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Protective clothing for firefighters — Physiological impact —

Part 1: Measurement of coupled heat and moisture transfer with the sweating torso

Vêtements de protection pour sapeurs-pompiers — Impact physiologique —

Partie 1: Mesurage du transfert de masse et de la chaleur couplé de chaleur et d'humidité à l'aide du torse transpirant

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 94, *Personal safety*, Subcommittee SC 14, *Firefighters PPE*.

A list of all parts in the ISO 18640 series can be found on the ISO website.

Introduction

The main functions of protective clothing are protection against hazards and maintenance of health and comfort for the wearer. Furthermore, protective clothing against heat and flame prevents the wearer from health risks or even life threatening heat stress in extreme environmental conditions. Today's standards provide requirements for the protective properties of protective clothing against heat and flame. However, the higher the protective properties of such clothing, the less the heat originating from the human body is dissipated. Firefighters reach metabolic rates above 500 W/m^2 during their work[5][6]. Thereof 75-85 % is released as heat[7], which has to be dissipated from the human body by thermo-regulative processes to avoid an increase in body core temperature. If heat dissipation is not restricted, the human body is able to maintain its temperature in the range of 36,5 °C to 37,5 °C (normothermia)[8]. However, in harsh environmental conditions and/or in situations of restricted heat dissipation due to protective clothing the human body is not able to maintain body core temperature within normothermia and suffers from heat stress. The working performance is gradually reduced and any further increases in body core temperature can become life threatening[16]. To reduce the risk of heat stress during high intensity physical activities, protective clothing should additionally be assessed with regard to its impact on human thermoregulation and heat stress.

Different approaches exist for the assessment of thermo-physiological impact. On the one hand, established standard parameters such as water vapour resistance, R_{et}, and thermal insulation, R_{ct}, of fabric samples are considered with regard to thermo-regulative impact. However, these parameters do not fully reflect the real impact of protective clothing; for example, moisture management properties and the combined effect of heat and moisture transfer are not considered. On the other hand, human subject trials reveal real thermo-physiological responses for a specific environmental condition and protective clothing ensemble. However, the outcome of this methodology does not only refer to the intrinsic properties of material samples but are influenced also by the design of the clothing and trapped air layers within the clothing. Furthermore, human subject trials are very time consuming and expensive, constricted by ethical guidelines and provide findings related to the collective of participants included. Thus, reproducibility between laboratories might be limited. The use of thermal manikins overcomes the limitations for human subject trials. As for human subject trials, full body manikins provide findings on ready-made protective garments including design and fit. Hence, the attribution to intrinsic material properties remains difficult.

A methodology referring to intrinsic clothing properties and taking into account combined heat and moisture transfer is the Sweating torso[9][10]. Sweating torso device is an upright standing heated cylinder, representing the surface of a human trunk, with the ability for perspiration[11]. The clothing sample is investigated by wrapping specimens around the sweating torso. Three phases are run to measure dry thermal insulation, dry and wet heat transfer and drying properties. Findings from the Sweating torso have been validated with standard methodologies, such as sweating guarded hotplate, and were shown to be highly reproducible[11]. Furthermore, validation studies have been conducted to relate human thermos-physiological measurements to Sweating torso findings under realistic environmental conditions and activities for firefighters. Based on this knowledge, guidelines are provided for intrinsic textile properties based on thermo-physiological responses. In addition to the standard procedure described above, the impact of more complex protective clothing systems including underwear, air gaps and/or design features is investigated optionally applying the same experimental protocol described in this document.

Protective clothing for firefighters — Physiological impact —

Part 1:
Measurement of coupled heat and moisture transfer with the sweating torso

1 Scope

This document provides a test method for evaluating the physiological impact of protective fabric ensembles and potentially protective clothing ensembles in a series of simulated activities (phases) under defined ambient conditions. This standard test method characterizes the essential properties of fabric assemblies of a representative garment or clothing ensemble for thermo-physiological assessment:

— dry thermal insulation;

— cooling properties during average metabolic activity and moisture management (dry and wet heat transfer);

— drying behaviour.

Default measurements are done on fabric samples representing the garment or protective clothing combination. Optionally and in addition to the standard test method, the same testing protocol can be applied to characterise more complex protective clothing ensembles including underwear, air layer and certain design features[1)]. In addition, measurements on readymade garments are possible.

