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Standard Practice for Determining the Physiological Responses of the Wearer to Protective Clothing Ensembles[1]

This standard is issued under the fixed designation F2668; 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

Protective clothing ensembles such as firefighter turnout gear, HAZMAT suits, and bomb suits may impose a physiological strain on the wearer. This strain can take the form of heat stress and cardiovascular and respiratory strain, which can result in injury to the wearer. This practice provides information on the measurement of the physiological responses of a wearer to a protective clothing ensemble. The protocol is designed to allow comparisons of the physiological responses of subjects wearing different protective clothing ensembles of the same type (for example, firefighter turnout gear) and from different types (for example, firefighter ensemble versus HAZMAT suit).

1. Scope

1.1 This practice specifies the test equipment and procedures for determining the physiological responses of subjects wearing a protective clothing ensemble.

1.2 This practice covers the physiological measurement of internal body core temperature, skin temperature, exposure time, heart rate response, oxygen consumption, and whole body sweat rate to assess the physiological responses of subjects wearing a protective clothing ensemble. This practice does not measure the musculoskeletal strain on the participant imposed by the protective clothing ensemble.

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

1.3 The present standard does not attempt to determine important clothing characteristics, such as thermal insulation and evaporative resistance of the protective clothing ensemble. Test Methods F1291 and F2370 can be used for these clothing measurements.

1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.5 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.

1.6 *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.*

1.7 *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]

F1291 Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin

F1494 Terminology Relating to Protective Clothing

F2300 Test Method for Measuring the Performance of Personal Cooling Systems Using Physiological Testing

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

2.2 *Other Standards:*[3]

ISO 8996 Ergonomics—Determination of Metabolic Heat Production

ISO 9886 Ergonomics—Evaluation of Thermal Strain by Physiological Measurements

[1] This practice 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.

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

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

3. Terminology

3.1 *Definitions:*

3.1.1 *acclimation, n*—physiological adaptations occurring within an organism, which reduce the strain or enhance 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 reduce the strain or enhance endurance of strain, caused by stressful changes in the natural environment.

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

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

3.1.4.1 *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.

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

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

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

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

3.1.7.1 *Discussion*—Metabolic rate, as with VO_{2max}, is commonly measured by indirect calorimetry, during long-term steady-state work. 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).

3.1.8 *protective ensemble, n*—the combination of protective clothing with respiratory protective equipment, hoods, helmets, gloves, boots, communication systems, cooling devices, and other accessories intended to protect the wearer from a potential hazard when worn together.

3.1.9 *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.

3.1.9.1 *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.

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

3.1.10.1 *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.

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

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

3.2 IUPS Thermal Commission document[4] was referenced for the modified definitions related to thermal physiology listed above. For terms related to protective clothing used in this practice, refer to Terminology F1494.

4. Significance and Use

4.1 This practice can be used for the evaluation of the physiological response of a user to protective clothing ensembles worn under controlled conditions.

4.1.1 This practice utilizes a treadmill for the exercise protocol. This method is believed to be appropriate for the evaluation of the majority of protective clothing ensembles, especially where the user will be walking or performing similar activities. In certain situations where a protective clothing ensemble is designed to be worn where the user is performing specialized functions (for example, sitting or standing with only arm movement), alternate exercise equipment (for example, arm cycle-ergonometer) or exercise protocols should be considered for use in determining the physiological response of the subject.

4.1.2 Where evaluations include the use of personal cooling systems, refer to Test Method F2300.

4.2 This practice establishes general procedures for the physiological evaluation based on the physiological measurement of core temperature, mean skin temperature, heart rate, exposure time, oxygen consumption, and whole body sweat rate.

4.2.1 The data obtained can be used to evaluate the overall physiological response of the test participant while wearing a protective clothing ensemble.

4.2.2 The data may also be used in the research and development of advanced ensembles that are designed to reduce the physiological strain on the wearer, thereby reducing the potential injury (for example, heat injury) associated with wearing the protective clothing ensemble. Workers may be able to wear a protective clothing ensemble for a longer duration due to a reduction in the physiological strain.

