Designation: F2300 – 10

StandardTest Method for Measuring the Performance of Personal Cooling Systems Using Physiological Testing[1]

This standard is issued under the fixed designation F2300; 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

Individuals in various occupations are exposed to high heat stress resulting from increased metabolism, or the environment, or both. Environmental heat stress can be especially severe when individuals are required to wear Personal Protective Equipment (PPE), which impairs or prevents evaporation of sweat from the skin, and thus nullifies the body's principal means of removing metabolic heat. Failure to dissipate this heat can dramatically limit work capacity and heat tolerance, thereby increasing the risk of heat-related illness. To reduce this risk, workers are wearing Personal Cooling Systems (PCS) to extend their exposure time to thermal stress. These systems are intended to limit the effects of external environmental heat and the internally generated metabolic heat on the body. For this purpose, standards that objectively quantify the effectiveness of PCS are essential. Therefore, tests that measure important physiological variables, such as core temperature, are essential in evaluating PCS applications and increasing worker's health and safety.

1. Scope

1.1 This test method covers the physiological measurement of internal body core temperature, skin temperature, thermal exposure time, heart rate response, oxygen consumption, and whole body sweat rate, to assess the effectiveness of Personal Cooling Systems (PCS) in reducing the effects of thermal stress.

1.1.1 To increase safety during physiological testing, this dynamic test requires the use of human participants who exhibit specific health and physical fitness requirements.

1.2 This test incorporates the use of protective clothing ensembles (outer garments) used in conjunction with or worn over top of the PCS. This scope is therefore oriented to industrial rather than athletic applications.

1.2.1 The effectiveness of different PCS will be quantified with the same protective clothing ensemble. Therefore, the physiological values obtained apply only to the cooling systems, the particular protective outer garment, and the specific test conditions.

1.2.2 When a protective outer garment is not provided, this test method requires that PCS shall be tested with the standard outer garment defined within this test method.

1.2.3 The present standard does not attempt to determine important clothing characteristics, such as thermal insulation and evaporative resistance, of the PCS or of the garments worn with the PCS. Test Methods F1291 and F2370 can be referenced for these clothing measurements.

1.3 The values stated in this test method shall be SI units.

1.4 It is the responsibility of the test laboratory to obtain the necessary and appropriate approval(s) required by their institution for conducting tests using human participants.

1.5 *This test method 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 test method 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]

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

[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 June 1, 2010. Published July 2010. Originally approved in 2004. Last previous edition approved in 2005 as F2300 - 05. DOI: 10.1520/F2300-10.

[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 *Other Standards:*

ISO 8996 Ergonomics—Determination of Metabolic Heat Production[3]

ISO 9886 Ergonomics—Evaluation of Thermal Strain by Physiological Measurements[3]

The Commission for Thermal Physiology of the International Union of Physiological Sciences (IUPS Thermal Commission) Glossary of Terms for Thermal Physiology[4]

U.S. Food and Drug Administration (FDA)—Cleared Sterilants and High Level Disinfectants with General Claims for Processing Reusable Medical and Dental Devices (March 2009) [5]

3. Terminology

3.1 *Definitions:*

3.1.1 *acclimation, n*—physiological adaptations occurring within an organism, which reduces the strain or enhances endurance of strain, caused by artificially or experimentally induced stressful changes in particular environmental conditions.

3.1.1.1 *Discussion*—Acclimation describes the adaptive changes that occur within an organism in response to artificially induced changes in particular climatic factors such as ambient temperature and humidity in a controlled environment.

3.1.2 *acclimatization, n*—physiological adaptations occurring within an organism, which reduces the strain or enhances endurance of strain, caused by stressful changes in the natural environment.

3.1.3 *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 velocity 0.1 m/s, or roughly the insulation value of typical indoor clothing.

3.1.3.1 *Discussion*—Numerically the clo is equal to 0.155 $K{\cdot}m^2/W$, which is equal to $0.18°C{\cdot}m^2{\cdot}h/kcal$.

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

3.1.5 *thermal core, n*—the deep tissues of the brain, neck and torso whose temperatures are not changed in their relationship to each other by circulatory adjustments.

