
**Protective clothing for firefighters —
Physiological impact —**

**Part 2:
Determination of physiological heat
load caused by protective clothing
worn by firefighters**

*Vêtements de protection pour sapeurs-pompiers — Impact
physiologique —*

*Partie 2: Détermination de la déperdition de chaleur provoquée par
les vêtements de protection portés par les sapeurs-pompiers*



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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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 — Protective clothing and equipment*, Subcommittee SC 14, *Firefighters' personal equipment*.

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

Introduction

Protective clothing for (structural) firefighting may have a serious physiological impact^{1),2)} on the wearer and a serious effect on the acute physical condition of the wearer during activities with increased metabolic heat production^{[3][4]}. Protective clothing impedes heat exchange by sweat evaporation and therefore maintenance of a constant core body temperature and thermal homeostasis is disturbed. This could increase the risk of heat strain and subsequently impact on the length and time that the firefighter is able to work safely. If this is identified in a risk assessment, it is important that (thermal) physiological parameters are obtained to ensure the suitability of the protective clothing chosen under the expected conditions of use. The assessment of the physiological impact of the protective clothing provides important information about the effect on individuals undertaking different tasks in various environmental conditions. In ISO 18640-1, relevant physical parameters of protective clothing are measured with a Sweating torso. Standard Sweating torso measurements provide physical parameters about combined and complex heat and moisture transfer (ISO 18640-1). By coupling the sweating torso to a mathematical model for thermo-physiological responses, the thermo-physiological impact of protective clothing is estimated and the maximum exposure time for defined environmental conditions and a defined activity protocol are predicted by Thermal Human Simulator (THS) measurements.

The purpose of this document is to consider aspects of protective clothing performance that cannot be determined by tests described in other standards. The aim of this document is to quantify the thermo-physiological impact of protective garments for (structural) firefighting under relevant exposures. This document provides the background for the specification of a minimum level of performance requirements during defined firefighting scenarios for the assessed firefighters' protective clothing by calculation of the maximum allowable work duration in order to avoid heat stroke.

NOTE The method allows to characterizing the thermo-physiological impact for different levels of complexity. This includes the characterisation of the single PPE ensembles (standard procedure) as well as the characterisation of protective clothing ensembles including under wear and protective clothing, including air layers or including design features of protective clothing ensembles (e.g. pockets, reflective strips) as optional procedures³⁾.

1) Nunneley (1989) reported a significant physiological burden due to the protective clothing upon the wearer, both in the form of increased metabolic rate and reduced heat dissipation.

2) Taylor (2012) showed that the relative influence of the clothing on oxygen cost was at least three times that of the breathing apparatus.

3) This listing of standard and optional procedures is a first proposal for prioritization. The expressiveness of the different levels of complexity for the characterisation of the thermo-physiological impact needs to be further investigated. Results will be presented at the next ballot.

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Protective clothing for firefighters — Physiological impact —

Part 2:

Determination of physiological heat load caused by protective clothing worn by firefighters

1 Scope

This document specifies a method for evaluating the thermo-physiological impact of protective fabric ensembles and potentially protective clothing ensembles in a simulated activity under defined relevant conditions for firefighters.

This document is intended to be used to assess the thermo-physiological impact of protective fabric ensembles and potentially protective clothing ensembles but not the risk for heat stress due to actual fire conditions. The results of this test method can be used as elements of characterisation and comparison of thermo-physiological impact of various types of protective fabric ensembles and potentially protective clothing ensembles.

Default measurements are undertaken 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 protective clothing ensembles including underwear, air layers and certain design features⁴⁾. In addition measurements on readymade garments are optionally possible.

NOTE The presently used evaluation methods are only validated for structural firefighting garments.

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 11092, *Textiles — Physiological effects — Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test)*

ISO 18640-1, *Protective clothing for firefighters-physiological impact — Part 1: Measurement of coupled heat and mass transfer with the sweating torso*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 18640-1 and the following apply.

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/>

4) A study conducted at Empa (Swiss Federal Laboratories for Materials Science and Technology, Switzerland) showed good correlation between results of standard torso tests (without both 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 different thermal insulation of the systems direct comparison of the results is not possible.