This test method is intended to be used to measure and describe the behaviour of fabric assemblies of a garment or clothing ensemble in response to a simulated series of activities under controlled laboratory conditions, with the results used to optimize garment combinations and material selection. Furthermore, this document together ISO 18640-2, is intended to be used to describe the thermo-physiological impact of protective clothing but not the risk for heat stress under actual fire conditions. The results of this test can be used as elements of a risk assessment with respect to thermo-physiological load.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 3696, *Water for analytical laboratory use — Specification and test methods*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

1) A study conducted by Empa (Swiss Federal Laboratories for Materials Science and Technology, Switzerland) showed good correlation between results of standard torso tests (without underwear and air layers on fabrics) to tests on fabrics with underwear, tests on fabrics with underwear and air layers and test on readymade garments (with underwear and with or without air layers) of the same material composition. Due to the added thermal insulation values of the additional layers direct comparison of results between different measurement configurations is not possible, however.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
cooling delay
CD
time delay until the effect of evaporation cooling will be detected in an experimental phase with simulated activity and sweating

Note 1 to entry: The cooling delay is given in minutes.

3.2
evaporated sweat water
fraction of supplied sweat water which is evaporated in active phase with sweating

3.3
experimental phase
part of an experiment with a defined sweat rate and surface temperature or heating power; an experiment can consist of multiple phases

Note 1 to entry: Each phase simulates a specific situation with defined temperature or heating power and sweat rate settings. A standard experiment consists of three phases.

3.4
initial cooling
IC
rate at which temperature changes after cooling delay CD in an experimental phase simulating activity with sweating

Note 1 to entry: The initial cooling is given in degrees (°C) per hour.

3.5
moisture uptake
amount of moisture stored in clothing system determined by torso weight

Note 1 to entry: The moisture uptake is given in grams.

3.6
post cooling
PC
end of cooling period in an experimental phase without sweating and heating power corresponding to a human being at rest following a simulated activity

Note 1 to entry: The evaporation of stored moisture will extract energy from the sweating torso which can be detected in a decrease of the surface temperature.

Note 2 to entry: The post cooling is given in minutes.

3.7
phase profile
series of experimental phases which define the experiment

3.8
sustained cooling
SC
rate at which temperature changes towards the end of an experimental phase simulating activity with sweating (steady state of cooling)

Note 1 to entry: The sustained cooling is given in degrees (°C) per hour.

3.9
spacer
air layer
frame or setup to add a defined air layer between torso surface and protective garment to be tested

Note 1 to entry: Simulation of air layers which are typically observed in real use. An air layer influences overall thermal resistance and moisture transport. A spacer may be used to simulate a defined air layer.

3.10
sweat water
supply of water used to simulate sweating

3.10.1
gravimetric system to deliver sweat water
control of sweat water delivery using a tank on a balance with a defined height difference to the sweat nozzles to deliver the set amount of water by opening and closing valves in a calibrated interval

Note 1 to entry: Other ways of sweat water deliver may be used as long as the requirements of this document are fulfilled.

3.11
thermal resistance
$R_{ct\ (torso)}$
calculated at steady state from the difference between torso surface temperature and ambient temperature, the surface area of the device and the heating power needed to maintain the temperature difference

Note 1 to entry: The thermal insulation is given in $m^2 \cdot K/W$.

3.11.1
correction value for $R_{ct\ (torso)}$
$R_{ct0\ (torso)}$
thermal resistance measurement without a sample on the sweating torso to determine a system specific correction value for the thermal resistance $R_{ct\ (torso)}$

Note 1 to entry: Thermal resistance as defined above depends on the geometry of the apparatus, convective conditions (wind or still air) and ambient conditions. $R_{ct0\ (torso)}$ is a cumulative measure of this and might differ slightly from device to device and installation to installation. By taking it into account differences in results from different installations can be reduced.

3.12
torso balance
device used to measure torso weight

3.13
torso surface temperature
average temperature on the surface of the measurement area of the torso

3.14
torso weight
overall weight of the sweating torso and test object during a test

3.15
total sweat water
amount of water supplied to torso surface during an active phase with sweating

3.16
wicking layer
thin hydrophilic textile layer with defined moisture transport and thermal properties used for homogeneous sweat water distribution

3.17
wind speed
ambient velocity of air flow around the torso during an experiment

Note 1 to entry: To avoid undefined boundary air layers due to random air exchange in the chamber and the temperature difference between torso surface and climatic chamber a fan system is used. The fan system consists of ventilators to achieve a set homogeneous wind speed at the torso surface of 1 m/s (turbulence level of up to 25 % measured with a hot-wire anemometer).

