Nederlands Instituut Publieke Veiligheid

Heat stress under simulated fire and rescue activities in two types of clothing

Nederlandse Academie voor
Crisisbeheersing en Brandweerzorg
Postbus 7010
6801 HA Arnhem
Kemperbergerweg 783, Arnhem
www.nipv.nl
info@nipv.nl
026 355 24 00

Publication details

Authors	K. Kuklane, R. Heus, L. Kistemaker en R. Weewer
With the cooperation of	K. Levels, I. Tanck, E. Mol, M. Kemmeren
Contact person	K. Kuklane
Date	8 June 2026
Photos	L. Kistemaker

Het Nederlands Instituut Publieke Veiligheid is bij wet vastgelegd onder de naam Instituut Fysieke Veiligheid.

Preface

It is getting warmer, drier, wetter, and sea levels are rising. The effects of climate change are felt increasingly, also by firefighters, who have to provide assistance in these often very different conditions wearing protective clothing. Turnout gear, primarily intended for indoor firefighting, can cause heat stress, especially in spring and summer. Heat stress is a perennial problem. We know its causes and consequences, and we know how to prevent it. Yet, this is becoming increasingly difficult when simultaneously sufficient protection is needed and temperatures are rising. This is why it is important to be climate adaptive in the field of protective clothing as well. Especially for technical assistance and wildfire fighting, which are activities that are becoming increasingly common and may not require the same protection as indoor firefighting, it is wise to explore other options. One such option is a so-called modular system: a clothing package where additional layers are added as the need for protection level increases.

This research is one piece of that puzzle. Measurements were made to determine how the current operational uniform, combined with a turnout suit (as it currently is), compares to a multilayered system for various types of work in terms of heat stress experienced by firefighters. In addition to research into clothing systems, it appears that climate adaptation for the fire service, at least in relation to clothing, not only concerns the clothing itself, but also about the way firefighters wish to and can cope with changes in its use: the culture.

This report is not a simple matter. Researching and measuring the effects of firefighter clothing on firefighters' physical system is a scarce and highly specialized area of expertise. Internationally, there is considerable interest in this topic from both professional practice and academia. We collaborate closely with universities and possess specialized knowledge. The NIPV researchers and advisors are internationally prominent members of standards committees, where they contribute this knowledge combined with the expertise from the research group on future-oriented firefighting. This research alone has led to multiple publications in scientific journals. The knowledge gained from this research is and will remain available within our group.

I would like to thank everyone who participated in this study, especially the participants, who volunteered their time and performed physical exertion under demanding conditions.

Enjoy reading this report!

Ricardo Weewer,
Professor of Fire Service Science

Table of contents

Summary

In this study, two different clothing systems were examined under three different conditions. The clothing systems consisted of the standard turnout garment worn over the operational uniform (the traditional Trad system) and a modular system consisting of the operational uniform covered by two layers. The first could be used for wildfire fighting and technical rescue, and the second worn over that for indoor firefighting (the modular Mod system). Work was carried out using these two systems under simulated conditions, namely technical rescue, a wildfire scenario, and an indoor fire scenario. Under these conditions, objective physiological parameters and subjective responses were recorded for both systems.

All relevant physiological parameters were measured, namely core temperature (measured rectally), average skin temperature, heart rate and oxygen consumption. Different clothing configurations within the different scenarios were compared. In all cases, the firefighters wore the new operational uniform under their turnout gear. The measurements were carried out with ten male subjects, who wore either the traditional turnout gear (5 test persons) or the modular turnout gear (5 test persons). They were tested in all three scenarios in random order. Due to illness, eight participants with a complete dataset remained (four per clothing configuration). This report focuses on descriptive statistics (such as means and standard deviations) and the suitability of existing predictive models for heat stress.

Due to the highly variable environmental conditions during the test period, the climate tent was less stable than expected. Nevertheless, all relevant physiological parameters were measured. Workload, skin temperatures and rectal temperature were found to be lower with the modular clothing type. The lower rectal temperature suggests a longer possible deployment time before critical core temperatures are reached. The recovery time with the modular clothing type was also significantly shorter.

No statistically significant differences in these parameters were measured between the two clothing systems. This means that in this study no difference in heat strain was measured between the traditional suit and the modular clothing system in these three scenarios. However, a few caveats should be noted, which allow us to conclude that the modular system performs better overall and, moreover, offers the possibility of scaling up or down in layers depending on the incident. For instance, it turned out that the ambient temperature during the testing of the modular system in the climate chamber was unintentionally 6°C higher than during the experiments with the traditional system. Furthermore, due to circumstances, the study was inadvertently conducted with fewer subjects (8 instead of 10), resulting in a wider spread in the results, and therefore, the differences were not always statistically significant.

The current dataset helps to improve existing thermo-physiological models for extreme conditions such as those encountered during firefighting. Currently, the existing models are not yet capable of reliably predicting physiological responses under firefighting conditions. Further and more in-depth analyses of these data will allow for a proper evaluation of the

models and of the effects of age on the physiological strain experienced by firefighters. This will contribute to establishing safe working limits for firefighters.

Introduction

In the context of climate adaptation, it is necessary to investigate how firefighters can be optimally protected in the future across the entire risk spectrum during low-, medium-, and high-risk tasks. Currently, there is insufficient coordination between the (protective) clothing packages used during operational deployments. In almost every deployment, professional firefighters wear their firefighting uniforms, with their operational uniforms underneath. Currently, volunteer firefighters only have firefighting uniforms available, which are worn over their everyday clothing.

In the RBC[1] meeting on 22 September 2019 regarding protective clothing for the fire services, the topic 'More collective approach for (deployment) clothing for the fire services in the Netherlands', was put on the agenda with reference to the decision of 21 June that year (‘Decision on the implementation of operational clothing’). At the time, it was proposed to develop a vision for an integrated clothing system for the fire services for the longer term. The Netherlands Institute for Public Safety (NIPV)[2] was commissioned to describe the development vision and fill the knowledge gaps. The ‘Customer Council Firefighters’ Clothing’ acted as delegated client on behalf of the Council of Commanders and Directors of Safety Regions (RCDV). At the request of the chairman of the Customer Council for Firefighters’ Clothing, the development of a future vision for protective fire services clothing has started, for which the present OU was taken as a starting point.

The underlying idea was that, in connection with future developments (including climate change, sustainable employability of fire services personnel), the fire service found that a more integrated vision of the entire protective clothing system would be desirable. Risk profiles, protection requirements, performance and wearing comfort play an important role in this to arrive at the protection concept best suited to the tasks.

This broad approach requires that regional principles, procedures and details must be identified and aligned where possible. Regarding functionality and protection, the minimum level has been established in the European Regulation 2016/425 on personal protective equipment[3] and formalised by means of standards (NEN-EN and NEN-EN-ISO).

Background

As indicated in the introduction, the RCDV[4] decided on 21 June 2019 that all Safety Regions in the Netherlands will have an operational uniform (OU) for professional firefighters. The OU will replace the previous station wear and, in addition to being used as work clothing, will also be used as protective clothing during operational low-risk tasks of the fire services. This

[1] Raad Brandweercommandanten.
[2] At the time Instituut Fysieke Veiligheid (IFV).
[3] Regulation (EU) 2016/425 of the European Parliament and of the Council of 9 March 2016 on personal protective equipment and repealing Council Directive 89/686/EEC (Text with EEA relevance).
[4] Formerly known as RBC (Council of Firefighters’ Commanders).

means that, in addition to the current turnout clothing, a larger range of protective clothing is available for the daily activities of the professional fire services.

Although both clothing packages meet minimum usage standards, no research has been carried out into the functioning and impact of the combination of both clothing packages, while this will be daily practice. For that reason, it was also decided during the RCDV meeting that an integral vision on protective clothing must be developed for the long term. The long-term goal is to arrive at a modular package of protective clothing that makes it possible to wear the right (= optimal protective) clothing for the task. The situation for volunteer firefighters is different than for professional firefighters but will also have to be considered for this group of firefighters whether and how a modular protective clothing concept can be used in the future.

Problem statement

Changes are currently taking place in the fire services operation (for example, there is more wildfire fighting) and the circumstances under which the fire services must perform those tasks (such as climate change). In addition, there are numerous developments in the field of protective clothing (including the use of the operational uniform). Due to these developments, separate initiatives are now emerging to adapt and purchase clothing. However, presently there is no good vision for an integral (modular) protection concept for the fire services in future.

Since the fire services almost always operate in protective clothing for (structural) firefighting, even when it concerns non-fire-related incidents, the physical burden resulting from the clothing worn is high (Dorman & Havenith, 2009; Holmér et al. 2006; Taylor et al. 2012). This additional burden can lead to overload and conflicts with the current ideas for sustainably deployable firefighters. With the introduction of the OU, more options are being created in protection for the fire services, which means that the physical burden for certain (low risk) tasks can be reduced.

However, there has not been any known research yet into the combination of different protective clothing packages for risks higher than low risk. There is also no clear coordination within the Dutch Fire Service between wearing the OU in combination with protective clothing for firefighting or not.

This project investigates whether the new OU can be used in combination with protective clothing for firefighting during fire services’ tasks with the qualification higher than low risk, and what the additional burden is for the wearer. Since both clothing packages have not been developed in conjunction with each other, it is also worth investigating whether the protective clothing can be optimised in the future by combining certain clothing items and possibly integrating smart elements into the clothing.

Scientific background

Firefighters are often exposed to dangerous situations that negatively impact their health and safety (Fullagar et al., 2021; Sandsund et al., 2024). Lee et al. (2017) reported that 404 out of 794 firefighters encountered significant hazards during operational tasks. During high intensity work, firefighters face high ambient temperatures, heat flux from flames and heat radiation, but also via contact with hot surfaces. Thermal energy is thereby transferred to the skin through radiation, conduction, and convection (Lei et al., 2023). Besides extreme temperatures, exertion level and clothing type also play critical roles (McLellan et al., 2023; Périard et al., 2021). Heavy and semi-permeable protective clothing is commonly used for protection against these hazards (Holmér et al., 2006; Rathour et al., 2021). The total weight, including gas bottles, can reach up to 20 kg or more, increasing metabolic load and thus the internal heat production as well (Holmér et al., 2006; Sköldström 1987, Tochihara et al. 2022).

Increasing the protection elevates the bulk and carried weight, which means lower physical performance, higher metabolic load and an increasing internal body heat production (Dorman, 2007; Dorman & Havenith, 2009; Teitlebaum & Goldman, 1972). Significant levels of heat stress develop quickly during hot and high-intensity activities when wearing heavy clothing, leading to negative physiological and psychological responses (heat strain) and heat-related disorders (Moran et al., 2003; Petruzzello et al., 2009). Physiological responses, including increased skin and core temperatures, increase the risk of heat-related injuries (Carballo-Leyenda et al., 2022; Eggenberger et al., 2018; Færevik & Reinertsen, 2003; Renberg et al., 2022). Reduced mobility, flexibility, and dexterity can also restrict the ability to successfully accomplish a task (Aljaroudi et al., 2022; Son et al., 2022; Tochihara et al., 2005; Wang et al., 2021). Psychological responses such as sleep problems, emotional fatigue and burnout contribute to dropout rates among firefighters (Yung et al., 2022). Mitigating these risks is essential for ensuring firefighter safety in hot environments.

Therefore, an objective aim of firefighter organizations is to be able to select the *optimal* protection per task and incident scenario. Risk profiles, protection requirements and comfort play an important role to arrive at the protection concept best suited for the tasks. It is desirable that such a protection concept leaves space for the integration of future (technological) developments.

With regards to functionality and protection, the minimum protection level has been laid down in (inter)national standards (such as NEN-EN and NEN-(EN)-ISO), for example NEN-EN 469:2020, the NEN-ISO 11999 series, NEN-EN-ISO 15384:2018 and NEN-ISO 21942:2019. However, most of the requirements are related to materials and material packages and not to the functional requirements for complete clothing items or clothing ensembles.

To investigate the effect of clothing on human thermal comfort and thermal stress across different environments, the thermal insulation and evaporative resistance of clothing should be considered (Xu et al., 2014). These parameters are important for thermal comfort and the prediction of heat strain when working in hot environments (Parsons, 2014). Kuklane et al. (2022) measured thermal insulation values of individual Dutch firefighting clothing items and their combinations on a thermal manikin. NEN-EN-ISO 15831 (2004) provides the requirements and guidelines for clothing insulation testing on thermal manikin and NEN-EN 17528 (2022) for evaporative resistance measurements.