3.1.5.1 *Discussion*—These deep tissues comprise the most thermally protected tissues of the body and are most critical to temperature regulation. The thermal core is distinct from changes in heat transfer to the environment that affects the appendages and other tissues of the body.

3.1.6 *core temperature, n*—the mean temperature of the thermal core.

3.1.6.1 *Discussion*—Core temperature is commonly represented by rectal temperature, or by the more rapidly responding esophageal temperature. Core temperature is also measured by ingested telemetric thermometers in the form of a capsule.

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

3.1.8 *maximum oxygen consumption (VO_{2max}), n*—the highest rate at which an organism can take up oxygen during aerobic metabolism.

3.1.8.1 *Discussion*—Determination of VO_{2max} requires very high motivation of the individual and is expressed in mL per min or as a term relative to body mass in mL per kg per min. Maximum oxygen consumption is often referred to as maximal aerobic power (MAP).

3.1.9 *metabolic rate, n*—the rate of transformation of chemical energy into heat and mechanical work by aerobic and anaerobic activities within an organism.

3.1.9.1 *Discussion*—Metabolic rate, as with VO_{2max}, is commonly measured by indirect calorimetry, during long-term steady-state work, and is typically expressed in Watts (W). Metabolic rate, also referred to as energy expenditure, is usually expressed in terms of unit area of the total body surface (W/m^2) or of total body mass (W/kg) when comparisons are made between individuals.

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

3.1.11 *thermal strain, n*—any deviation of body temperature induced by sustained thermal stress that cannot be fully compensated by temperature regulation.

3.1.11.1 *Discussion*—Thermal strain results in the activation of thermoeffector activities that causes sustained changes in the state of non-thermal regulatory systems. Thermal strain is measurable by an increased heart rate and whole body sweat rate, as determined by pre and post nude mass loss.

3.1.12 *thermal stress, n*—any thermal change between a temperature regulator and its environment, which if uncompensated by temperature regulation, would result in hyperthermia.

3.1.12.1 *Discussion*—Thermal stress is often referred to as heat stress.

3.2 IUPS Thermal Commission document[6] was referenced for the modified definitions related to thermal physiology listed above, and for terms related to protective clothing used in this test method, refer to Terminology F1494.

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) worn with a standard outer garment or with a specified protective outer garment.

4.1.1 This test method will assess the performance of PCS based on the physiological measurement of core temperature, mean skin temperature, heart rate, exposure time, oxygen consumption, and whole body sweat rate.

4.2 Evaluating the effectiveness of PCS is an extremely complicated endeavor that involves many factors related to

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

[4] Available from Physiology & Biophysics School of Medicine, Case Western Reserve University, 10900 Euclid Avenue Cleveland, OH 44106-4970, http://www.iups.org.

[5] Available from Food and Drug Administration (FDA), 5600 Fishers Ln., Rockville, MD 20857, http://www.fda.gov.

[6] *The Japanese Journal of Physiology*, Vol 51, No. 2, 2001.

thermal exchange between the PCS, the environment, and the participant. It would not be practical in a test method of this scope to establish details sufficient to cover all contingencies. Therefore, a valid physiological method of measuring core temperature, along with other variables of thermal strain, provides an acceptable means of classifying the performance of PCS. This test method will also measure the amount of time the PCS maintains core temperature within safe limits during a specified condition of thermal stress.

4.3 Departures from the instructions in this test method may lead to significantly different test results. Technical knowledge concerning thermoregulatory responses, the theory of heat transfer, physiological and environmental temperature measurement, and testing practices is needed to evaluate which departures from the instructions given in this test method are significant. All departures must be reported with the results.

5. Materials

5.1 *Controlled Environmental Chamber*—Testing will take place within a chamber that is large enough to accommodate a treadmill, the test participant, and at least two people at the same time. Also, the chamber must provide uniform conditions, both spatially and temporally.

5.1.1 *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 0.6, 1.0, 1.4, and 1.8 m above the floor at the location occupied by the participant.

5.1.2 *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.

