rate will vary with time.

7.7 *Replication of Tests*—Perform three independent replications of the cooling test. Remove the PCS from the manikin at the end of each test, and don again at the beginning of the next replication. In this way, normal variations in dressing and instrumentation will be taken into account.

7.8 *Nude Test*—Measure the evaporative resistance (R_{ea}) provided by the air layer around the nude manikin by conducting a test in the same environmental conditions used for the clothing tests in accordance with Test Method F 2370. Test the nude manikin at the beginning of each series of PCS tests.

8. Calculation

8.1 Calculate the cooling rate as the time average of the power input to the manikin from the time the data was recorded (PCS donned or cooling turned on), until the effective power (power input to the manikin minus the baseline value obtained in 7.5.2) has decreased to 50 W, for a maximum of 2 hours. The time-average power is obtained from the numerical integration of the power input versus time until the effective cooling rate has decreased to 50 W, divided by the time it took to reach that value (from when the time data is recorded). Effective cooling rate is determined by subtracting the average power input value and the baseline power value.

8.2 Record the duration of cooling as the time required for the net cooling power to decrease to 50 W (use cooling power values corrected for the baseline power value). If such a decrease was not observed within the two-hour maximum testing period, the duration is defined as "more than 2 hours."

9. Report

9.1 State that the specimens were tested in accordance with this test method.

9.2 Report the following information:

9.2.1 Describe the PCS and garments(s) used and the type of sampling used. In particular, describe in detail the outer garment used in conjunction with the PCS, if applicable. Take a photograph (for example, digital) of the ensemble on the manikin and include it in the report.

9.2.2 Describe the baseline test in detail, mention whether the PCS was worn during these tests, and report the baseline power value.

9.2.3 Report the average cooling rate values for each sample set, in accordance with the calculation method outlined in Section 8.

9.2.4 Report the duration of cooling, as specified in Section 8. If the cooling is generated by a "non-depletable" power source, such as power from an electrical plug or a fixed chiller, report that the cooling duration is not relevant. Report the power source, if any.

9.2.5 Report the coverage area of the PCS in square metres. This information can be provided by the manufacturer.

9.2.6 Specify the environmental test conditions.

9.2.7 Explain any departures from the specified apparatus or procedure.

10. Precision and Bias

10.1 *Precision*—In comparing two independent observations of the effective cooling rate values, the variation must not exceed $\pm 10\%$ of the average of the two measurements when the measurements are taken by the same well-trained operator using the same testing equipment. Otherwise, additional replications must be conducted until this criterion is met.

10.2 *Bias*—The procedure in this test method for determining the effective cooling rate of PCS's has no bias because the value can be defined only in terms of a test method.

11. Keywords

11.1 comfort; cooling rate; heat stress; personal cooling systems; personal protective equipment; sweating manikin; thermal manikin

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