While the study of Kuklane et al. (2022) assessed the new Dutch OU (operational uniform) and prototypes of scenario-based clothing systems, it did not include the current Dutch firefighter clothing system. Therefore, a follow-up study was performed on a firefighter protective clothing system currently used (Kuklane et al., 2024a). Detailed information on both future and currently used firefighter turnout gear allows the objective evaluation of the performance of the OU in combination with these sets, as well as the evaluation of any thermo-physiological models and smart wearables that become available for rescue services to plan their activities in a variety of scenarios and/or use warning systems. A report on these measurements has been published recently (Heus et al., 2025).

Advanced models for assessing heat strain are increasingly emerging (De Freitas & Grigorieva, 2014; Havenith & Fiala, 2016). The Predicted Heat Strain (PHS) model is one of the few models that considers both exogenous and endogenous factors (Ioannou et al., 2019) and is available for use by wide user groups as a standard (NEN-EN-ISO 7933). It predicts the physiological responses of industrial workers in hot environments and takes clothing properties into account (Malchaire et al., 2001). However, the model has been validated for a 1.2 clo limit for clothing thermal insulation (Malchaire, 2006), while firefighter turnout gear may exceed 2.5 clo (Holmér et al., 2006; Kuklane et al., 2022; Kuklane et al., 2024a). The standard has also not been validated for intermittent work in extremely hot environments and at very heavy physical workloads.

Aims and objectives

In order to develop a long-term vision on protective clothing, it is necessary to have knowledge about (future) tasks and developments in the field of (modular) protection. As a goal for the long-term vision, we will provisionally assume the following:
Firefighters are always adequately protected for the tasks they have to perform, whereby each task has its own optimal protection, and the clothing can be modularly constructed into an integral protection concept.

The extent to which this vision is feasible must be investigated. The aim of this specific project is to gain insight into the heat strain of different clothing configurations and to develop knowledge on and substantiation for a vision on integral (modular) protection concepts for the fire services. As a basis for substantiating this vision, it is investigated to what extent the present protective clothing of the fire services is adequate for tasks higher than low-risk. In addition, it is investigated whether the use of protective clothing during these tasks causes inconvenience and where possible bottlenecks lie in the protective clothing for high-risk tasks of the fire services.

The research results must eventually lead to a substantiated vision on an optimal protection concept for the fire services, whereby the correct protection is worn for each task. The different situations for professional and volunteer firefighters must be considered. The present study only examines the combination of OU with two varieties of turnout gear. Proposals are made on how possible bottlenecks and hindrance of the protective clothing can be tackled in order to minimise the burden on firefighters.

The results of this subject research can be used to validate different thermo-physiological models. These models may be useful for the fire department to evaluate exposure in rescue scenarios or to develop specialized decision aid tools and reliable prediction-based warning systems. Therefore, in this study, a first attempt was made to validate existing models with these results.

Thus, the next step of this work would be to utilize the results of this study for the validation of various thermophysiological models. These models may be useful for the fire department to evaluate exposure in rescue scenarios or to develop specialized decision aid tools and reliable prediction-based warning systems.

Delimitation

This research focuses solely on the physical burden, hindrance, and (dis)comfort of currently used clothing combinations in various firefighting scenarios. The modular protection project does not include the production or implementation of a new integrated (modular) protection system for firefighters. Furthermore, this project does not incorporate smart elements, such as wearables or sensors, into the firefighters' current protective equipment.

Reading guide

In chapter 1 the used method is explained. Chapter 2 contains the results; a discussion of these results is also included in this chapter. Chapter 3 contains the conclusion.

1 Methods

The work involved compiling a list of fire services tasks in the Netherlands with possible (protective) clothing configurations and any additional fire services activity needs, selecting the most relevant exposure scenarios and executing a research protocol with test persons.

The thermal properties of firefighter clothing ensembles that affect physiological responses and heat stress development will be measured by available standard methods and will be related to human test data.

Analysis of clothing heat transfer properties allows to evaluate if the clothing matches the required protection for the execution of fire services tasks. Further, the first model calculations are performed in order to determine the minimum required protection for selected fire services scenarios.

1.1 User scenarios

An initial list of incident scenarios and other firefighter occupational activities was compiled (Table 1.1).

Table 1.1 Firefighter tasks and activities

Structural firefighting (SIF)	**Fires in transport sector**
Residential buildings	Seafaring vessels (open water, harbour area)
Multiple-level buildings	Airplanes (airfield, wilderness)
High-rise buildings	Trains (populated areas, wilderness)
Parking garages	Cars, electrical vehicles, trucks and trailers (populated areas, highways)
Underground structures (including tunnels)	**Technical rescue operations (TRW)**
Industrial firefighting	Work with heights
Production facility	Use of hydraulic tools
Process industry	**Other activities**
Chemical plant	Activities at fire stations: > Cleaning up equipment > Maintenance of trucks and equipment > Office work > Waiting
Warehouse fires	Fire investigation
Agricultural facilities	Prevention
Distribution centres	Dirty work, e.g. saving animals from sewer
Outdoor firefighting	Chemical accidents
Trash burning, etc.	Water rescue
Wildland firefighting (WLF)	Search and rescue
Open field	Training: > Instructors > Trainees
Forest	
Bushfires	
Hills / steep slopes	
Turf fires / fires in the ground	

Out of these tasks, the three most common incident scenarios were selected to be simulated in a human test series in a climate-controlled tent (Table 1.2). These are the following scenarios: technical rescue during warm season (TRW), wildland firefighting (WLF) and structural interior firefighting (SIF).

Table 1.2 Incident scenario comparison

Scenario's	Interior fire fighting interior		Interior fire fighting exterior		Outdoor fire fighting Outdoor	Wildland fire fighting	Technical rescue	Other tasks
Parameters	**Offensive**	**Defensive**	**Offensive**	**Defensive**				
Duration	Short, commonly <30 min	Short, commonly <45 min	Medium, commonly <90 min	Medium, commonly <90 min	Short, <30 min	Long, 8u	Medium, to long, 1-3u	Long, tot 8u
Work intensity	High, >500 W	Moderate to high, ≈400 W	Moderate to high, ≈400 W	Moderate, ≈300 W	Moderate, ≈300 W	Moderate, ≈300 W	Moderate, ≈300 W	Light to moderate ≈200 W
Air temperature	Up to 100 °C with short peaks to 200 °C	Up to 50 °C	Over 30 °C	Over 30 °C	Over 30 °C	Up to 40 °C	From -10 to 35 °C	From -10 to 35 °C
Relative humidity	About 50 %	About 50 %	About 70 %	About 70 %	About 70 %	About 60 %	10-90 %	10-90 %
Heat radiation	Up to 10 kW/m²	Up to 3 kW/m²	Up to 10 kW/m²	Up to 1 kW/m²	Up to 1-2 kW/m²	Up to 4 kW/m²	Up to 1 kW/m²	Up to 1 kW/m²

1.2 Clothing

The detailed information of the used clothing (Table 1.3) is available in Kuklane et al. (2022, 2024a) and Heus et al. (2025). Effects of size and fit and influence of accessories on thermal protection of the used garments are described in Kuklane et al. (2023, 2024a).

The ergonomics evaluation of a firefighter protective clothing system used in this study was described by van Harten (2023) and van Harten et al. (2023) where test procedures and recommendations according to EN 17528 (2023), Havenith and Heus (2004) and ISO 20141 (2022) were followed.

In all three scenarios, the firefighters wore new OU under the turnout gear. All clothing items were washed at least five times before the experiments.

Table 1.3 Images of the tested clothing used in this human study

Trad_TRW	Trad_WLF (SIF-Pre)	Trad_SIF	REC
			
I_{cl}=1.92 clo; R_{ecl}=61.7 m^2Pa/W; $i_{m,cl}$=0.28	I_{cl}=2.17 clo; R_{ecl}=74.2 m^2Pa/W; $i_{m,cl}$=0.25	I_{cl}=2.39 clo; R_{ecl}=78.7 m^2Pa/W; $i_{m,cl}$=0.27	I_{cl}=1.12 clo; R_{ecl}=33.0 m^2Pa/W; $i_{m,cl}$=0.32
Mod_C9A_TRW	**Mod_C8_WLF**	**Mod_C4_SIF**	**Mod_C7_SIF-Pre**
			
I_{cl}=2.09 clo; R_{ecl}=54.0 m^2Pa/W; $i_{m,cl}$=0.38	I_{cl}=2.33 clo; R_{ecl}=67.4 m^2Pa/W; $i_{m,cl}$=0.33	I_{cl}=2.69 clo; R_{ecl}=76.7 m^2Pa/W; $i_{m,cl}$=0.34	I_{cl}=2.60 clo; R_{ecl}=74.0 m^2Pa/W; $i_{m,cl}$=0.32

Mod – modular clothing system (for ensemble details see ensembles C4, C7, C8 and C9A in Kuklane et al., 2022), Trad – traditional clothing system (for ensemble details see ensembles TRW, WLF-L and SIF in Kuklane et al. 2024a), REC – ensemble used during recovery (see REC in Kuklane et al. 2024a), TRW – ensemble used for technical rescue; WLF – ensemble for wildland firefighting, SIF – ensemble for structural interior firefighting.

1.3 Equipment and instruments

1.3.1 Climate-controlled room

Measurements were conducted in the climate chamber at the military site in Soesterberg between December 2023 and January 2024. The three firefighter scenarios had the following temperatures and humidities:

> technical rescue in warm weather (TRW, 25 °C and 60 % relative humidity (RH))
> wildland firefighting in hot weather (WLF, 30 °C and 50 % RH)
> structural firefighting (SIF, 45 °C and 40 % RH).

1.3.2 Radiation panel

A radiation panel was used (Figure 1.1). The radiation panel was manufactured by Jac. de Vries INFRAROODTECHNIEK (SINUS JEVI ELECTRIC HEATING B.V., Medemblik, The Netherlands) for experimental purposes to simulate exposure to heat radiation. It was meant to irradiate an exercising person evenly with heat radiation up to 4.6 kW/m^2 [5]. The maximum surface to be heated was 700 x 1900 mm (width x height). For this purpose, 10 infrared (IR) radiators with a maximum power of 1300 W each (3 phase 230 V, 22.5 A) were mounted on a mobile frame made of aluminium profile. The regulation box is placed on the bottom of the back side of this frame.

a) b)

Figure 1.1 Radiation panel (a); and an exercising person at the side of the panel (b)

Before the test series the panel performance was evaluated with the Hukseflux water-cooled heat flux sensor SBG01, connected to LI19 handheld datalogger (Hukseflux Thermal Sensors B.V., Delft, The Netherlands), and with the Thermal Environment Monitor (QuesTemp° 46, TSI Instruments Ltd., Shoreview, MN, USA).

During the experiments, it was not possible to set up these instruments at the position of the test persons (TP) due to them moving at this spot. During these panel calibration tests, the QuesTemp front panel was covered with aluminium folium to avoid any high heat flux damage to the instrument, whereby only the sensors were exposed to the radiation. Despite these precautions, the instrument was not used at all the measuring points during the

[5] Maximum allowed heat radiation for short time deployment (maximum 5 minutes) of (company) firefighters and operators at industrial companies (2016).

highest applied IR radiation levels due to the risk of damage caused by long-term IR exposure.

For applying the intended heating power on the TP, the heat flux (intensity kW/m^2) was calibrated based on the distance from the panel (Figure 1.2). Both heat flux and environmental parameters were measured at two locations:

1. In an open hall at air temperature of about 18 °C
2. At 35 °C in the climate-controlled room

The power at the centre point was also measured at an air temperature of 45 °C. In all cases the panel power was set to maximum, and the power was regulated by the distance from the panel. Heat flux was initially measured at the distances of 0.5, 1.0 and 2.0 m from the panel (the centre point of the panel also at 1.5 m). The predictions were then checked at the distances of 1.5, 0.5 and 0.2 m, which were the initially estimated distances to the clothing surface at the TP's lateral upper arm, i.e. the skin point expected closest to the panel.

Differently from heat flux measurements, at 35 °C the QuesTemp° 46 sensors were located at the expected central plane of the TP, i.e. in the middle of the treadmill and 0.3 m further away from the radiation panel.