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

4.2.3 The data can also be used to compare similar classes of ensembles and can be used to evaluate protective clothing ensembles as a hazard to the wearer as compared to a baseline ensemble.

4.2.4 In addition, the practice could also be used by consensus standards organizations in the development of physiological test criteria for protective clothing ensemble certification.

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

5. Materials

5.1 *Controlled Environmental Chamber*—A chamber that is large enough to accommodate a treadmill, the test participant, and at least two people at the same time. Also, the test 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 test 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, relative humidity ±5 %, air velocity ±20 % of the mean value for data averaged over 5 min.

5.1.3 *Relative Humidity Measurement*—A humidity-sensing device shall be used and have an accuracy of ±5 % relative humidity and a repeatability of ±3 % to be acceptable (for example, wet bulb/dry bulb, dew point hygrometer). At least one location shall 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. The sensor shall have an overall accuracy of ±0.15 °C (for example, RTD, thermocouple, sensor). 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 participant. 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 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 the 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 air temperature.

5.2 *Treadmill*—A treadmill shall be used with a physical structure that accommodates 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 shall 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 20 % grade. The speed shall be variable from 2 to 20 km/h in increments of 0.2 km/h. The speed and incline of the treadmill shall be calibrated prior to each series of tests or study.[5] 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) which shall be calibrated prior to use.

5.3.1 *Temperature Sensors*—The temperature measurements shall be carried out with thermocouples, resistance temperature devices (RTD), or thermistors. The sensors 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. Their response time to 90 % of the value must be the lowest possible and less than 10 s. Skin temperature measurements shall be taken at four, eight, 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 Sensor Cleaning*—Special requirements are to be made concerning the hygiene of the core temperature sensor. Laboratories must follow specific biohazard control procedures as stipulated by their institution for the use and disposal of sensors.

5.3.2.1 *Core Temperature Sensors*—Reusable and disposable sensors are available for measurement of core temperature. Disposable sensors are strongly recommended but not required for core temperature measurements. If reusable sensors are used, the sensors shall be cleaned and disinfected between trials for the same participant and then discarded once the participant has completed all test conditions. Sensors shall only be used by one individual and shall be cleaned and disinfected in accordance with the manufacturer's instructions between trials. Refer to ISO 9886 for additional 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 *Data Acquisition Systems*—All physiology laboratories shall be equipped with 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

[5] The calibration procedure as written in *Procedures for Exercise Physiology Laboratories*, NASA TM-1998-104826.

easy interpretation. Also, the data acquisition system must be capable of storing a sufficient amount of data (for example, approximately 2.5 h) for each variable being measured.

5.6 *Participant Clothing Ensembles*—Participants shall be required to wear a standard base ensemble under the protective clothing ensemble during all test conditions.

5.6.1 The base ensemble shall be appropriate for the protective clothing ensembles being tested. If the base ensemble is not specified, then a T-shirt, shorts, socks, and underwear shall be used as the default base ensemble and shall be constructed of 100 % cotton where possible. Sock selection shall be based on the type of footwear used (for example, boot socks with boots).

5.6.1.1 The garments in the base ensemble shall be laundered prior to each use.

5.6.1.2 *Athletic Shoes*—Unless the protective clothing ensemble includes specific or required footwear, athletic shoes with a soft rubber sole shall be worn during testing. Other types of footwear (for example, hard-soled shoes) can become problematic, not only because of possible foot soreness, but because they can cause a change in gait due to discomfort and can affect mechanical efficiency and physiological strain.

5.6.2 Where appropriate, protective clothing ensembles shall be cleaned in accordance with the manufacturer's instructions and the specific care method.

6. Sampling, Participants, and Familiarization Period

6.1 *Sampling*—A minimum of eight different participants shall be tested for evaluating the performance of each protective clothing ensemble.

6.2 *Test Participants*—Individuals who participate in this test will do so strictly on a volunteer basis. Test laboratories must adhere to all government regulations regarding human testing and obtain the required human testing approval from their respective institution. Participants shall be informed of all the details of this practice and the associated risks and benefits prior to providing their informed written consent. Complete anonymity and confidentiality shall be given to each participant.