5.1.3 *Relative Humidity Measurement*—Any humidity-sensing device must have 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.

5.1.4 *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 to 1.0 m in front of the subject. 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.

5.1.5 *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 the 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 air temperature.

5.2 *Treadmill*—An adequately sized treadmill shall be used with a physical structure that must be able to accommodate the smallest and the largest participant safely and comfortably.

5.2.1 *Treadmill Characteristics*—The treadmill running surface shall be not less than 1.8 m by 0.6 m. The treadmill must have a calibrated analog scale or digital indicator of speed and angle of inclination (degrees or % grade). Elevation shall be variable over a range of at least 0 to 25 % grade. The speed shall be variable from 2 to 20 km/h in increments of 0.2 km/h. Calibrate treadmills for speed and grade. The control mechanism must provide for error of less than 1.0 % of the testing load both during the test and between tests (that is, 0.15 % grade at 15 % treadmill grade).

5.3 *Equipment for Measuring Body Temperature*—The core and skin temperatures shall be measured with temperature transducers (that is, point sensors) that must be calibrated prior to testing.

5.3.1 *Temperature Transducers*—The temperature measurements may be carried out with liquid thermometers, thermocouples, resistance temperature devices (RTD), or thermistors. The transducers shall provide an accuracy of ±0.1°C between the range of 30 to 42°C for core temperature and 25 to 40°C for skin temperature. The transducers shall be of low thermal capacity. Their response time to 90 % of the value must be the lowest possible and less than 30 s. Skin temperature measurements can be taken at 4, 8, or 14 different locations. Refer to ISO 9886 for the location of the various measurement sites, and the weighting coefficients to determine overall skin temperature.

5.3.2 *Core Temperature Transducers*—The recommended method is to use disposable transducers for core temperature measurements. These transducers must be sterilized for initial use and then cleaned and disinfected between trials if reused by the same participant. The transducers should then be discarded once the participant has completed all test conditions to eliminate the risk of contamination between different subjects from using the same transducer.

5.3.2.1 *Core Temperature Transducer Cleaning*—Special requirements are to be made concerning the hygiene of the core temperature transducer. Laboratories must follow specific biohazard control procedures as stipulated by their institution. Generally, this includes thoroughly cleaning and removing all organic matter prior to disinfection with an agent such as such as hydrogen peroxide, isopropanol, ethanol, or those recommended by the FDA. Following cleaning, the transducer must be rinsed thoroughly with water to remove all traces of the disinfectant which might provoke irritation or allergy in the next user. Refer to ISO 9886 for more information.

5.4 *Measuring Heart Rate*—Heart rate can be measured with either a portable heart rate monitor or by using an electrocardiogram (ECG).

5.5 *Metabolic Rate Measurement*—Metabolic rate is measured using indirect calorimetry methods. The equipment used to measure oxygen consumption will depend on the testing institution (for example, gas collection bags or metabolic

carts). Testing institutions are required to follow proper laboratory procedures and to calibrate the equipment prior to testing. An accuracy of ±1 % for gas analyzers and ±5 % for volume and flow measurement is acceptable.

5.6 *Data Acquisition Systems*—All thermophysiology laboratories will be equipped with their own valid data acquisition hardware and software. A maximum sampling rate of 5 s can be used; however, rates of 15, 30 or 60 s are also adequate. This will depend on the data acquisition system and the physiological variable being sampled. It is important that sampling rates from different physiological variables (for example, heart rate and core temperature) are all the same or at least divisible to allow for easy interpretation. Also, the data acquisition system must be capable of storing a sufficient amount of data (for example, approximately 2.5 h).

5.7 *Participant Clothing Ensembles*—To standardize the testing, subjects will be required to wear a standard under garment during all tests and a standard outer garment when no other protective outer garments are provided for testing.

5.7.1 *Under Garments*—Participant under garments will be worn underneath the PCS during all test conditions. The clothing ensemble will include a T-Shirt, shorts, sport socks, underwear, and athletic shoes. If female participants are used, an athletic bra may be worn.

5.7.1.1 *Shirt*—65 % polyester, 35 % cotton T-shirt.