4 Symbols and abbreviations

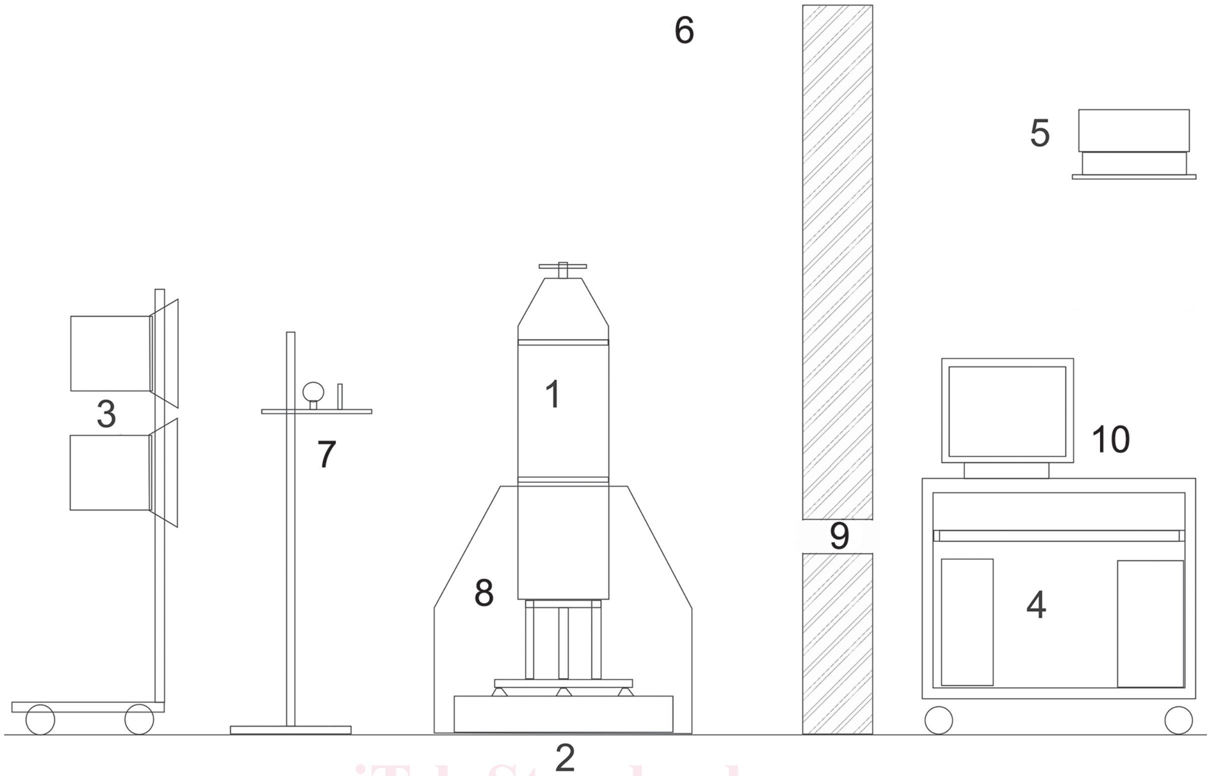
CD	Cooling delay, in minutes
HDPE	High Density Polyethylene
IC	Initial cooling in °C/h
PC	Post cooling, in minutes
PTFE	Polytetrafluoroethylene
$R_{ct\ (torso)}$	Thermal resistance in $m^2·K/W$
$R_{ct0\ (torso)}$	Correction value for $R_{ct\ (torso)}$
RH	Relative humidity
SC	Sustained cooling, in °C/h
THS	Thermal Human Simulator

5 Apparatus

The sweating torso is an upright standing cylindrical test apparatus, simulating the human trunk with thermal guards on the upper and lower end (see Figure 1). The apparatus is equipped with heating foils, sweating nozzles, a multi-layer shell (simulation of the skin layers) and electronics to control the valves and sensors.

The whole measurement system (see Figure 1) consists of the sweating torso (key element 1) on a balance (key element 2) positioned in a climatic chamber. A fan system (key element 3) is used to set the wind speed. The control system (key element 4) power supplies, controllers, and computer with data acquisition) can be placed either inside or outside the chamber. A sweat water tank positioned outside the climatic chamber placed on a balance (key element 5) provides the water to the sweating nozzles. The water supply is controlled by valves.

NOTE The design and control system of the sweating torso has been validated in numerous research projects with respect to different types of clothing systems for the assessment of coupled heat and mass transfer (see Annex E).