3.1
core body temperature

T_{co}
temperature of deep body tissues of the human body

3.2
firefighting scenario

set of environmental conditions, a defined workload and a defined exposure time relevant for a firefighters' task

3.3
heart rate

number of heartbeats per unit of time

Note 1 to entry: The heart rate is usually expressed in per minute.

3.4
heat storage

heat accumulation in the body affected by metabolic heat produced, external heat load and heat dissipated from the body

3.5
maximum allowable work duration
MAWD

value calculated from thermo-physiological simulation (THS measurement) predicting the time to reach heat stress based on the definitions of this document

Note 1 to entry: See also [Annex A](#).

Note 2 to entry: This value is given in minutes.

3.6
mean skin temperature

$T_{m,sk}$
mean temperature of the outer surface of the (human) body measured at several locations of the skin

3.7
skin diffusion

E_{sk}
evaporative heat loss due to insensible skin perspiration and has to be provided for THS measurements

3.8
sweating torso

upright standing cylindrical test apparatus, simulating the human trunk with thermal guards on the upper and lower end as defined in ISO 18640-1

3.9
sweat rate

amount of moisture perspired per time on the surface of the torso

Note 1 to entry: The term sweat rate is also used as the physiological response of the human body to elevated metabolic rate and/or activity wearing protective clothing with high thermal insulation.

3.10
thermal human simulator measurement
THS

measurement with the sweating torso according to ISO 18640-1 where the device is coupled with a validated physiological model

Note 1 to entry: Test cases and requirements for the validation of the physiological model are provided in [A.3](#).

3.11**torso surface temperature**

average temperature on the surface of the measurement area (0,43 m²) of the torso device

4 Symbols and abbreviations

For the purposes of this document the following symbols and abbreviated terms apply, in addition to the terms and definitions in ISO 18640-1.

C_{sk}	Wicking layer correction
E_{sk}	Skin diffusion
MAWD	Maximum allowable work duration (in minutes)
$T_{m,sk}$	Mean skin temperature in °C
T_{co}	Core body temperature in °C

5 Evaluation method**5.1 General**

Physical parameters based on thermal properties of protective clothing resulting from standard torso measurements do not contain direct information about the thermo-physiological impact on the wearer for various firefighters' scenarios. Physiological data are deducted by doing measurements coupling sweating torso system to a physiological model as described in this document.

The results of these measurements are used to predict the maximum allowable work duration (MAWD) according to thermal characteristics and moisture management properties of the tested protective clothing system. This procedure was validated based on human subject trials (see [Annex A](#)).

5.2 Firefighting scenarios

Firefighters deal with a variety of tasks and challenges. Therefore, many scenarios have to be considered. In order to ensure a maximum level of comparability a moderate scenario has been defined which is applicable to a wide range of protective clothing inclusive of firefighting. The background and reasoning and the relevance for this standard are described in [Annex C](#).

5.2.1 Standard scenario for THS measurements

For the purpose of this standard a scenario was selected which reflects a moderate firefighter activity without fighting fire (see also [Annex C](#)).

The applied scenario is defined as follows:

- Ambient condition is set to 40 °C air temperature and 30 % RH;
- No radiation is present;
- Unidirectional wind speed of 1 m/s is applied;
- Physical activity is set to 6 Met⁵⁾ (350 W/m² metabolic rate, which equals 285 W/m² metabolic heat production);
- Initial condition of the human body is assumed to be thermo-neutral ($T_{co} = 36,8$ °C; $T_{m,sk} = 34,2$ °C);

5) MET: Metabolic Equivalent of Task (1 MET = 1 kcal/(kg·h) = 4,184 kJ/(kg·h) alternatively 1 MET = 58,2 W/m²).

- Exposure time is set to 90 min;
- The onset of heat stress is defined at the core body temperature of 38,5 °C.

NOTE This scenario was selected in order to be compatible with an ethically acceptable work load for human subject trials used to validate the physiological impact of firefighter clothing (See [Annex C](#)).