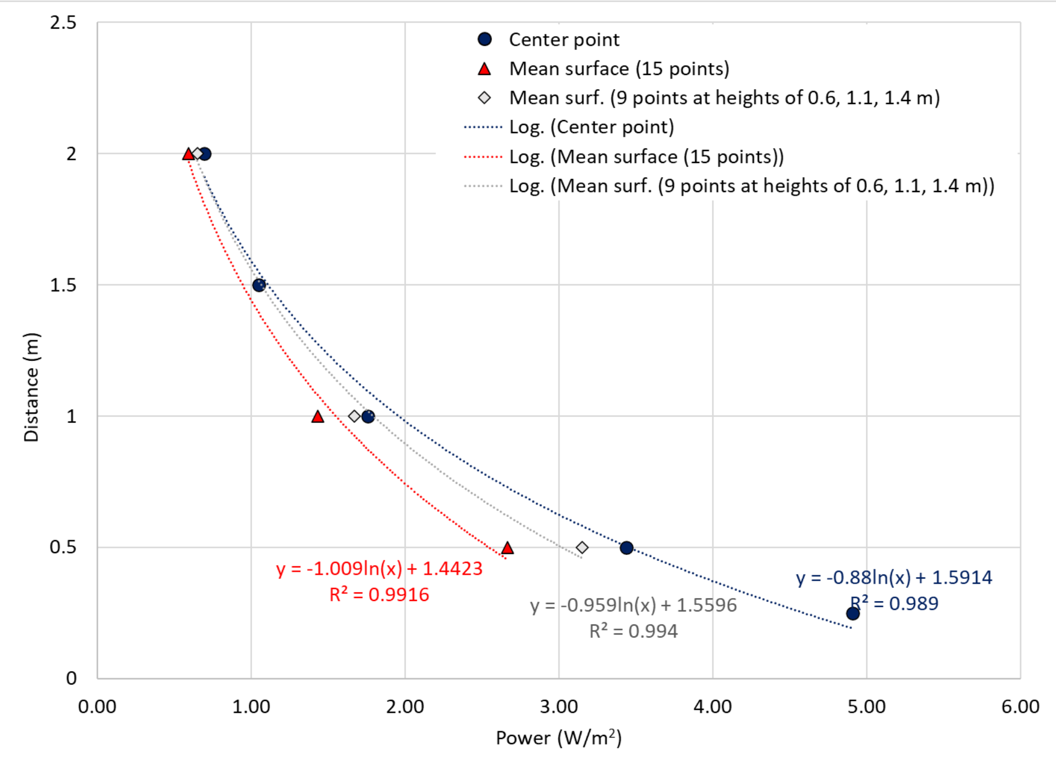


Figure 1.2 Power versus distance relationships at room temperature (~18 °C) and validated at 35 °C at the test site

The relationships in Figure 1.2 were used to decide the radiation panel distance from the TP's upper arm. Since the upper measuring row (1.7 m) was at the tip of the head (close to panel upper edge) and lowest row at the foot level (close to panel lower edge), the mean of nine measuring points was used to decide the distance between the panel and the upper arm.

The heat flux recordings and estimations were similar at both air temperatures, showing that a relatively small difference in air temperature – compared to radiation power – had minimal influence on the outcome when the sensor faced the panel. The best prediction of the expected power was acquired with a logarithmic (ln) function. The curves in Figure 1.2 represent the power (measured with the Hukseflux SBG01 with LI19) at the centre point of the panel, means based on nine measuring points at three verticals (centre and ± 0.2 m) at 0.6, 1.1 and 1.4 m height, and a full mean based on 15 points (the previous points and additionally corresponding three points at 0.1 and 1.7 m level) and the corresponding regression lines. The points at 0.1 and 1.7 m heights were just below the lower and the upper edge of the panel. Thus, for safety the mean radiant power for the TP exposures was calculated based on the area covered by the nine points, as most of the skin temperature sensors were located within this area. The regression equations allowed calculating the distance necessary to reach the intended power. Very close to the panel surface (~1 cm) in centre point, the power was a bit above 5 kW/m^2, but during tests a moving test person was not allowed to be so close to the panel due to the risk of contact.

1.3.3 Mean radiant temperature

As the study setup created a complex, intermittent environment, and the mean radiant temperature calculation itself is complex, and measuring instruments could not be placed in the spot where the TP was walking, we made some assumptions and simplifications. We followed Gebhardt et al. (1995) and ISO 7726:1998, see Annex B for mean radiant temperature ($\overline{T}_r$) calculations.

In the periods when IR radiation was not applied, we used air (T_a) and globe (T_g) temperatures and the ISO 7726 equation for calculating natural convection for $\overline{T}_r$:

$$\overline{T}_r = \left[\left(T_g + 273\right)^4 + \frac{0.25 \times 10^8}{\varepsilon_g} \times \left(\frac{|T_g - T_a|}{D}\right)^{1/4} \times \left(T_g - T_a\right) \right]^{1/4} - 273 \qquad (1)$$

where:

ε_g – the emissivity of the black globe (this study used 0.99).
D – the diameter of the black globe (this study used 0.05 m).

For the test periods outside the climate-controlled room, such as the pre-work of SIF and the recovery period for all test conditions, the mean radiant temperature was assumed to be equal to air temperature, which in turn was assumed to be equal to the globe temperature[6]. In the test room, the QuesTemp instrument was always placed outside the direct IR radiation from the panel. However, it was affected by indirect radiation. We presumed that the other surface areas that were not exposed to the direct radiation or were positioned far enough from the panel were affected in the same way.

The radiation panel was positioned at the right side of the TP, perpendicular to the body. Thus, a ratio of 0.23 was used for the radiated part of the body (ISO 7726). For the body parts in other directions, the temperature of the surrounding surfaces was assumed to be the average of the air and globe temperatures.

[6] The temperature one experiences due to heat radiation.

In the case of the radiation periods, the mean radiant temperature was calculated based on estimated plane radiant temperatures (T_{pr}) from all six directions, assuming that T_{pr} from five directions was equal to T_r calculated by equation (1), and the radiation panel temperature from the radiation power was calculated according to Gebhardt et al. (1995). Thus, for radiated side T_{pr} would be:

$$T_{pr} = \sqrt[4]{\left(\frac{I_s}{\sigma \varepsilon_s} + (T_a + 273)^4\right)} - 273 \qquad (2)$$

where:
I_s – the heat flux from the radiation panel reaching the test person (W/m^2) (in our case 1000, 3000 or 4000 W/m^2)
σ – the Stefan-Boltzmann constant (5.67×10^{-8} W/(m^2·K^4))
ε_s – the emissivity of the surrounding surfaces and common textiles (0.95).

Then, the mean radiant temperature was calculated using projected surface area factors for a standing person (0.08 for up and down, 0.23 for left and right sides and 0.35 for front and back sides, ISO 7726) by:

$$\overline{T}_r = \frac{0.08\times(T_{pr,up}+T_{pr,down})+0.23\times(T_{pr,right}+T_{pr,left})+0.35\times(T_{pr,front}+T_{pr,back})}{2\times(0.08+0.23+0.35)} \qquad (3)$$

According to our assumptions that $T_{pr,up}$=$T_{pr,down}$=$T_{pr,left}$=$T_{pr,front}$=$T_{pr,back}$ (°C), the equation above becomes:

$$\overline{T}_r = \frac{1.09\times T_{pr,other}+0.23\times T_{pr,right}}{1.32} \qquad (4)$$

1.3.4 Skin and rectal temperature sensors

Skin temperatures were measured at eight body sites (Figure 1.3) with two loggers (MSR145W2D (WiFi) and MSR145WD (Bluetooth), MSR Electronics GmbH, Seuzach, Switzerland). The sensors were taped to the skin with Blenderm surgical tape 1525 (3M, USA). Mean skin temperature ($\overline{T}_{sk}$) calculations were carried out in two ways:

Based on four measuring points on the skin, according to Ramanathan (1964):

$$\overline{T}_{sk} = 0.30 \times T_{chest} + 0.30 \times T_{u.arm} + 0.20 \times T_{thigh} + 0.20 \times T_{calf} \qquad (5)$$

And based on eight measuring points, according to Gagge & Nishi (1977):

$$\overline{T}_{sk} = 0.07 \times T_{forehead} + 0.175 \times T_{back} + 0.175 \times T_{chest} + 0.07 \times T_{u.arm} + 0.07 \times T_{f.arm} + 0.05 \times T_{hand} + 0.19 \times T_{thigh} + 0.2 \times T_{calf} \qquad (6)$$

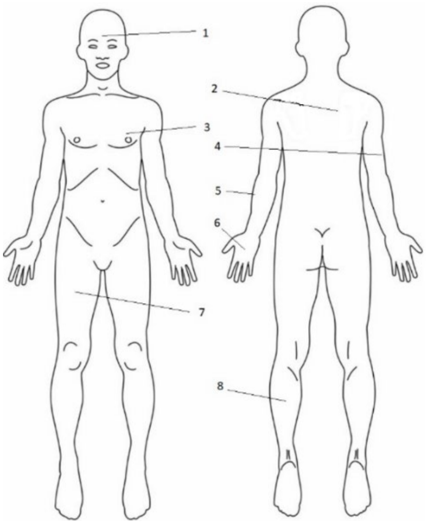


Figure 1.3 Local skin temperatures

1 – forehead; 2 – right scapula; 3 – left upper chest; 4 – right lateral upper arm; 5 – left lateral lower arm; 6 – left dorsal hand; 7 – right anterior thigh; 8 – left calf.

The body core temperature was measured by a rectal (T_{rec}) sensor, connected to the MSR145W2D WiFi logger. The mean body temperature (T_b) calculation was performed according to:

$$T_b = 0.2 \times \overline{T}_{sk} + 0.8 \times T_{rec} \tag{7}$$

Based on the mean body temperature, the body heat content and body heat storage rate could be calculated:

$$Q = m_s \times c \times (t_b^e - t_b^0) \tag{8}$$

where:

m_s – mass of the (naked) subject (kg)

c – specific heat capacity of the human body (2980 J/(kg·°C))

t_b^e – mean body temperature at the end of the test or selected time period (°C)

t_b^0 – mean body temperature at the start of the test or selected time period start (°C)

The heat storage per unit area (ΔS) is then calculated using:

$$\Delta S = \frac{Q/D}{A_{Du}} \tag{9}$$

where:

ΔS – body heat storage (W/m^2)

D – duration of the test or selected time period (s)

A_{Du} – body surface area (m^2)

The body surface area was calculated using:

$$A_{Du} = 0.202 \times m_s{}^{0.425} \times h^{0.725} \tag{10}$$

where:

m_s – mass of the undressed person (kg) *h* – test person's height (m)

1.3.5 Environment and clothing microenvironment monitoring

Environmental parameters were recorded with Thermal Environment Monitor (QuesTemp° 46, TSI Instruments Ltd., Shoreview, MN, USA) that was set outside the direct IR radiation. Air temperature, air humidity and globe temperature were monitored. Air velocity in the test premises, including climate-controlled room stayed around 0.1 m/s. Thus, TP activity dominated the convection around the body.

Temperature and humidity between skin and clothing was monitored with sensors built in the MSR145WD and MSR145W2D logger housings. These dataloggers were fixed to the chest and the left upper arm. Temperature and humidity between station wear and turnout gear were monitored at the right upper arm near the position of the skin temperature sensor, without covering it. Another temperature sensor was positioned close to this location on the outer layer of the turnout gear.

As the clothing surface temperature at the upper arm (outer layer) stayed about 1 °C above air temperature values during periods of no IR radiation in the TRW scenario, and in average close to air temperature (± 4 °C depending on measurement before or after applying radiation) in the SIF scenarios, these values were assumed to be clothing surface temperatures of unaffected areas during radiation periods.

In the WLF condition, where the radiation panel was continuously on, it was also assumed – based on the results of TRW (~25 °C) and SIF (~44.5 °C) – that on average the clothing surface temperature in other areas except the radiated side stayed close to mean of air and globe temperature, as mean skin, air and globe temperatures in WLF differed minimally compared to the other conditions.

The radiated side temperature was taken as average of the start and end temperatures of the time period when IR radiation was applied. Similarly, during the periods of no radiation during intermittent radiation period the radiated side temperature was taken as average of the end and start temperatures of the time period of applying IR radiation.

Based on the measurements and assumptions above, the mean clothing outer surface temperature (T_{clo}) could be estimated by equation 4 if using local clothing temperatures instead of local plane radiant temperatures.

1.3.6 Oxygen consumption, heart rate and metabolic rate

Oxygen consumption was measured with Vyntus CPX (Vyaire Medical GmbH, Hoechberg, Germany) and based on that metabolic rate was calculated. The same equipment recorded also heart rate that was transmitted by a Polar H10 heart rate sensor connected to the chest strap (Polar Electro, Finland).

$$M = \frac{5.873 \times (0.23 \times RQ + 0.77) \times VO_2 \times 60}{A_{Du}} \quad (11)$$

where:

RQ – respiratory quotient (non-dimensional).