5.7.1.2 *Shorts*—65 % polyester, 35 % cotton shorts.

5.7.1.3 *Sport Socks*—80 % cotton, 20 % nylon; covers only area distal to the malleolii; jersey and rib knit.

5.7.1.4 *Underwear*—100 % cotton underwear; jockey or boxer style.

5.7.1.5 *Athletic Shoes*—Unless protective outer garments include specific or required footwear, athletic shoes with a soft rubber sole must be worn during testing. Other footwear (for example, hard sole shoes) can become problematic, not only because of possible foot soreness, but they can cause a change in gait due to discomfort and can affect mechanical efficiency, and therefore heat production at a fixed workload.

5.7.2 *Outer Garments*—This test method is applicable to testing the performance of PCS when worn underneath protective outer garments (for example, HAZMAT protective ensemble). If a particular outer garment is not provided, then a standard outer garment as described below must be used during testing.

5.7.2.1 *Standard Outer Garment*—A two-piece coverall, including trousers, 65 % polyester and 35 % cotton durable press and 2 by 1 twill weave with two front and hip pockets, and a long sleeve jacket, 65 % polyester and 35 % cotton single layer plain or twill weave will be used. If unavailable, then an outer garment of similar fabrics with a combined intrinsic thermal resistance representing 1 clo (0.155 K × m^2/W) should be used.

5.7.3 No outer garment is necessary if the PCS evaluated do not require the use of such protective ensembles. This circumstance, however, will increase the heat exchange between the environment and the PCS and will likely decrease the available heat exchange between the PCS and the human body.

5.7.4 PCS and protective outer garments shall be cleaned in accordance with the manufacturer's instructions, and report the specific care method and number of times repeated.

6. Sampling, Participants, and Familiarization Period

6.1 *Sampling*—A minimum of five different participants shall be tested for evaluating the performance of each PCS.

6.2 *Test Participants*—Individuals who participate in this test method will do so strictly on a volunteer basis. To undertake this testing, all test laboratories must adhere to and obtain the proper approval for human testing that their respective institution requires. As part of the approval process, participants will be informed of all the details of this test method and the associated risks and discomforts before providing their informed written consent. As well, complete anonymity and confidentiality will be given to each participant.

6.2.1 *Medical Evaluation*—Screen participants for medical problems. This would involve answering a questionnaire assessing their past and current personal health (for example, Canadian Par-Q). Participants may be required to undergo a medical examination depending upon each respective institutional review committee's rules and regulations for physiological thermoregulation research.

6.2.2 *Participant Fitness Level*—A strong aerobic level of fitness is required for individuals to participate in this test method. Screen out participants who do not partake in regular aerobic activities at least ½ h three to five times a week. An evaluation determining the participant's maximum oxygen consumption (VO_{2max}), or maximal aerobic power, will be used as an objective measure to screen for successful participants and allow some comparison of findings between research results.

6.2.2.1 *Maximum Oxygen Consumption*—Only individuals with a VO_{2max} between the range of 35 and 65 mL/kg/min will be used as participants in this test method. Refer to ISO 8996 for the proper method for measuring oxygen consumption. Otherwise, physiological testing laboratories shall follow their own specific procedures for testing VO_{2max}. The only requirements are that the test is continuous, the exercise is walking, and it is performed using a treadmill. Continuous tests generally start at relatively low intensities and progress by increasing the work rate (treadmill velocity, or % grade, or both) at preset time intervals until the participant is unable to continue. This form of test causes the participant to progressively increase power output over time. If it is continued long enough to allow the body to adapt and is short enough so that factors such as lactate accumulation, thermal load, or muscular soreness do not force termination of the exercise, the participant will eventually achieve their aerobic energy maximum.

6.2.3 *Participant Gender*—Participants being tested must either be all male or all female in gender. Since conditions will be tested at a maximum frequency of two per week, with the probability of multiple test conditions, the effects of physiological heat production variability associated with the menstrual cycle of female participants needs to be controlled. If females are used, it is recommended that participants be tested within nine days after start of menstruation (follicular phase) to control for hormonal effects. For safety concerns, pregnant