5.3 THS measurement

5.3.1 General

Thermal Human Simulator (THS) measurements are based on coupling the sweating torso system, in accordance with ISO 18640-1, with validated physiological model in accordance with [Annex A](#), in a climatic chamber simulating a defined activity according to the firefighters' scenario. In order to have a common starting point for the measurements initial conditions for THS measurements are set such that the torso mimics thermal neutral state.

5.3.2 Apparatus and software

THS is controlled with the same hardware and software as for standard torso experiments in accordance with ISO 18640-1, with the addition and cooperation of a physiological model (coupling with continuous data exchange).

5.3.3 Heat flux

For THS measurements heat flux data off the surface shall be measured, as they are is needed as input for the physiological model. Accuracy for heat flux measurement shall be better than 5 W/m² in the range of 0 W/m² up to 500 W/m². Measurement can be done by the procedure described in [5.3.3.1](#) or equivalent methods matching the requirements of this clause.

5.3.3.1 Heat flux measurement with additional temperature sensors

In this configuration the torso needs to be equipped with additional temperature sensors in the aluminium interior part of the device (see [Figure 1](#)) to allow more accurate assessment of heat flux from the surface. These temperature sensors are used to calculate the average surface heat flux based on the thermal resistance of the outer layers of the torso according to [Formula \(1\)](#) below:

$$q_{\text{torso}} = (T_{\text{NF}} - T_{\text{Ni}}) \cdot \frac{1}{R_{\text{torso}}} \quad (1)$$