VO_2 – oxygen consumption (l/min)

A_{Du} – body surface area (m^2)

1.3.7 Anthropometric data

During the first visit height, weight, age and skinfold thickness were measured at four body sites (scapula, iliac crest, triceps and biceps). On the basis of these measurements, the Body Mass Index (BMI) and body fat percentage were calculated according to Durnin and Womersley (1974).

$$BMI = \frac{m_s}{h^2} \qquad (12)$$

In all three scenarios, the firefighters were weighed several times: nude (with briefs/boxers, and rectal sensor) and with full equipment at the start, after exiting the climate chamber with and without jacket, gloves, and helmet, and nude after the recovery period. For the SIF scenario, two more weighing moments were added: after the bicycle exercise with and without breathing apparatus cylinders and gloves. These weight measurements allowed to evaluate the body total weight loss, evaporation during specific experiment periods and moisture accumulation in the clothing.

1.3.8 Subjective responses

Depending on scenario and activity level duration the test persons rated their subjective responses (based on ISO 10551) each 10 or 15 minutes of the exercise and recovery phase. The subjective responses included:

- Thermal sensation (9-point scale, with emphasis on heat): “What is your thermal sensation right now?” 5 = unbearably hot; 4 = very hot; 3 = hot; 2 = warm; 1 = slightly warm; 0 = neither warm nor cool; -1 = slightly cool; -2 = cool; -3 = cold.
- Skin wetness sensation (4-point scale): “How does your skin feel?” 0 = normal; 1.0 = slightly wet; 2.0 = wet; 3.0 = very wet.
- Comfort sensation (5-point scale): “How do you rate your thermal comfort right now?” 0 = neutral; 1 = slightly uncomfortable; 2 = uncomfortable; 3 = very uncomfortable; 4 = very, very uncomfortable.
- Pain sensation (6-point scale): “How painful is it for you right now?” 0 = no pain; 1 = slightly painful; 2 = painful; 3 = very painful; 4 = very, very painful; 5 = unbearable pain.
- Perceived exertion: Borg scale from 6 to 20: “How is the exertion perceived right now?” 6 = extremely light (no exertion); 7-8 = very light; 9-10 = light; 11-12 = moderate: (you are still able to talk during the physical activity); 13-15 = hard; 16-17 = very hard; 18-19 = extremely hard; 20 = maximal exertion (Borg, 1982).

1.3.9 Predicted heat strain (PHS, ISO 7933:2004)

Predictions before the study

For the execution of the actual measurements, all selected scenarios were simulated according to the predicted heat strain model (PHS, ISO 7933:2004), which was modified for an earlier firefighter study (Holmér et al. 2006). This modified version allowed input of higher insulation values, activity levels and a wider range of environmental parameters. However, these modified algorithms did not allow for intermittent conditions, which meant that the estimated time weighted average activity levels and environmental conditions were utilized to predict the exposure.

The workload during walking was estimated according to Givoni and Goldman (1971) and increased by 20 % for protective clothing and equipment restrictions, based on experience from earlier studies (Dorman & Havenith, 2009; Holmér et al., 2003; Jones et al., 1984; Kuklane et al., 2007; Teitlebaum & Goldman, 1972).

The aim of the predictions was to select the experimental conditions where the TP could manage to endure the whole planned exposure period. Due to the fact that the related literature did not consider the effect of IR radiation, the originally selected air temperature for the WLF scenario (with constant IR radiation) was reduced from 35 °C to 30 °C, based on the publication by Carballo-Leyeda et al. (2017).

The outcome of these simple estimations compared to the experimental data are not presented in this report but can be found in another publication (Kuklane et al. 2024b).

Model validation after the study

The first attempts to evaluate the Predicted Heat Strain (PHS) model (ISO 7933) for firefighter scenarios were performed with the turnout gear that is presently used by Dutch firefighters (corresponding to EN 469). There are two BSc thesis projects addressing the PHS model algorithms available online.

One of these projects focused on the version created at Lund University (https://www.eat.lth.se/fileadmin/eat/Termisk_miljoe/PHS/PHS.html). This version was adjusted for allowing more timesteps and conditions outside the PHS normal validity range (https://github.com/Rikuklane/PredictedHeatStrainModel), performed by Jacobs (2024). The second project focused on the version created by FAME Lab (https://www.famelab.gr/research/downloads/) and the work was performed by Klomp (2024). As the FAME Lab version during that time did not allow enough timesteps for all tested scenarios, and there was an interest to compare both PHS versions, time weighed average environmental conditions and activity levels were utilized for WLF and SIF scenarios in both cases. Now there is a new FAME Lab PHS version available, corresponding to the last PHS standard (ISO 7933:2023, https://www.habitatscience.org/), allowing for more timesteps.

Although both evaluations gave a clear indication on the PHS model expected performance, a detailed validation based on the human test results of this study needs to be done in the future for model and standard improvement. Therefore, this report only refers to both BSc thesis reports and includes their summaries in Annex 1 (Jacobs, 2024) and Annex 2 (Klomp, 2024).

1.4 Test environment

The air velocity in all tested conditions stayed below 0.2 m/s. This means that natural convection and activity-based air movement around the body of the TP as well as the pumping effect in the clothing were the dominating related factors in air movement. In all conditions, clothing set REC (Table 1.3) was used during the recovery period.

1.4.1 Technical rescue warm (TRW)

Clothing sets Trad_TRW and Mod_C9A_TRW, with an approximate total weight of 10 kg, were used (Table 1.3). Four (4) TPs used each clothing set. Preparation, testing and recovery were performed at the same air temperature. The air temperature (T_a) was set to 25

°C and was initially equal to the mean radiation temperature (T_r). Relative humidity (RH) was set to 60 % (absolute humidity (water vapour pressure) at this temperature had to be 2.8 kPa).

The tasks consisted of 30 minutes of light activity corresponding to a treadmill walk at 2.1 km/h with 10 kg protective gear, 60 minutes of medium heavy activity corresponding to a treadmill walk at 3.5 km/h with 10 kg protective gear, and 30 minutes of light activity while sitting during recovery (for detailed procedures see Table 1.4). During the second half of the medium heavy activity (walk at 3.5 km/h), a radiation load of 1 kW/m^2 was applied (radiation panel set to a distance of 1.5 meters from the TP's expected upper arm position).

1.4.2 Wildland firefighting (WLF)

The preparation of the TP was performed at 18 °C. Clothing sets Trad_WLF and Mod_C8_WLF with an approximate total weight of 11 kg were used (Table 1.3). Air temperature (T_a) in the climate-controlled room was set to 30 °C. The radiation load in this condition was set to 1 kW/m^2 from the start. Relative humidity (RH) was set to 50 % (absolute humidity at this temperature had to be 2.1 kPa).

The tasks consisted of 10 minutes of light activity corresponding to treadmill walk at 2.1 km/h with 11 kg protective gear, 15 minutes of medium heavy activity (corresponding to treadmill walk at 3.5 km/h with 11 kg protective gear), 15 minutes of heavy activity (corresponding to treadmill walk at 4.5 km/h with 11 kg protective gear), 15 minutes of medium heavy activity (walk at 3.5 km/h) and 15 minutes of heavy activity (walk at 4.5 km/h), followed by 20 minutes of light activity (walk at 2.1 km/h).

During the first pass of heavy activity and the second pass of medium heavy activity the TP got alternating IR radiation of 3 kW/m^2 for 2 minutes and 1 kW/m^2 for 3 minutes (30 minutes in total). The heat radiation load was created by shifting the radiation panel from 1.5 to 0.5 meters from the TPs expected upper arm position. The test ended with 30 min recovery while seated at room temperature (18 °C), without radiation load.

1.4.3 Structural internal firefighting (SIF)

The preparation of the TP was performed at 18 °C. Clothing sets Trad_SIF and Mod_C4_SIF with an approximate weight of 20 kg were used during the heat exposure, and the same set without breathing apparatus and gloves, similar to C7 (Kuklane et al. 2022), Mod_C7_SIF-Pre was used during the pre-work on the bicycle ergometer, set to 50 W and driven at 60 rotations per minute.

Air temperature (T_a) in the test chamber was set to 45 °C and was initially equal to the mean radiation temperature (T_r). Relative humidity (RH) was set to 40 % (absolute humidity at this temperature had to be 3.8 kPa). The experiment started at room temperature (18 °C) with light-medium heavy activity on the bicycle ergometer for 18 minutes. The TP then donned the breathing apparatus and gloves and moved into the test chamber. The TP started performing the medium heavy activity, corresponding to treadmill walk at 3.1 km/h, with 20 kg protective gear for the first 10 minutes. This was followed by 20 minutes of altering heavy activity (corresponding to treadmill walk at 4.0 km/h) for 5 minutes and very heavy activity (corresponding to treadmill walk at 5.4 km/h) for 5 minutes.

During the first 10 minutes of heavy and very heavy activities the test person was regularly exposed to IR radiation (each second minute for a minute). The radiation panel was set at a distance of 0.23 meters from the TPs expected upper arm position, creating a heat load of 4 kW/m^2 at that point. IR radiation was created by turning the radiation panel towards and away from TP. Exposure ended with a 30-minute recovery in a seated posture at 18 °C.

1.5 Termination criteria

The participants were allowed to end the test at any point in time for any reason. The participants were obligated to terminate the test if their rectal temperature (T_{rec}) reached 39.0 °C, or if their skin temperature at any measurement point reached 43.0 °C.

If the study leader observed unsafe behaviour, such as unclear communication or abnormalities in gait, he had the authority to stop the test.

1.6 Ethical considerations

The study was designed in accordance with the Declaration of Helsinki (https://www.wma.net/policies-post/wma-declaration-of-helsinki/). The study procedures were approved by the Scientific and Ethical Review Board (VCWE) of VU Amsterdam (VCWE-2023-134R1).

After briefing, the test persons had time to consider their participation. They filled out an anamnesis form and sent it to an independent medical doctor for evaluation. Before the first experiment they signed a consent form.

1.7 Procedures

The study was planned following a Latin square design[7], however, due to the availability of the TPs on the days the climate chamber was available for this study some adjustments into the exposure order were necessary. Table 1.4 shows the activities during all three simulated incident scenarios. The preparations started about an hour before the start of the experiment and the procedures after ending the experiment took about 30 minutes.

Participants were asked to refrain from strenuous exercise, alcohol, and caffeine for 24 hours before attending experimental sessions. After arrival, the TP was led to the preparation site and was given information about the test of that day. He got about 30 minutes to rest and was provided 0.5 litres of water to drink beforehand. During this period, a fitting face mask was selected for oxygen consumption (VO_2) measurements.

Around 30 minutes after arrival, the rectal sensor was handed over to the TP and was explained how to insert it. Then it was suggested to visit the toilet and pee and defecate

[7] A Latin square design is an experimental method which uses a $n \times n$ raster to organize experimental setups, with n different treatments, so every treatment occurs exactly once in every row and every column. This design is often used in tests where the weather, environmental conditions, locations or test persons play a role.

before inserting the rectal sensor. At the TPs return, the rectal sensor wire was secured to the back with a skin friendly surgical tape (3M™ Blenderm™ Surgical Tape 1525).

On the first visit, the TPs height and skinfold thickness on four sites (biceps, triceps, subscapular site and iliac crest) were measured for the calculation of the body fat percentage based on Durnin and Womersley (1974). Thereafter, the test person was weighed in underwear (boxer shorts).

After weighing, the skin temperature sensors, connected to one MSR145W2D (WiFi) and one MSR145WD (Bluetooth) logger (MSR Electronics GmbH, Seuzach, Switzerland) were taped to the skin at eight measuring points (see Figure 1.3). A Polar pulse belt with H10 heart rate transmitter was fixed around chest and thereafter the test person could put on the test garments.