6.2.1 *Medical Evaluation*—Participants shall be medically screened to ensure they can safely participate. This involves assessing their past and current personal health. 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 *Baseline Physiological Assessment*—A baseline physiological assessment shall be completed on each participant. During the baseline assessment each participant's maximum oxygen consumption (VO_{2max}) shall be determined to the nearest mL/kg/min while wearing the base ensemble. The participant's (VO_{2max}), or maximal aerobic power, shall be used as an objective measure to screen for possible participants.

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 practice. 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}. 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 may either be male or female in gender. However, 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 women will not be used as participants in this practice in order to avoid unnecessary physiological strain.

6.2.4 *Participant Stature*—Adults between the ages of 18 and 40 years shall be selected. If testing males, mass of the participants shall be between 65 and 100 kg and body height between 1.70 and 1.95 m. If testing females, mass of the participants shall be between 50 and 90 kg and body height between 1.60 and 1.85 m.

6.2.5 *Test Preparation*—Pre-test standardization regarding exercise and food consumption must be followed. Individuals must avoid moderate to high-level exercise 24 h prior to the test and avoid stimulants or diuretics (for example, cigarettes and caffeine) 12 h prior to testing. Testing shall occur between morning and mid-afternoon hours. A large meal shall be avoided less than 3 h prior to testing, with food consumption stopped 2 h prior to testing. In addition, all individuals shall be normally hydrated prior to testing. A small amount of water (5 mL/kg) shall be ingested ½ h prior to testing to assist with proper esophageal sensor placement, if used for core temperature measurement.

6.2.6 *Test Sessions*—Participants shall be willing to commit to multiple test sessions at a rate of no more than once a day. The number of test conditions shall depend on the number of ensembles being evaluated. The ensemble conditions shall be tested in accordance with an appropriate experimental design.

6.2.6.1 *Acclimation Period*—More than two tests per week shall be performed only if the participants are acclimatized or have gone through a proper acclimation period prior to testing. Research institutions shall follow their proper laboratory protocol throughout the testing period in order to maintain acclimation for all participants. All participants should be acclimatized or acclimated, or both, if possible.

6.3 *Familiarization Period*—A familiarization session shall be provided prior to the actual testing, which would introduce individuals to the test protocol and allow them to get "comfortable" with core temperature measurement, the protective clothing ensemble, and the test area. This familiarization period shall determine the appropriate treadmill settings that result in each participant working at a selected percentage of their individual VO_{2max} while wearing the protective clothing ensemble. The velocity of the treadmill shall be determined to

the nearest 0.1 m/s. The % grade of the treadmill shall be determined to the nearest 0.1 %. The selection of the % VO_{2max} is dependent on the objective of the study and shall be set at a level that is appropriate for the protective clothing ensembles and the expected activities of users wearing the ensemble. If a % VO_{2max} is not specified, then 50 % VO_{2max} shall be used as the default value.

6.3.1 *Familiarization Protocol*—Participants shall wear the base ensemble and a protective clothing ensemble. A sensor shall be used to measure core temperature in the rectum or esophagus, or core temperature shall be measured with an ingestible core temperature capsule. Should an esophageal probe be used, it is important that individuals have this done during the familiarization period because the "gag" reflex is usually stimulated during the first experience leading to the risk of vomiting. Participants will then walk on the treadmill at the required oxygen consumption and environmental conditions for approximately 15 to 30 min. The familiarization period will provide the opportunity to determine the approximate speed and percent grade of the treadmill for each individual. In addition, this period will provide enough time to show that the individual is competent to perform the actual test protocol.

NOTE 1—If an exercise other than a treadmill is utilized, the familiarization protocol will still be used to obtain the equipment settings or specific procedures required to attain the selected % VO_{2max} for each participant.

7. Procedure

7.1 *Environmental Test Conditions*—The environmental conditions provided below shall be standard for all tests.