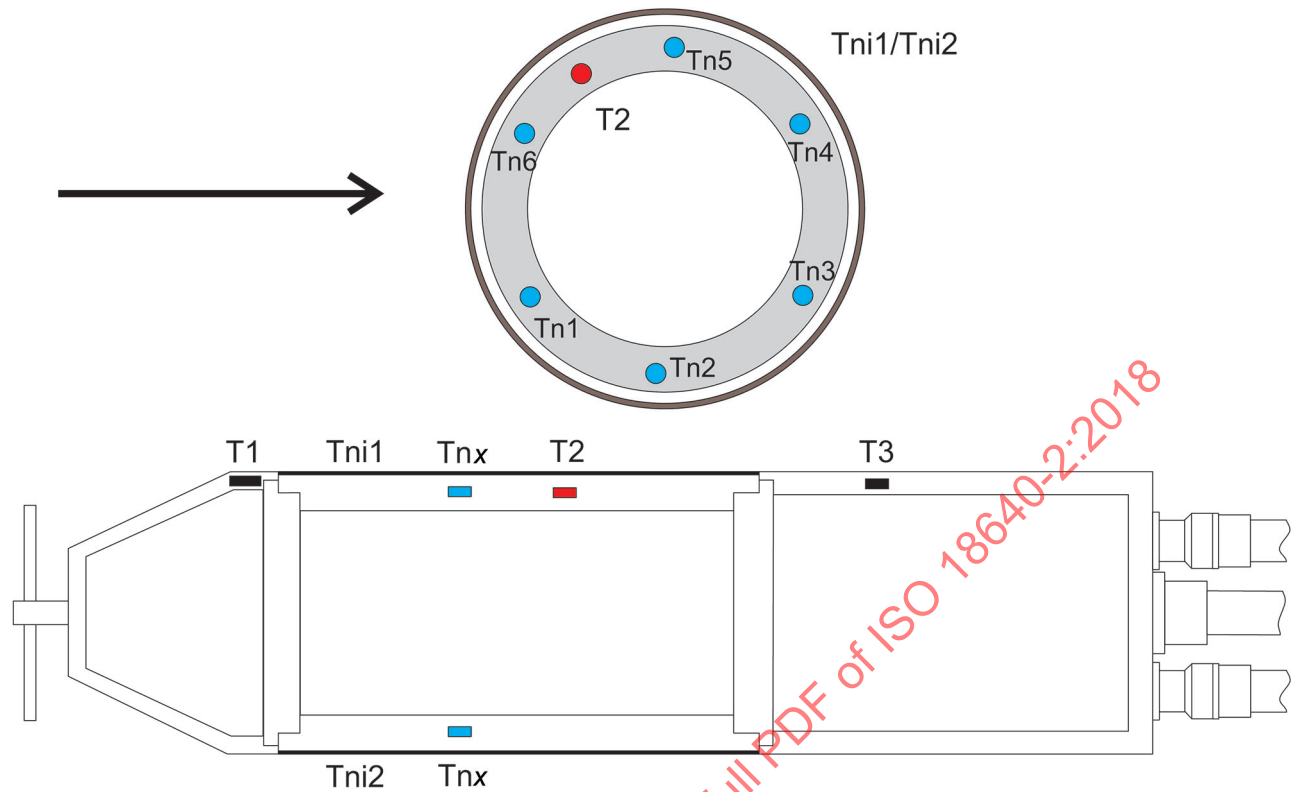
where

T_{NF} is the average temperature of additional sensors in °C;

T_{Ni} is the average temperature of nickel wire sensors (surface temperature) in °C;

R_{torso} thermal resistance of the aluminium/HDPE layers between additional sensors and nickel wires in m²·K/W;

q_{torso} average surface heat flux of the cylinder in W/m².

**Key**

- Tni1 nickel wire sensor 1
- Tni2 nickel wire sensor 2
- T1 temperature sensor in upper guard
- T2 temperature sensor in measurement section
- T3 temperature in lower guard
- Tnx optional additional sensors for THS measurements

Figure 1 — Configuration of temperature sensors for heat flux assessment

5.3.4 Wicking layer correction

A wicking layer according to ISO 18640-1:2018, 5.1.6, is used for all THS measurements.

A correction value (wicking layer correction) is used to compensate for the increase in thermal resistance by using the wicking layer on the torso main cylinder. The correction is calculated as a ratio between thermal resistances of the torso with the wicking layer to the thermal resistance of the nude torso (see [Formula 2](#)). Thermal resistances are calculated for torso surface temperature at 35 °C, air velocity <0,25 m/s at 20 °C ambient temperature with no radiation and exposure time of at least 60 min.

$$C_{sk} = \frac{R_{ct,sk\ layer}}{R_{ct,nude}} \quad (2)$$

The wicking layer correction has to be provided to the physiological model.

5.3.5 Skin diffusion (E_{sk})

E_{sk} is calculated from skin temperature (initial skin temperature; T_{sk}) and total R_{et} of clothing system applied (see [Formula 3](#)).

$$E_{sk} = -0,0014 \cdot R_{et} \cdot T_{sk} + 0,8022 \cdot T_{sk} + 0,0211 \cdot R_{et} - 15,151 \quad (3)$$

If R_{et} of the clothing system is unknown, it shall be measured in accordance with ISO 11092. Alternatively an estimate can be calculated based on R_{ct} and estimated permeability index (PI) according to ISO 9920:2007, Annex C.

$$R_{et} = \frac{60 \cdot R_{ct}}{PI} \quad (4)$$

NOTE R_{ct} refers to thermal insulation according to ISO 11092.

5.3.6 Data exchange with physiological model

Torso software and the physiological model shall exchange data within an iterative control loop on an interval of 30 s.

From torso to phys. model: surface heat flux, q , (accounting for wicking layer correction and skin diffusion) in W/m^2 ;

From phys. model to torso: average skin temperature ($^{\circ}C$) and Sweat rate [$g/(h \cdot m^2)$].

5.3.7 Measurement control

Measurements are based on standard torso hardware, torso software and a validated physiological model with an interface for data exchange. The physiological model shall have the possibility to run simulations with data from an external source and provide resulting data via a common interface. Data exchange shall be such that torso software provides surface heat flux data and the physiological model, after calculating the thermo-physiological responses based on surface heat flux, provides the resulting surface temperature (average skin temperature) and sweat rate. Data exchange is updated with 30 s interval.