Table 1.4 Exercise procedures for TRW, WLF and SIF

Time from start	**TRW** Preparation, testing and recovery at 25 °C and 60 % RH	Time from start	**WLF** Preparation and recovery at ~18 °C, testing at 30 °C and 50 % RH	Time from start	**SIF** Preparation, prework and recovery at ~18 °C, testing at 45 °C and 40 % RH
00:00	Light activity, walk 2.1 km/h	**00:00**	IR radiation 1 kW/m^2 **on**; Light activity, walk 2.1 km/h	**00:00**	Light-medium heavy activity, walk 2.7 km/h at room temperature
		00:10	Medium heavy activity, walk 3.5 km/h		
				00:18	Don the bottles, weight the test person and move into climate tent
				00:20	Medium heavy activity, walk 3.1 km/h
		00:25	IR radiation 3 kW/m^2; Heavy activity, walk 4.5 km/h		
		00:27	IR radiation 1 kW/m^2		
00:30	Medium heavy activity, walk 3.5 km/h	**00:30**	IR radiation 3 kW/m^2	**00:30**	Heavy activity, walk 4.0 km/h
				00:31	IR radiation 4 kW/m^2 **on**
		00:32	IR radiation 1 kW/m^2	**00:32**	No radiation
				00:33	IR radiation 4 kW/m^2
				00:34	No radiation
		00:35	IR radiation 3 kW/m^2	**00:35**	IR radiation 4 kW/m^2; Very heavy activity, walk 5.4 km/h
				00:36	No radiation
		00:37	IR radiation 1 kW/m^2	**00:37**	IR radiation 4 kW/m^2
				00:38	No radiation
				00:39	IR radiation 4 kW/m^2
		00:40	IR radiation 3 kW/m^2; Medium heavy activity, walk 3.5 km/h	**00:40**	IR radiation **off**; Heavy activity, walk 4.0 km/h
		00:42	IR radiation 1 kW/m^2		
		00:45	IR radiation 3 kW/m^2	**00:45**	Very heavy activity, walk 5.4 km/h
		00:47	IR radiation 1 kW/m^2		
		00:50	IR radiation 3 kW/m^2	**00:50**	Recovery, seated rest, remove gloves, helmet, jacket
		00:52	IR radiation 1 kW/m^2		
		00:55	Heavy activity, walk 4.5 km/h		
01:00	IR radiation **on,** 1 kW/m^2				
		01:10	Light activity, walk 2.1 km/h		
				01:20	End of test, stop all recording
01:30	IR radiation **off**; Recovery, seated rest, remove gloves, helmet, jacket	**01:30**	IR radiation **off**; Recovery, seated rest, remove gloves, helmet, jacket		
02:00	End of test, stop all recording	**02:00**	End of test, stop all recording		

The operational uniform (OU; Dutch firefighters' station wear, set C2 in Kuklane et al. 2022) was used under all outer layer combinations. After putting on the OU and shoes, a temperature sensor was fixed on the lateral upper arm on top of the OU. After putting on the outer layer a sensor was also fixed to the outer layer at the lateral upper arm. Then, the face mask for VO2 measurements was added and finally the helmet and gloves were put on. Before any further steps were taken, it was ensured that the signals from the instruments were coming in and recorded. Before starting the experiment and before or after changing the environment or clothes, the TP was weighed again for estimating the evaporation during the task periods (prework, exercise and recovery) and the total body fluid loss. Drinking was not allowed during exercise and recovery. Water was offered immediately after the last weighing.

1.8 Test persons

Based on earlier studies, eight test persons were considered to be sufficient for this type of experiments, where the test persons belong to a relatively homogenous group/population. The TPs were recruited from the population of active firefighters via direct contacts with Safety Region representatives. The TPs were healthy and fit male firefighters, with a valid PPMO (Periodiek Preventief Medisch Onderzoek = Periodic Preventive Medical Examination), who were in active service and familiar with the work tasks and equipment used. The aimed age range was from 18 to (preferably) below 45 years old. With higher age, more health effects are expected to appear. Due to a limited number of TP the upper limit was set in dependence on the individual’s health status and not the age. If the person had passed the PPMO – thus having an approval for active duty – and there were no health conditions that came up during discussion with study leaders, especially the ones affecting normal thermoregulation, then the conditions of this study were considered to be well manageable for older participants as well.

The criteria for exclusion from the study were a smoking habit and age below 18 years. All the test persons were male because the variation in temperature in females is higher, which makes comparing results more complex – especially in a small population sample.

Ten TPs were available for the study. Half of them were above 40 years old (Table 1.5). One TP fell out due to sickness at the very start of the study, while another one missed the last scheduled test due to the flu. Eventually, we were able to perform tests on eight TPs in all simulated scenarios: four with the presently used (traditional, Trad) and four with the prototype of the modular (Mod, double layers of jackets) clothing set. Simulated WLF and SIF scenarios had an additional person (TP6) wearing set Mod performing the tests (Table 1.5).

The test persons’ anthropometric data is shown in Table 1.5. Each subject took part in three sessions, separated by at least one full day. Each session lasted about 3-4 hours, including preparation and ending.

Table 1.5 Test person data and tested conditions

Test person	Age	Weight	Height	BMI	A_{Du}	Fat	Ensemble
	years	*kg*	*m*		*m^2*	*%*	
1	29	98.1	1.84	29.1	2.21	18.5	Mod
3	19	66.7	1.87	19.0	1.89	12.9	Trad
4	48	96.6	1.83	28.9	2.19	26.9	Trad
5	58	93.4	1.83	28.0	2.16	28.9	Mod
6*	47	88.9	1.85	25.8	2.12	16.6	Mod
7	31	104.7	1.83	31.1	2.26	23.6	Mod
8	51	105.8	1.94	28.1	2.37	26.7	Trad
9	38	74.7	1.83	22.3	1.96	16.1	Trad
10	53	71.2	1.71	24.1	1.82	15.1	Mod
Mean all	41.6	88.9	1.84	26.3	2.11	20.6	
SD all	13.0	14.6	0.06	3.8	0.18	6.0	
Mean Mod	43.6	91.3	1.81	27.6	2.11	20.5	
SD Mod	13.0	12.7	0.06	2.7	0.17	5.7	
Mean Trad	39.0	86.0	1.87	24.6	2.10	20.6	
SD Trad	14.4	18.3	0.05	4.7	0.22	7.2	
Mean <40 years	29.3	86.1	1.84	25.4	2.08	17.8	
SD <40 years	7.8	18.2	0.02	5.7	0.18	4.5	
Mean >40 years	51.4	91.2	1.83	27.0	2.13	22.8	
SD >40 years	4.4	12.8	0.08	2.0	0.20	6.5	

* TP did not participate in TRW scenario due to illness

Mod – modular clothing system; Trad – traditional clothing system; BMI – body mass index; ADu – body surface area; body fat % was calculated based on skin fold thickness according to Durnin and Womersley (1974).

1.9 Statistics

When planning the tests, the recommendations of EN 17558:2023, Annex A on Experimental design and statistical testing were followed. The study was designed as a comparative study, looking at the differences in the use of different types of turnout gear and the validation of thermo-physiological models. Due to the influence of an instable environment during several tests, the variation in the dependent variables increased. Therefore, a strong focus was laid on the development trends of the physiological data, e.g. factors related to thermal stress. In this report the focus was thus set on descriptive statistics (means, standard deviation).

2 Results and discussion

2.1 Environment

During the main testing period in December 2023, the outdoor weather stayed relatively stable around +10 °C. However, in January 2024 the weather turned cold to about -10 °C. As the room around the climate-controlled room was not heated, the outdoor weather affected the temperature for the preparation and recovery of conditions WLF and SIF, and the prework part of SIF for the last tests as well. For TRW, this effect was avoided as the preparations and recovery were performed inside the climate-controlled room.

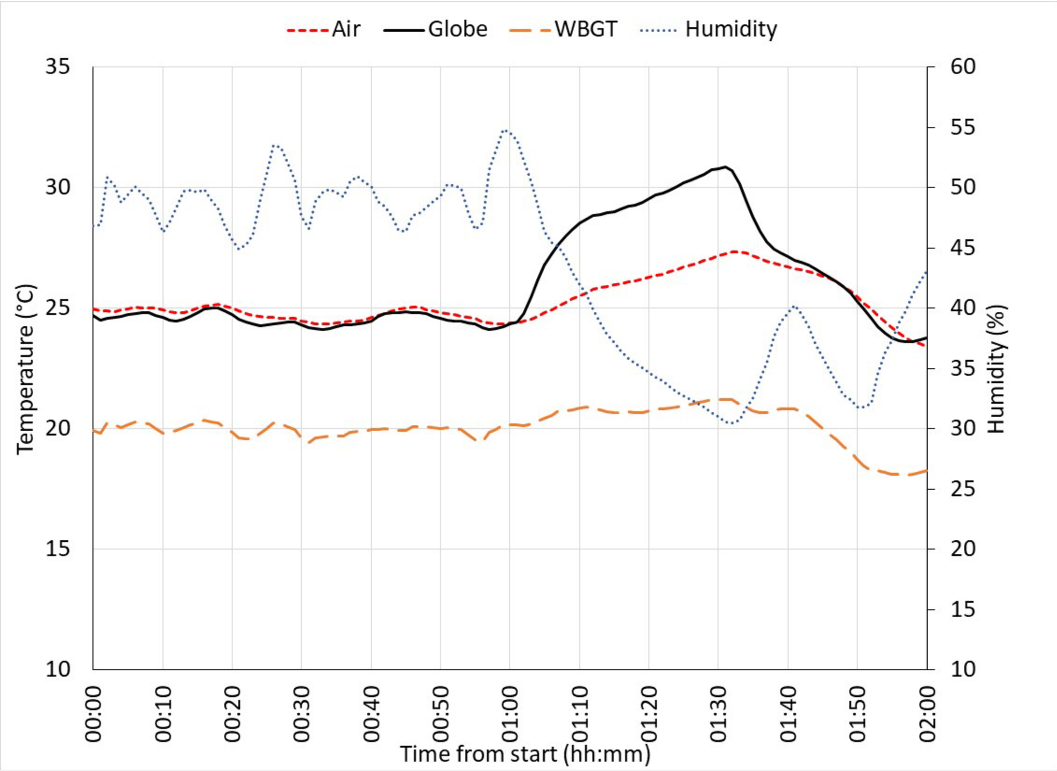
During some of the last test days, the humidity regulation of the climate-controlled room malfunctioned, making the humidity in the room fully dependent on the outside humidity. The effect could be clearly seen in the humidity measured. Thus, the evaporative heat loss was affected, as this is determined by the difference between the water vapour pressure at skin and in the air (Tables 2.1-2.3). In TRW and SIF, the water vapour pressure in the air in the affected tests was up to twice as low as in other tests, and in WLF even about trice as low. Unfortunately, the tests could not be postponed or redone.

Considering the climate control in the test room, there was always some delay in the room climate regulation connected to the start and stop of the radiation panel (Figures 2.1-2.3). The effects of switching on the power source had a larger effect on the environment at lower test room temperatures (TRW) and a smaller effect at higher (SIF) temperatures. In WLF, the temperature rise began immediately from the start as the panel was switched on, and the radiation power reaching the TP was changed by adjusting the panel distance. The temperature rise stabilized after about only one hour.

2.1.1 TRW

The air velocity in the climate-controlled room always stayed around 0.10 m/s for all tests. Figure 2.1 presents the average temperature and humidity trends for all TRW exposures. Table 2.1 shows the mean air and globe temperatures and relative humidity for various periods of the exercise and recovery for TRW. The temperatures could differ to some extent for different tests, and therefore the mean values are given per each individual test, although in general the conditions stayed relatively stable.

Relative humidity for TP7 and TP9 deviated more because the test room humidity control got an error. Although this increased the variation in the test results, comparison of the clothing sets was still possible as TP7 wore ensemble Mod and TP9 ensemble Trad, and the means and changes of the physiological parameters were affected in the same manner. When comparing age related differences, there may be a bias in the favour of younger TPs as both TP7 and TP9 belonged to this group.