Key

1	torso	6	climatic chamber
2	torso balance	7	environmental sensors
3	fan system	8	frame to minimize influence of wind
4	control system	9	wall of climatic chamber with opening for cables
5	sweat water balance	10	computer, monitor and printer

Figure 1 — Example of torso system

5.1 Sweating torso

5.1.1 General

The sweating torso was designed to simulate the human trunk. The cylinder shall consist of an aluminium tube a layer each of HDPE-[2)] and PTFE which has an outer diameter of (30,0 ± 0,25) cm (circumference of ~94,25 cm) and a length of (46,0 ± 0,25) cm .Heating foils are situated inside the aluminium tube. On the lower and upper end of the upright standing cylinder there are thermal guards with individually controlled heating. There are temperature sensors in the aluminium part (Pt-100 sensors or equivalent) as well as on the surface of the measurement cylinder (Ni wires or equivalent).

The electronic components to control the valves for the 54 sweating nozzles can be situated in the lower guard (see Figure A.1) or in an electronic box outside the torso. Transducers converting the resistance values of the temperature sensors may also be located here. Also data acquisition and temperature controlling electronics or parts of these may be placed in the cavity of the guards. Care has to be taken that the heating power of these components shall not disturb temperature control of lower guards and, hence, affect measures obtained from main cylinder.

2) HDPE: High density Polyethylene. E.g. PAS-PE3, thermal conductivity: (0,41 ± 0,02) W/(m·K); thermal capacity: (2,0 ± 0,3) kJ/(kg·K).

The compartment between cylinder and guards shall be separated by thermally insulating discs (thermal conductivity less than 0,35 [W/m·K]) to limit heat exchange between the measurement cylinder and the guards. A more detailed technical description is given in Annex A.

The mass of cylinder, thermal guards and equipment shall be designed to have a mass of ~(82,5 ± 2,5) kg.

5.1.2 Heated cylinder

The central part of the torso is the area where the measurement takes place (surface area: ~0,433 5 m^2). The internal aluminium tube is covered by layers of synthetic material with similar thermal properties as the human skin (6 mm HDPE and PTFE foil, see Annex A).

5.1.3 Thermal guard sections

There is a thermal guard on each end of the measurement cylinder made of aluminium of the same diameter as the measurement cylinder. These two segments are controlled and heated separately to ensure that there is no parasitic heat flow from or to the measurement cylinder which is supported by the insulating discs between the sections. In addition, the space in the lower guard can be used to incorporate the electronics to register temperatures and to control the valves.

The upper guard has a conical end and is smaller compared to the lower guard to allow donning of readymade garments to the device.

5.1.4 Heating and temperature control

Heating elements shall be provided for each segment of the torso. Power supplies and means to regulate the temperature and heating power of each segment are needed. The power supplies shall be able to provide an output power of at least 500 W for the measurement cylinder and 240 W for each of the guards.

5.1.5 Temperature measurement

Temperature sensors (Pt100 or equivalent) in the aluminium part of the torso and nickel wires (or equivalent) for integral assessment of the surface temperature are used to control and monitor the temperature in the individual segments of the torso device. Optionally additional sensors placed close to the outer layers can be used for Thermal Human Simulator (THS) measurements according to ISO 18640-2. Temperature sensors shall have an accuracy of at least 0,1 °C in the range from 15 °C to 50 °C. See A.7 for more details.

5.1.6 Simulation of perspiration

Hardware to control sweat water supply is needed. This can be a gravimetric sweat water control system (see 5.5.1) or any other system capable to fulfil the requirements of 5.5. Temperature of the water coming out of the nozzles shall be within 0,5 °C of the temperature of the measurement cylinder.

NOTE The inner diameter and length of the tubes from the water storage to the nozzles will influence the amount of water delivered.

5.1.7 Wicking layer

A thin hydrophilic textile layer with defined moisture transport and thermal properties shall be used for homogeneous moisture distribution on the torso surface. The wicking layer shall be applied for all measurements and fulfil the requirements according to Table 1. This shall provide a sufficiently even sweat water distribution also when testing combinations with hydrophobic inner surfaces[16].

NOTE 1 The human skin has 50 to 250 sweat glands per cm^2 varying for body areas[14] while torso contains 0,01 sweating nozzles per cm^2 only. The use of a wicking layer with good, symmetrical wicking properties and insignificant added thermal insulation will ensure even spread of the moisture.