Parameters for THS measurement:

- Simulated activity level (Met)⁶⁾;
- Surface resistance R_{torso} if additional temperature sensors are used to measure the heat flux off the torso surface (static, device dependent, see also [5.3.3.1](#));
- Wicking layer correction (static based on textile used, see [5.3.4](#)); and
- E_{sk} skin diffusion (dynamic see [5.3.5](#)).
- Initial conditions for the physiological model and the climatic chamber:
 - Exposure time: according to simulated scenario (standard 90 min);
 - Ambient temperature: according to simulated scenario (standard $40^{\circ}C$);
 - Relative humidity: according to simulated scenario (standard 30 %);
 - Radiant temperature: according to simulated scenario (standard $40^{\circ}C$);

6) MET: Metabolic Equivalent of Task ($1 \text{ MET} = 1 \text{ kcal}/(\text{kg} \cdot \text{h}) = 4,184 \text{ kJ}/(\text{kg} \cdot \text{h})$ alternatively $1 \text{ MET} = 58,2 \text{ W}/\text{m}^2$)

- Air velocity: according to simulated scenario (standard 0 m/s).

Depending on the used physiological model the above data needs to be stored in configuration files or entered to the program using dialog boxes.

6 Measurement

6.1 General

Calculation of MAWD is based on the results of THS measurements as described in this clause.

6.2 THS measurement

Perform the following steps to conduct a THS measurement and prepare the test report. Prior to dressing the torso, confirm that the surface temperature of the device is on the default temperature of $(34,2 \pm 0,1) ^\circ\text{C}$ and the climatic chamber is stabilized on the desired ambient condition according to the selected scenario.

Measurements will be conducted according to the flow chart shown in [Figure A.1](#).

6.2.1 Test preparation

Use the test protocol template proposed in [Annex B](#) or a similar form to make sure all steps of the experiment are followed correctly.

Follow ISO 18640-1:2018, 8.1 (preparation of climatic chamber, wind speed, dressing of the torso).

Set the ambient conditions for testing according to the selected scenario and make sure the torso is turned on and the surface temperature is set to the specified values [(default $34,2 \pm 0,1) ^\circ\text{C}$].

6.2.2 Software settings

Select a single phase profile with the appropriate starting conditions according to the selected scenario. Select THS as control mode for the measurement (data exchange with 30 s interval; export surface heat flux; import (set values) calculated surface temperature and sweat rate).

6.2.3 Sampling and test specimen

Specimens shall be selected according to [Clause 6](#) and prepared according to ISO 18640-1:2018, Clause 7. Conditioning shall be adjusted to the selected initial conditions for THS testing. It is recommended to apply samples without additional clothing layers (i.e. underwear), air gaps and design features for a standard characterisation of the thermo-physiological impact⁷⁾.

6.2.4 Measurement procedure

6.2.4.1 General

Start the software for the physiological model and setup the desired simulation (according to selected profile) by inputting test conditions according to the definitions of this standard and the specifications of the software for the physiological model. The data exchange with the torso software will then be prepared. The physiological model shall simulate the selected profile and wait for the torso to input

7) A study conducted by Empa (Swiss Federal Laboratories for Materials Science and Technology, Switzerland) showed good correlation between results of standard torso tests (without both 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 of the additional layers direct comparison of results between different measurement configurations is not possible.

its data (input data: surface heat flux in W/m²). Exchange interval shall be set to 30 s with the output data from the physiological model being surface temperature (in °C) and sweat rate (in g/h), as the loop continues with data exchange throughout the test.

6.2.4.2 Data acquisition

Data acquisition of the torso software shall start automatically when starting the measurement. All relevant data as outlined in ISO 18640-1:2018, 8.2.4.1 will be recorded twice per minute. The definition of the physiological model data acquisition will include relevant physiological parameters calculated according to the selected scenario. Alongside this, the control parameter (heat flux), from the torso software, is recorded in the same frequency as the torso data (twice per minute).

6.2.4.3 End of measurement

The THS measurement shall be terminated if the simulated physiological values exceed the set limits or the set maximal measurement time has been reached.

6.2.5 Data evaluation

Calculate MAWD based on the registered core body temperature from the physiological model as the first time when the core temperature physiological limit is exceeded.

Optionally, other criteria can also be considered and in turn indicated in the report to calculate MAWD which is based on core body temperature on default.

If core temperature is still below the limit set in the selected scenario after the end of the measurement, extrapolate core temperature assuming a linear increase to the last recorded data point based on the last 15 min of the measurement.

If the slope of core body temperature is ≤ 0 at the end of the THS measurement report the resulting MAWD as being infinite.