WBGT – 'wet bulb globe temperatuur'

Figure 2.1 Curves of average environmental parameters of all TPs during the TRW scenario

Table 2.1 Average air (T_a) and globe (T_g) temperatures and relative humidity (*RH)* for the exercise and recovery periods of TRW

Activity Time period		Walk 2.1 km/h 0-30 min			Walk 3.5 km/h 30-60 min			Walk 3.5 km/h, 1 kW/m², 60-90 min			Sit recovery 90-120 min		
Parameter		T_a (°C)	T_g (°C)	*RH* (%)	T_a (°C)	T_g (°C)	*RH* (%)	T_a (°C)	T_g (°C)	*RH* (%)	T_a (°C)	T_g (°C)	*RH* (%)
TP	**Clothing**												
1	Mod	25.2	25.2	56.8	24.6	24.5	56.8	25.8	28.9	51.3	27.3	27.8	43.2
3	Trad	25.2	25.1	57.7	24.2	24.2	58.6	26.2	29.5	47.8	27.1	27.4	41.9
4	Trad	24.9	24.7	48.8	24.9	24.7	49.0	26.2	29.2	36.4	24.7	25.2	39.6
5	Mod	24.7	24.5	49.3	24.7	24.6	48.9	25.9	29.7	36.1	27.0	27.6	39.9
7	Mod	24.9	24.6	32.6	24.6	24.4	33.5	25.3	27.5	23.4	24.6	25.5	18.7
8	Trad	24.7	24.4	62.1	24.7	24.4	60.8	25.8	28.6	48.6	26.5	26.8	47.3
9	Trad	25.3	24.6	32.7	25.2	24.6	33.4	26.3	29.1	23.1	25.2	25.9	18.1
10	Mod	24.1	24.0	51.5	24.3	24.1	54.1	25.5	27.0	45.5	24.3	24.8	38.3
Mean all		**24.9**	**24.6**	**48.9**	**24.6**	**24.5**	**49.4**	**25.9**	**28.7**	**39.0**	**25.8**	**26.4**	**35.9**
SD tot		*0.4*	*0.4*	*11.0*	*0.3*	*0.2*	*10.7*	*0.3*	*0.9*	*11.2*	*1.3*	*1.2*	*11.1*
Mean Mod		**24.7**	**24.5**	**47.6**	**24.5**	**24.4**	**48.3**	**25.6**	**28.3**	**39.1**	**25.8**	**26.4**	**35.0**
SD Mod		*0.5*	*0.5*	*10.5*	*0.2*	*0.2*	*10.4*	*0.3*	*1.2*	*12.2*	*1.6*	*1.5*	*11.1*
Mean Trad		**25.0**	**24.7**	**50.3**	**24.7**	**24.5**	**50.5**	**26.1**	**29.1**	**39.0**	**25.8**	**26.3**	**36.7**
SD Trad		*0.3*	*0.3*	*13.0*	*0.4*	*0.2*	*12.5*	*0.2*	*0.4*	*12.0*	*1.1*	*1.0*	*12.8*
Mean <40 years		**25.1**	**24.8**	**45.0**	**24.6**	**24.4**	**45.6**	**25.9**	**28.7**	**36.4**	**26.0**	**26.6**	**30.5**
SD <40 years		*0.2*	*0.3*	*14.2*	*0.4*	*0.2*	*14.0*	*0.4*	*0.9*	*15.3*	*1.3*	*1.1*	*14.0*
Mean >40 years		**24.6**	**24.4**	**52.9**	**24.6**	**24.5**	**53.2**	**25.8**	**28.6**	**41.6**	**25.6**	**26.1**	**41.3**
SD >40 years		*0.3*	*0.3*	*6.2*	*0.3*	*0.3*	*5.6*	*0.3*	*1.1*	*6.3*	*1.3*	*1.3*	*4.1*

Yellow shaded cells with humidity data point out experiments where climate room humidity control failed. Recovery continued inside the climate room.

2.1.2 WLF

The air velocity in the climate-controlled room always stayed around 0.10 m/s for all tests. Table 2.2 shows the air and globe temperatures and relative humidity for various periods of the exercise and recovery for WLF. All TPs did quit this scenario simulation before 90 minutes of exposure, usually between 60 and 70 minutes (from 58 to 83 minutes). Only TP9 lasted 83 minutes, allowing to summarize the average environmental parameters for the last exercise level of his exposure (walking 2.1 km/h): T_a = 31.6 °C, T_g = 36.5 °C; *RH* = 11.3 %.

Table 2.2 Average air (T_a) and globe (T_g) temperatures and relative humidity (*RH*) for the exercise and recovery periods of WLF

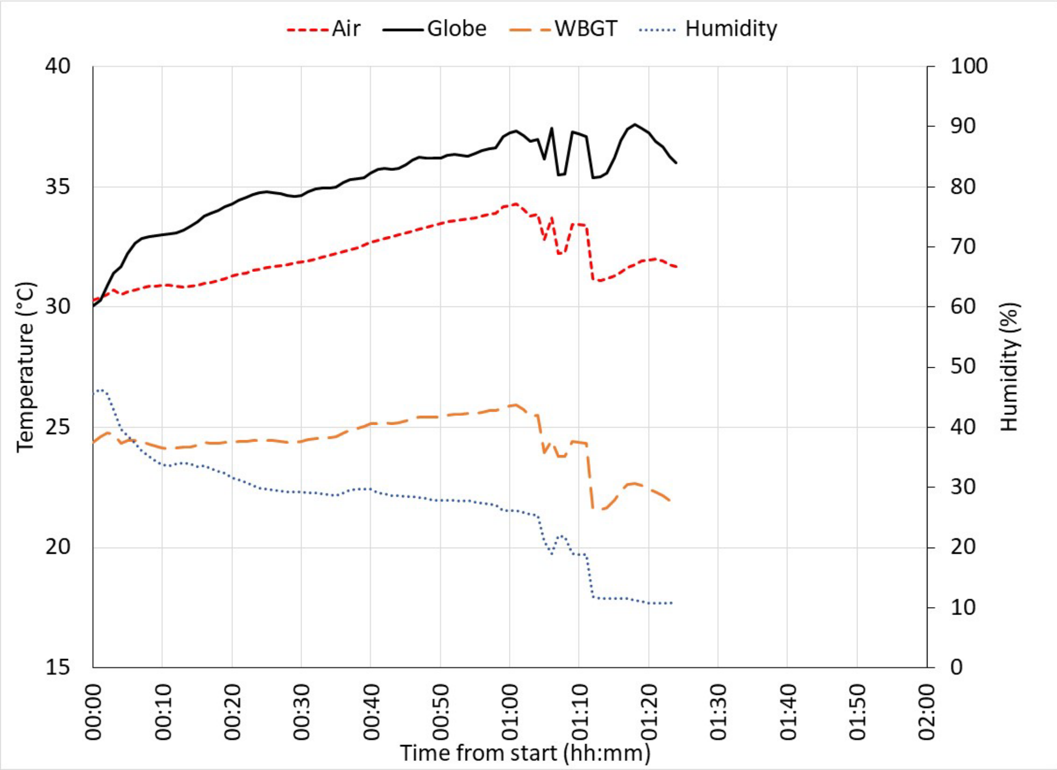
Activity Time period		Walk 2.1 km/h, 1 kW/m², 0-10 min			Walk 3.5 km/h, 1 kW/m², 10-25 min			Walk 4.5 km/h, 1 and 3 kW/m², 25-40 min			Walk 3.5 km/h, 1 and 3 kW/m², 40-55 min			Walk 3.5 km/h, 1 kW/m², 55-70 min			Sit recovery 90-120 min	
Parameter		T_a (°C)	T_g (°C)	*RH* (%)	T_a (°C)	T_g (°C)	*RH* (%)	T_a (°C)	T_g (°C)	*RH* (%)	T_a (°C)	T_g (°C)	*RH* (%)	T_a (°C)	T_g (°C)	*RH* (%)	T_a=T_g (°C)	*RH* (%)
TP	**Clothing**																	
1	Mod	29.7	30.2	53.2	31.1	33.0	51.3	34.2	36.7	49.8	37.1	39.3	49.3	38.8	40.7	48.4	21.0	63.6
3	Trad	30.0	30.8	39.0	30.1	31.5	34.3	29.7	31.2	29.3	29.7	31.5	28.2	29.9	31.8	27.6	21.0	63.6
4	Trad	33.1	32.9	39.3	30.6	30.9	37.6	30.7	32.1	37.6	31.7	33.3	36.0	32.3	33.8	35.3	20.2	37.8
5	Mod	30.1	31.3	48.2	31.6	35.4	39.3	32.8	36.3	31.3	34.0	37.2	29.6	35.2	38.2	27.2	19.2	46.1
6	Mod	30.7	34.8	45.1	33.3	37.2	31.0	34.0	37.4	28.6	35.0	38.1	28.0	35.8	39.0	27.0	20.1	38.6
7	Mod	32.1	34.2	42.3	32.7	36.6	31.6	33.9	37.3	29.2	35.3	38.5	28.1	36.3	39.4	27.1	21.3	41.9
8	Trad	30.1	29.8	39.3	29.9	31.0	35.5	29.2	30.1	32.8	29.5	31.0	31.8	29.4	31.1	29.1	19.3	49.2
9	Trad	28.7	32.1	16.7	30.1	34.8	13.4	30.9	34.9	12.1	31.1	35.0	12.0	31.1	35.5	11.9	13.6	27.6
10	Mod	30.8	31.5	21.1	31.0	35.4	16.7	33.7	38.9	12.8	36.2	41.0	10.9	37.7	42.6	10.1	13.4	30.1
Mean all		**30.6**	**32.0**	**38.3**	**31.2**	**34.0**	**32.3**	**32.1**	**35.0**	**29.3**	**33.3**	**36.1**	**28.2**	**34.0**	**36.9**	**27.1**	**18.8**	**44.3**
SD all		*1.3*	*1.7*	*12.0*	*1.2*	*2.5*	*11.5*	*2.0*	*3.1*	*11.6*	*2.9*	*3.6*	*11.6*	*3.5*	*4.0*	*11.4*	*3.1*	*12.9*
Mean Mod		**30.7**	**32.4**	**42.0**	**32.0**	**35.5**	**34.0**	**33.7**	**37.3**	**30.4**	**35.5**	**38.8**	**29.2**	**36.8**	**40.0**	**28.0**	**19.0**	**44.1**
SD Mod		*0.9*	*2.0*	*12.3*	*1.0*	*1.6*	*12.7*	*0.6*	*1.0*	*13.2*	*1.2*	*1.4*	*13.6*	*1.4*	*1.7*	*13.6*	*3.2*	*12.4*
Mean Trad		**30.5**	**31.4**	**33.6**	**30.2**	**32.0**	**30.2**	**30.1**	**32.1**	**28.0**	**30.5**	**32.7**	**27.0**	**30.7**	**33.0**	**26.0**	**18.5**	**44.6**
SD Trad		*1.9*	*1.4*	*11.2*	*0.3*	*1.9*	*11.3*	*0.8*	*2.0*	*11.1*	*1.1*	*1.8*	*10.5*	*1.3*	*2.0*	*10.0*	*3.3*	*15.4*
Mean <40 years		**30.1**	**31.8**	**37.8**	**31.0**	**34.0**	**32.7**	**32.2**	**35.0**	**30.1**	**33.3**	**36.1**	**29.4**	**34.0**	**36.9**	**28.7**	**19.2**	**49.2**
SD <40 years		*1.4*	*1.8*	*15.3*	*1.2*	*2.2*	*15.5*	*2.2*	*2.8*	*15.5*	*3.5*	*3.6*	*15.3*	*4.2*	*4.0*	*15.0*	*3.7*	*17.7*
Mean >40 years		**31.0**	**32.1**	**38.6**	**31.3**	**34.0**	**32.0**	**32.1**	**35.0**	**28.6**	**33.3**	**36.1**	**27.3**	**34.1**	**36.9**	**25.7**	**18.5**	**40.4**
SD >40 years		*1.2*	*1.9*	*10.5*	*1.3*	*2.9*	*9.1*	*2.1*	*3.7*	*9.4*	*2.7*	*4.0*	*9.7*	*3.3*	*4.5*	*9.4*	*2.9*	*7.5*

Yellow and red shaded cells in Table 2.2 point out experiments where weather and/or humidity control considerably affected the environment compared to other tests or where air and globe temperatures were either considerably higher or lower than originally intended. Recovery was outside the climate room.

Figure 2.2 presents the average temperature and humidity trends for all WLF exposures in the test room. The start of big temperature changes around 60th minute of exposure reflects TPs quitting the exposure one by one before the intended exposure time was reached. This also reflects the influence of the environment on the exposure length, as – beside differences that may depend on individual TPs – the main trend shows TPs lasting longer at lower temperature and humidity.

In the WLF scenario, there was also a considerable difference in the measured air and globe temperatures for different exercise periods and between individual tests (Table 2.2). These happened to be considerably higher for Mod and lower for Trad clothing sets, leading to a systematic bias.

In the case of relative humidity, it was considerably lower for TP9 and TP10 because of a test room humidity control error and the weather. As one of these TP used a Mod and the other a Trad set of clothing, these particular factors would affect the clothing set averages less than the test room temperature, which was on average up to 6.6 °C higher for TP10 (Mod) than for TP9. At the same time, age-dependent trends can be compared, as the mean environmental conditions and number of clothing types in both groups are similar.



WBGT – 'wet bulb globe temperature'. The abrupt changes at the beginning of the curves at around the 60th minute of exposure reflect TPs quitting the exposure at different time points before intended exposure time was reached.