7.1.1 *Air Velocity*—Air velocity shall be set at a level that is appropriate for the protective clothing ensembles being tested. If air velocity is not specified, an air velocity of no greater than 0.5 m/s prior to test initiation shall be used as the default value.

7.1.2 *Relative Humidity*—Relative humidity shall be set at a level that is appropriate for the protective clothing ensembles being tested. Relative humidity shall be controlled during testing within a range of ±5 %. If relative humidity is not specified, 50 % shall be used as the default value.

7.1.3 *Air Temperature*—Air temperature shall be set at a level that is appropriate for the protective clothing ensembles being tested. Air temperature shall be controlled during testing within a range of ±1 °C. If air temperature is not specified, 21 °C shall be used as the default value.

7.2 *Physiological Measurements*—Evaluation of the protective clothing ensemble shall be based on the change in core temperature, final mean heart rate, and test duration time. Other physiological variables, such as mean skin temperature, oxygen consumption, whole body sweat rate, and subjective ratings of perceived exertion and thermal comfort may be examined for additional performance assessment and safety in order to indicate participant fatigue and heat stress. Hardware and software filtering may be used to smooth out the data to eliminate erroneous artifacts in any of the physiological measured variables.

7.2.1 *Core Temperature Measurement*—Core temperature is the most appropriate measurement available to determine the level of thermal strain of the participant. It represents the internal tissues of the torso, head, and neck regions. Three different sites represent the most efficacious measurement: esophageal, rectal, and intestinal. The proper measurement and placement of esophageal and rectal temperature is outlined in ISO 9886.

7.2.1.1 *Esophageal Temperature*—The esophageal temperature is more sensitive to changes in the temperature of central venous and arterial blood than rectal measurements. This improved sensitivity is due to the low heat capacity of the esophagus and the proximity to the heart and pulmonary circulation. Esophageal temperature shall be measured to the nearest 0.1 °C.

(1) Esophageal Temperature Sensor Location—The sensor (or thermocouple) shall be introduced through the nasal cavity into the lower part of the esophagus to the level of the left atrium. The length of the catheter at this point to the origin of insertion at the nose should be about 25 % of the participant's height. If it is placed too low it could read gastric temperature; too high and it might be affected by breathing. Artifacts in the signal are produced when swallowing (saliva) and drinking fluids. Therefore, the times when the participant swallows should be indicated or the participant shall be told to avoid swallowing during a specific time period (for example, 1 min out of 5, or the last 15 s of every min).

7.2.1.2 *Rectal Temperature*—The rectal temperature tends to be influenced by local muscle contractions and is higher when work is performed with the legs than when it is carried out exclusively with the arms. Rectal temperature measurement is also susceptible to a slower frequency response and lags behind as compared to esophageal during some activities. Rectal temperature shall be measured to the nearest 0.1 °C.

(1) Rectal Temperature Sensor Location—The rectal temperature sensor shall be inserted into the rectum no less than 10 cm and no greater than 15 cm in depth past the edge of the anal sphincter.

7.2.1.3 *Intestinal Temperature*—The stomach temperature may be influenced by the consumption of cold liquids. Intestinal temperature measurements can be affected by a sensor being positioned too close to the abdominal wall as it transits through the upper intestinal tract. Intestinal temperature shall be measured to the nearest 0.1 °C.

(1) Intestinal Temperature Sensor Location—The ingestible thermal transducer capsule shall be provided to the participant with instructions on activation and ingestion of the capsule. Prior to the test, the time of ingestion should occur in accordance with the capsule manufacturer's instructions. If specific instructions are not provided, the capsule shall be ingested no later than 4 h before the test and no more than 10 h before the test.

7.2.2 *Skin Temperature Measurement*—This practice recommends eight skin temperature measurement site locations, on the forehead, right scapula, left upper chest, upper right arm, lower left arm, left hand, right anterior thigh, and left calf. Skin temperature measurements shall be taken at four, eight, or 14 positions located on the participant's forehead, neck, scapula, upper chest, arm, hand, abdomen, lower back, thigh, shin, calf, and foot. Refer to ISO 9886 for the location of the different