7 Test report

7.1 General

Report the results as described from [7.1.1](#) to [7.1.3](#).

7.1.1 Specimen identification

Describe the specimen(s) in terms of the following information: garment/ensemble type, size, fabric basic weight, fibre type, colour, and non-standard garment features and design characteristics. Include a description of any pre-treatment of the garment/ensemble components, such as laundering.

7.1.2 Measurement conditions

Report the environmental conditions set for the measurement and the applied phase profile referring to the report according to ISO 18640-1. Environmental data is defined by ambient temperature, radiant temperature, rel. humidity and wind speed. Phase profile is described in a list of entries containing information about control mode and set value, duration, sampling interval, sweat rate, wind speed and other parameters necessary to reproduce a measurement.

7.1.3 Results of THS measurement

Report the physiological parameters according to [5.3](#) and results described in [6.2](#).

7.2 Predicted physiological parameters

Report MAWD (min) based on THS results as described in [7.1.3](#).

7.3 Contents of test report

The test report shall consist of a reference to this document and the above mentioned data.

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Annex A (normative)

Single-sector Thermo-physiological Human Simulator (THS)

A.1 System components

A validated mathematical model⁸⁾ of human thermal physiology⁹⁾ is used to control THS measurements. This model shall be able to simulate human thermal responses under both steady-state and transient conditions, including the thermal history prior to an experiment. The model shall represent an average male body size with average fitness level. The model has to be validated over a wide range of environmental conditions showing root-mean-square deviation for the mean skin and core temperatures of max. 2,0 °C and 0,5 °C, respectively (typical standard deviations observed in human subject studies 1,0 °C and 0,2 °C, respectively).

The thermo-physiological model shall be capable of representing the human body by 19 body parts with additional spatial subdivisions to consider local exposures and heat transfer. Therefore, ending up with 63 sectors and tissue discrimination of up to 5 nodes in the radial direction and simulating the thermoregulatory responses of the central nervous system (e.g. cutaneous vasomotion, sweat excretion and shivering thermogenesis).

The hardware is a sweating torso according to ISO 18640-1, which is used to measure the environmental heat exchange. For THS measurements the torso is equipped with a tight-fitting textile 'skin' to guarantee a more even distribution of water over the surface of the main cylinder.

A.2 Coupling method

In order to simulate the overall physiological response, the torso is taken to represent the entire human body (trunk, head and extremities: single sector). The coupling method is based on real-time iterative exchange of the relevant data between torso and the physiological model (see Figure A.1). Area-weighted averages of the local skin temperatures and the local sweat rates from the physiological model are used as control parameters for the torso. The average heat flux from the cylinder surface of the torso is then used as the feedback signal, which represents the mean amount of heat exchanged with the environment for the clothing worn during a set time interval. Other physiological and perceptual parameters, such as core temperature, skin blood flow, heart rate, and thermal sensation, are calculated by the physiological model and stored in data files for post-processing.

8) See B.3 for requirements and test scenarios.

9) E.g. Fiala model by D. Fiala [5, 6, 7, 8].