Figure 2.2 Curves of average environmental parameters of all TPs during the heat exposure period in the WLF scenario

The QuesTemp instrument was not moved to the recovery area. The conditions there stayed stable due to the large room volume. Air temperature and humidity there were recorded with a MSR logger (Table 2.2) and are not reflected in Figure 2.2. The globe temperature in the recovery area was assumed to be equal to the air temperature.

2.1.3 SIF

The air velocity in the climate-controlled room always stayed around 0.10 m/s for all tests. Table 2.3 shows the air and globe temperatures and relative humidity for various periods of the exercise and recovery for SIF, and Figure 2.3 shows the average curves for the environmental parameters in heat. The QuesTemp instrument was not placed in the area for prework and recovery. Air temperature and humidity there were recorded with a MSR logger (Table 2.3) and are not reflected in Figure 2.3. The globe temperature outside the climate-controlled room was assumed to be equal to the air temperature.

In SIF, the environmental conditions stayed most stable compared to the other scenarios, except for the humidity regulation problem during the last tests (Table 2.3, TP7, TP9 and TP10). This scenario also had the shortest heat exposure, while it had the highest temperature and the highest work rates. All TPs managed the full intended exposure. The environmental conditions thus allow a good comparison between clothing sets and age groups.

Table 2.3 Average air (T_a) and globe (T_g) temperatures and relative humidity (*RH*) for the exercise and recovery periods of SIF

Activity Time Period		Cycling 50 W, dressing, 0-20 min		Walk 3.1 km/h, 20-30 min			Walk 4 km/h, 30-35 min			Walk 5.4 km/h, 0 and 4 kW/m², 35-40 min			Walk 4 km/h, 0 and 4 kW/m², 40-45 min			Walk 5.4 km/h, 45-50 min			Sit recovery 50-80 min	
Parameter		*Ta=Tg* (°C)	*RH* (%)	T_a (°C)	T_g (°C)	*RH* (%)	T_a (°C)	T_g (°C)	*RH* (%)	T_a (°C)	T_g (°C)	*RH* (%)	T_a (°C)	T_g (°C)	*RH* (%)	T_a (°C)	T_g (°C)	*RH* (%)	$T_a=T_g$ (°C)	*RH* (%)
TP	**Clothing**																			
1	Mod	16.9	56.5	45.1	44.0	29.8	44.5	43.6	31.6	44.1	44.1	34.2	43.9	44.1	32.5	42.2	40.5	35.5	16.3	56.4
3	Trad	**19.5**	58.5	44.5	43.6	34.6	44.3	43.8	36.6	44.4	45.2	38.3	44.4	44.4	33.1	42.7	41.0	39.8	20.0	62.7
4	Trad	**18.4**	58.6	44.0	42.8	32.8	43.9	43.3	34.6	43.9	44.4	36.7	43.8	43.7	34.9	43.9	44.3	35.3	17.1	63.4
5	Mod	**19.0**	58.0	44.0	42.8	35.6	42.8	42.1	39.5	42.6	43.1	41.6	43.1	44.6	40.3	43.7	44.0	36.2	19.6	60.5
6	Mod	**20.2**	63.0	44.0	43.1	35.6	43.2	42.7	39.8	43.4	44.4	39.7	43.3	43.1	37.5	43.3	43.8	39.5	20.3	65.6
7	Mod	**18.3**	42.9	45.0	44.2	16.1	45.6	44.9	16.2	46.0	45.5	15.9	46.2	46.0	16.2	45.8	44.6	16.6	19.7	53.1
8	Trad	**16.5**	58.7	44.9	44.1	28.8	44.4	43.5	32.2	44.1	44.1	33.8	44.2	45.1	34.8	44.3	44.4	33.1	16.0	55.9
9	Trad	**17.1**	48.3	44.3	43.4	16.2	45.3	44.5	16.0	45.9	45.5	15.8	46.1	46.0	16.0	45.5	44.3	16.1	17.4	49.0
10	Mod	**16.6**	45.8	44.0	43.5	15.8	44.4	43.8	15.8	44.8	44.7	15.9	44.7	44.4	16.0	43.6	42.6	16.7	17.0	49.0
Mean all		**18.0**	**54.5**	**44.4**	**43.5**	**27.2**	**44.3**	**43.6**	**29.1**	**44.3**	**44.5**	**30.2**	**44.4**	**44.6**	**29.0**	**43.9**	**43.3**	**29.9**	**18.1**	**57.3**
SD all		***1.3***	***6.9***	***0.5***	***0.5***	***8.7***	***0.9***	***0.8***	***10.3***	***1.1***	***0.8***	***11.0***	***1.1***	***1.0***	***10.0***	***1.2***	***1.5***	***10.2***	***1.7***	***6.2***
Mean Mod		**18.2**	**53.2**	**44.4**	**43.5**	**26.6**	**44.1**	**43.4**	**28.6**	**44.2**	**44.3**	**29.5**	**44.2**	**44.4**	**28.5**	**43.7**	**43.1**	**28.9**	**18.6**	**56.9**
SD Mod		***1.5***	***8.5***	***0.6***	***0.6***	***10.0***	***1.1***	***1.1***	***11.9***	***1.3***	***0.9***	***12.7***	***1.3***	***1.0***	***11.7***	***1.3***	***1.6***	***11.3***	***1.8***	***6.4***
Mean Trad		**17.9**	**56.0**	**44.4**	**43.5**	**28.1**	**44.5**	**43.8**	**29.9**	**44.5**	**44.8**	**31.2**	**44.6**	**44.8**	**29.7**	**44.1**	**43.5**	**31.1**	**17.6**	**57.8**
SD Trad		***1.3***	***5.1***	***0.4***	***0.5***	***8.3***	***0.6***	***0.6***	***9.4***	***0.9***	***0.6***	***10.4***	***1.0***	***1.0***	***9.2***	***1.1***	***1.6***	***10.4***	***1.7***	***6.7***
Mean <40 years		**17.9**	**51.6**	**44.7**	**43.8**	**24.2**	**44.9**	**44.2**	**25.1**	**45.1**	**45.1**	**26.1**	**45.2**	**45.1**	**24.5**	**44.1**	**42.6**	**27.0**	**18.3**	**55.3**
SD <40 years		***1.2***	***7.2***	***0.4***	***0.3***	***9.5***	***0.6***	***0.6***	***10.6***	***1.0***	***0.7***	***11.9***	***1.2***	***1.0***	***9.7***	***1.9***	***2.1***	***12.4***	***1.8***	***5.8***
Mean >40 years		**18.1**	**56.8**	**44.2**	**43.3**	**29.7**	**43.7**	**43.1**	**32.4**	**43.8**	**44.1**	**33.5**	**43.8**	**44.2**	**32.7**	**43.8**	**43.8**	**32.2**	**18.0**	**58.9**
SD >40 years		***1.6***	***6.4***	***0.4***	***0.5***	***8.3***	***0.7***	***0.7***	***9.8***	***0.8***	***0.6***	***10.3***	***0.7***	***0.8***	***9.6***	***0.4***	***0.7***	***8.9***	***1.8***	***6.6***

Yellow shaded cells in Table 2.3 point out experiments where weather and/or humidity control considerably affected the environment compared to other tests. Recovery was outside the climate room.

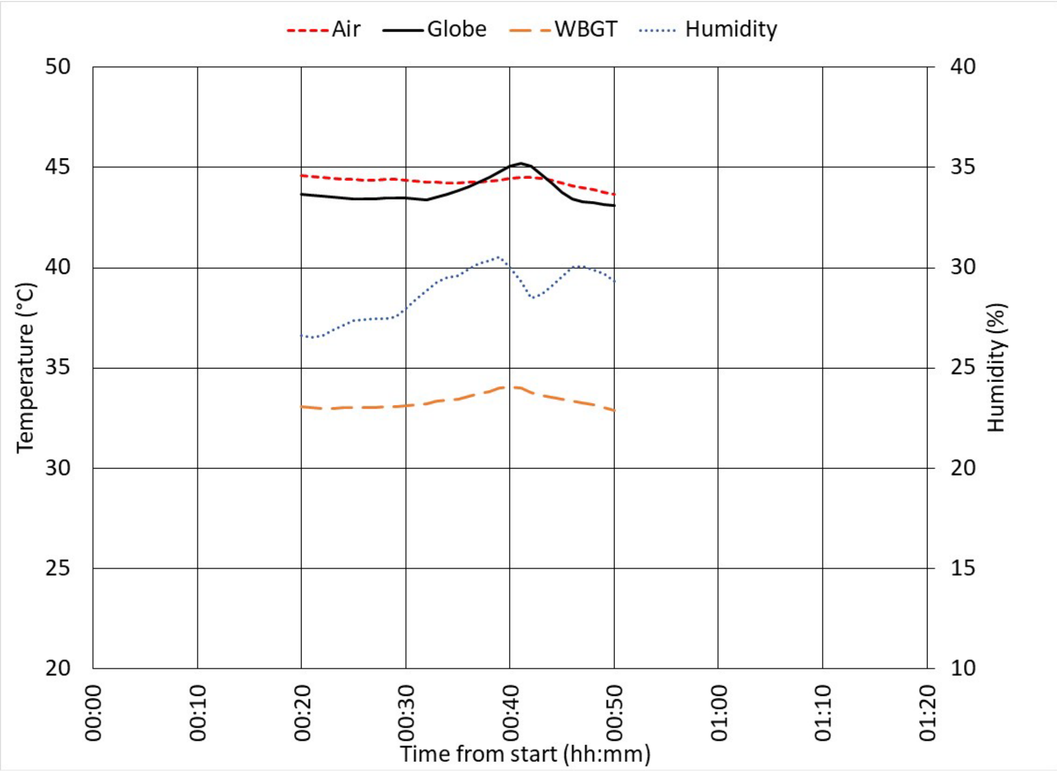


Figure 2.3 Average environmental parameters curves from all TPs during the SIF scenario heat exposure period

2.2 Clothing

The clothing insulation, clothing evaporative resistance and permeability index of the clothing are shown in Figure 2.4. These results come from the manikin studies that were performed earlier and were reported separately (Kuklane et al., 2022; Kuklane et al., 2024a). The clothing ensembles are sorted from the lowest to the highest clothing evaporative resistance. The station wear (operational uniform, C2_OU) is displayed separately, as this was used as the base under all other ensembles. Also, alternative sets C6_WLF and C6A_SIF are included for comparison, as they are similar combinations as Trad_WLF and Trad_SIF, and illustrate some variation in the existing traditionally used turnout gear in Netherlands. To understand the differences in the results, the clothing properties are the parameters to refer to.

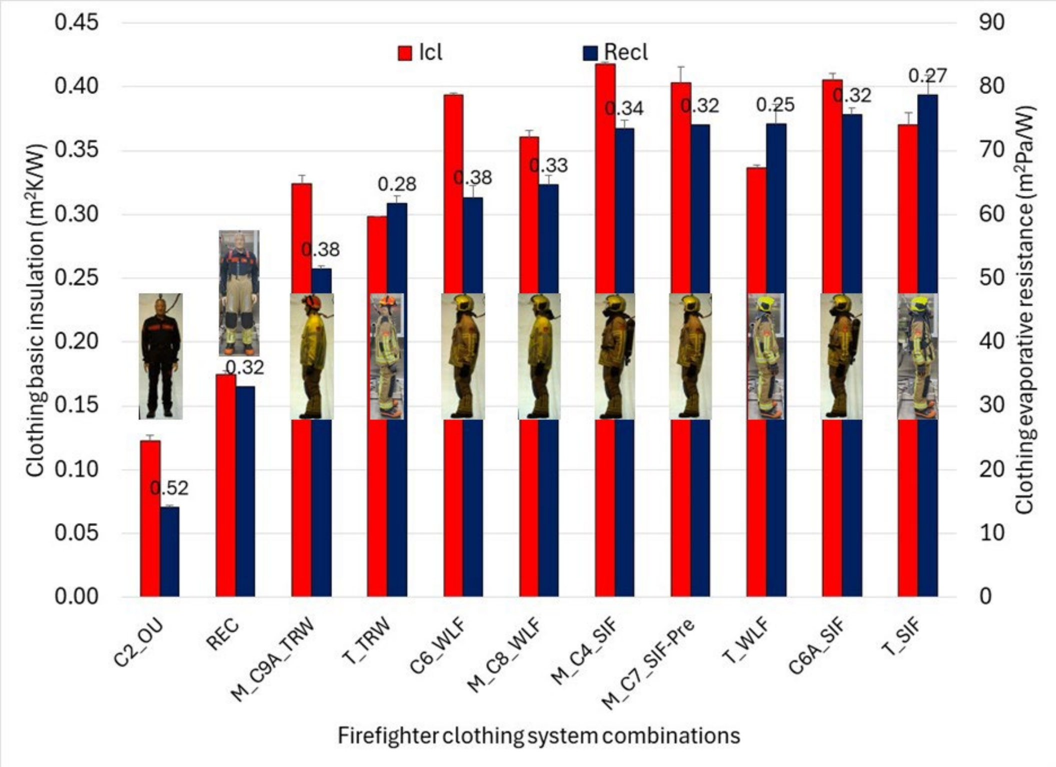


Figure 2.4 Basic clothing insulation (I_{cl}, m²K/W) and clothing evaporative resistance (R_{ecl}, m²Pa/W) of the used and comparable clothing ensembles: M – modular clothing system Mod; T – traditional clothing system Trad; the values above the bars represent clothing permeability index

For details of the clothing ensembles properties see Kuklane et al. (2022) and Kuklane et al. (2024a). Ensembles C6_WLF and C6A_SIF were not used in human study but are comparable combinations to Trad_WLF and Trad_SIF, respectively, that consisted of the components tested earlier (Kuklane et al., 2022).