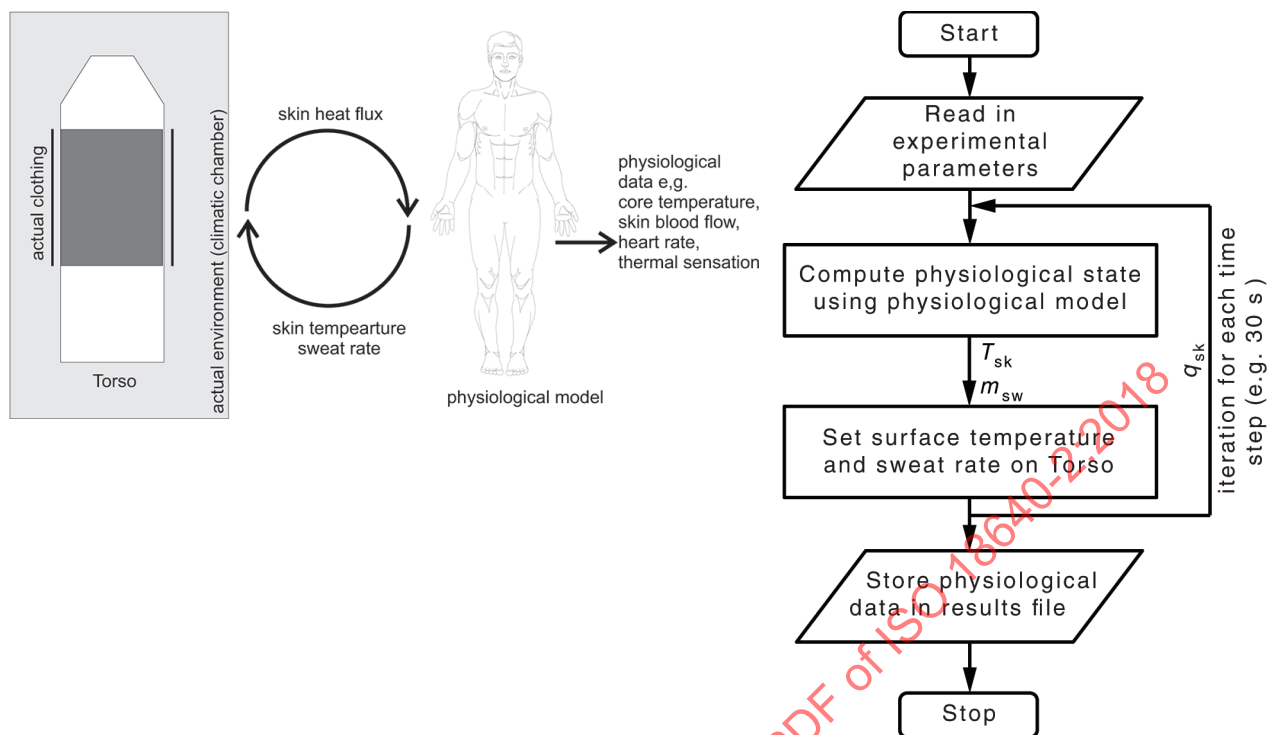


Figure A.1 — Schematic coupling torso to physiological model (left) and flow chart of measurement

Key

- q_{sk} torso surface heat flux (equals skin heat flux of physiological model)
- T_{sk} torso surface temperature (equals skin temperature of physiological model)
- m_{sw} torso sweat rate (equals sweat rate of physiological model)
- 1 actual clothing on torso
- 2 actual environment (climatic chamber)
- 3 physiological model

A.3 Validation of THS

A.3.1 Validation of physiological model

Since the torso is a single-sector device, the feedback heat flux consists of a single average value applied to all body parts of the physiological model. However, as the true physiological state of a person is associated with diverse local skin temperatures and sensitivity coefficients for different body parts, the approach of using a homogeneous heat flux had to be evaluated for its predictive accuracy. For an appropriate physiological model, skin temperature predicted shall be virtually unaffected for warm conditions and $\leq 0,75$ °C higher for cold conditions regardless of the metabolic rate of the subject. The core temperature predicted shall not vary by more than 0,25 °C. The predicted sweat rates shall be better than 1 % (difference) for combinations of low to moderate metabolic rates and cool to warm environments. Even for high activity levels (above 7 Met), the difference observed shall be below 25 %.

The coupled system shall be validated by comparison with results of human subject tests according to Table A.1.

Table A.1 — validation of THS and thermo-physiological model

Exposure	Data source	T_a °C	RH %	v_{air} m/s	MR met	n —	Clothing items	Mean skin temp.		Core temperature	
								RMSd °C	Bias °C	RMSd °C	Bias °C
cold	Wagner & Horvath, 1985[10]	15,0	40	0,08	0,9	20	semi-nude	0,37		0,07	
cool	Wagner & Horvath, 1985[10]	20,0	40	0,1	0,9	20	semi-nude	0,24		0,12	
neutral	Stolwijk & Hardy, 1966[11]	28,0	31	0,1	1,0	3	semi-nude	0,18		0,24	
warm	Stolwijk & Hardy, 1966[11]	33,3	34	0,1	1,0	3	semi-nude	0,62		0,16	
hot	Stolwijk & Hardy, 1966[11]	37,5	33	0,1	1	3	semi-nude	0,45		0,17	
sleeping bag	Camenzind et al. 2005[12]	−18	-	0,2	0,8	6	long underwear, pullover, sleeping bag	Chest: 0,69 Back: 0,84	Chest: 0,45 Back: −0,65	-	-
winter protective clothing	Mäkinen et al. 2000[13]	−5	40	0,2	1,4	8	long underwear, pullover, winter jacket and trousers	0,51	−0,46	0,15	0
NBC protective impermeable suit	Gonzalez et al. 1997[14]	35	50	1	3,75	10	long thin underwear, NBC suit	-	-	0,12	0,07
chemical protective impermeable suit	Marszałek et al. 2006[15]	40	30	0,2	2	6	long underwear, suit	1,02	0,74	0,35	0,1
protective cotton overall	Marszałek et al. 2006[15]	40	30	0,2	2	6	long underwear, overall	0,6	−0,26	0,36	−0,35
high performance sport suit	Jack 2009[16]	28	50	3,3	9,2	7	suit	0,35	−0,3	0,15	0,18
T_a ambient temperature v_{air} air velocity MR metabolic rate RH relative humidity RMSd root mean square deviation											

A.3.2 Validation THS

For an appropriate physiological model, the THS measurements need to accurately predict skin and core temperatures for the selection of clothing ensembles and environmental conditions within the shown RMSd and bias results and confidence intervals according to [Table A.1](#). Concerns regarding the negative effect of overheating when wearing highly insulating clothing or at high environmental temperatures due to the low heat flux were not evident. Hence, the single-sector human simulator demonstrated its accuracy and stability in a variety of conditions when clothing is worn.

Compared to cold conditions, hot exposures are more difficult to simulate due to limitations of the hardware and climatic chamber restrictions. Although the single-sector thermo-physiological human simulator performed well in validation trials under hot environmental conditions, special care has to be taken to ensure proper heat exchange at the beginning of the exposures. During validation tests, typically, human volunteers were prepared in a thermo-neutral climatic chamber ($T_{\text{skin}} = 34\text{ °C}$) before the actual exposure and only then they entered a hot environment (e.g. at 40 °C), whereas the human simulator had to remain continuously in the hot climatic chamber. To minimize the risk of too high an initial surface temperature (equal to at least the ambient temperature), the simulator has to be exposed first to an ambient temperature lower than the predicted initial surface temperature and once a steady-state is reached, the temperature in the climatic chamber will have to be increased to the required value (higher than the initial required surface temperature of the simulator). Effectively, the required surface temperature of the simulator is maintained by active heating and onset of sweating.

A.3.3 Limitations THS measurements

Simulation using clothing systems with non-homogenous distribution of thermal insulation is limited as the single-sector device uses one heat flux value representing the entire body to simulate physiological response. For example, the physiological response of vasoconstricted lower extremities with low skin temperature when wearing fewer layers on the lower body cannot be predicted accurately. For the simulation of hot environments the use of a single sector manikin is suitable since body temperature tends to be homogeneous due to vasodilation.

A.4 Standardization of thermo-physiological models

The technical committee dealing with standardisation of the physiological models is ISO/TC 159/SC 5 *Ergonomics of the physical environment*. They are currently preparing a standard for this topic:

ISO/TS 16418, *Ergonomics of the thermal environment — Mathematical model for predicting and evaluating the dynamic human physiological responses to the thermal environments*.

Textile clothing systems are extremely complicated to simulate in a computer model. Thermo-physiological models are suitable to simulate firefighter activities but without an accurate clothing model they will not predict valid results or will not be able to differentiate between clothing combinations.

A.5 Open source models

So far no standardized thermo-physiological model exists. In literature many models are described but without source code apart from Stolwijk model^[11] and the Lotens model^[17]. The otherwise published equations and coefficients are not enough to reprogram it. In addition the validation of these models for different environmental conditions and workloads is mostly missing.

A.6 Requirements for physiological models suitable for THS measurements according to this document

A thermo-physiological model suitable for THS measurements will have to show results within the requirements according to [Table A.1](#) when simulating the attributed expositions and boundary conditions.