The clothing permeability index ($i_{m,cl}$) is a non-dimensional weighted ratio between insulation and evaporative resistance. A higher $i_{m,cl}$ value is corresponding to better breathability, where 0.38 is a common value ordinary clothing for indoor environments and values below 0.32 indicate reducing breathability.

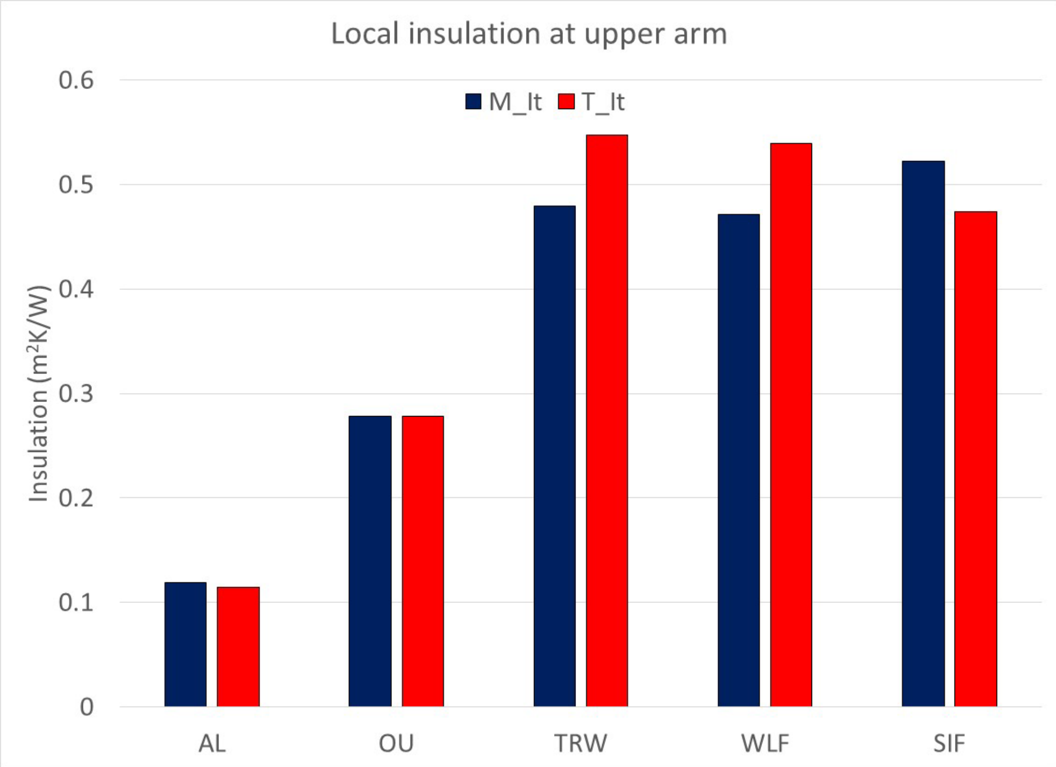


Figure 2.5 Total clothing insulation at the upper arm (AL is insulation of adhering layer of air at the manikin): M – modular clothing system Mod; T – traditional clothing system Trad

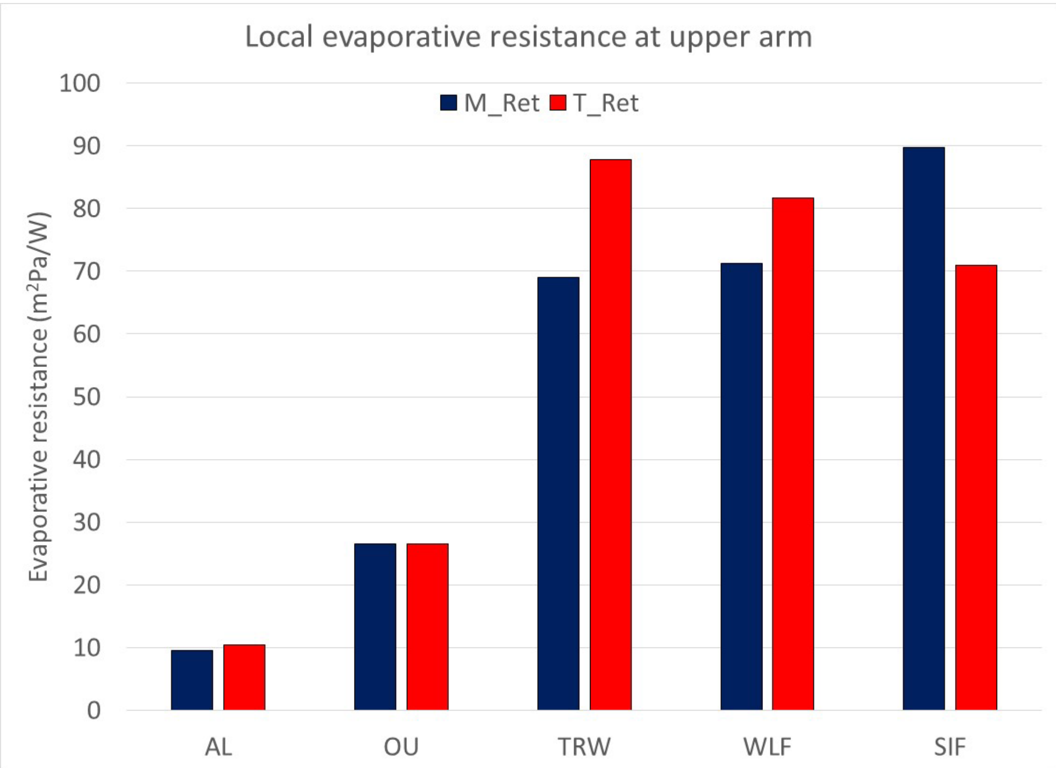


Figure 2.6 Total evaporative resistance at the upper arm (AL is evaporative resistance of adhering layer of air and textile skin at the manikin): M – modular clothing system Mod; T – traditional clothing system Trad

During the tests, IR-radiation was applied from the right side of the TP. The closest point to the radiation panel was the right upper arm where the outer layer (OL), station wear (OU) and skin temperatures were measured. For this point, the length of the radiation period was estimated based on earlier experience (Heus & den Hartog, 2017; Heus et al., 2022) to avoid skin temperatures raising up to or above 43 °C.

To evaluate the effect of radiation and protective clothing on skin temperature development, the total clothing insulation and evaporative resistances of the local region – i.e. the region surrounding the upper arm – are given in Figures 2.5 and 2.6. These local clothing properties were measured and reported in detail in earlier studies on a thermal manikin (Kuklane et al. 2022, Kuklane et al. 2024a).

2.3 (Psycho)physiological data

This chapter covers the results and discussion of the physiological and subjective responses of the TP for each simulated incident scenario.

2.3.1 TRW

Heart rate and metabolic rate

The heart rate (HR) for each activity level in Mod was on average about 20 beats/min lower than in Trad (Figure 2.7). The presented values are the mean HR and the metabolic rate (Met) for the last minute of each activity.

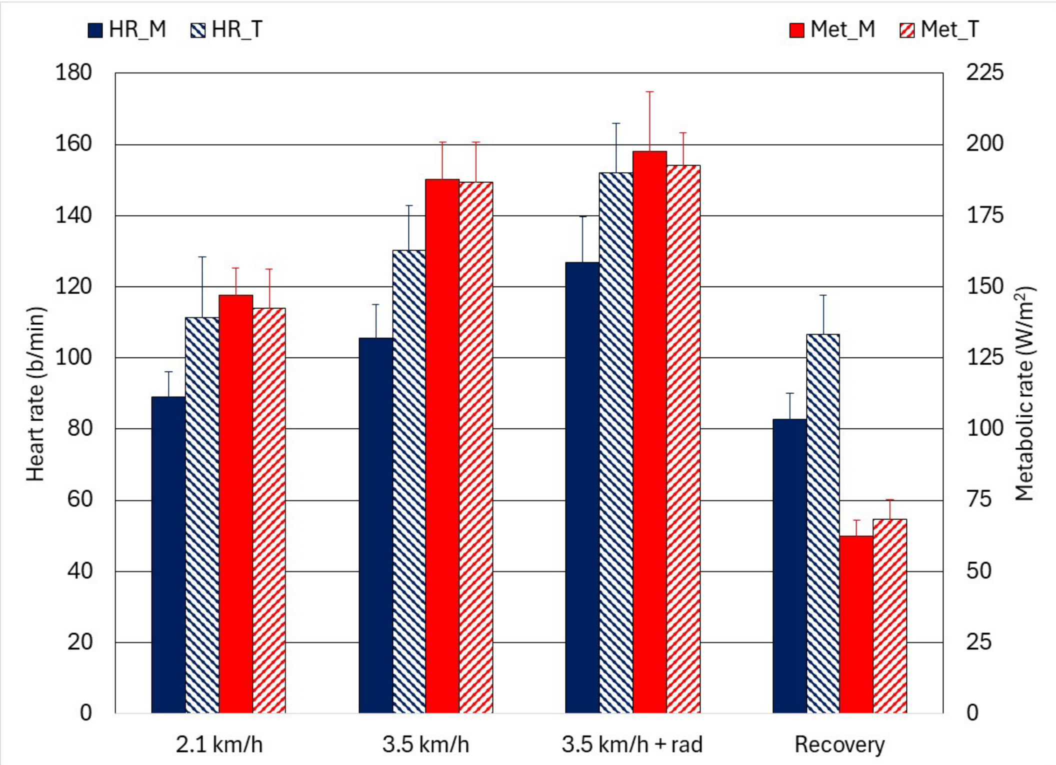


Figure 2.7 Heart and metabolic rates for Mod and Trad in the TRW scenario: M – modular clothing system Mod; T – traditional clothing system Trad

NIPV Nederlands Instituut Publieke Veiligheid

The HR is increasing not only due to activity, but also with time and it is also about 20 beats/min higher for every 30 minutes of heat exposure. During seated recovery, the HR drops but is still only slightly lower after 30 minutes than at the end of the first activity level. This ongoing elevation of the HR clearly reflects the rising body temperature and the increased heat stress.

A slight increase can be seen in Met for the activity of 3.5 km/h with and without radiation (Figure 2.7). Some of this may be caused by individual differences between the persons in the groups (different persons using ensembles Mod and Trad), increase in moisture content in the clothing, increased friction between the layers due to moisture, and the Q10 effect (Chaui-Berlinck, 2002)[8]. However, this increase is small compared to the changes in HR. If considered that Met in all activities differed minimally between Mod and Trad, then there is a considerable difference in HR between Mod and Trad that reflects the difference in heat stress and cardiovascular load. This difference is even more important if we consider that in the other scenarios the HR difference between Mod and Trad is lower (Figures 2.17 and 2.27), showing a stronger effect of more permeable clothing in less strenuous working conditions.

Skin temperature

In the TRW scenario, the mean skin temperatures at the start of the exposure were very similar (Figure 2.8). This allows the observation of the clearly increasing differences between Mod and Trad over time. The differences even increased during recovery when the jackets were removed, and the rest of the clothing components were relatively similar (REC in Table 1.3). This reflects higher heat storage in the clothing system Trad than in Mod. However, the variation in skin temperatures is high, and therefore, the differences were not statistically significant. The wavy pattern in the mean skin temperature reflects the fluctuation in the chamber temperature (Figure 2.1).

[8] Q_{10} is a measure for temperature sensitivity based on chemical response speeds and is applicable to most physiological processes.

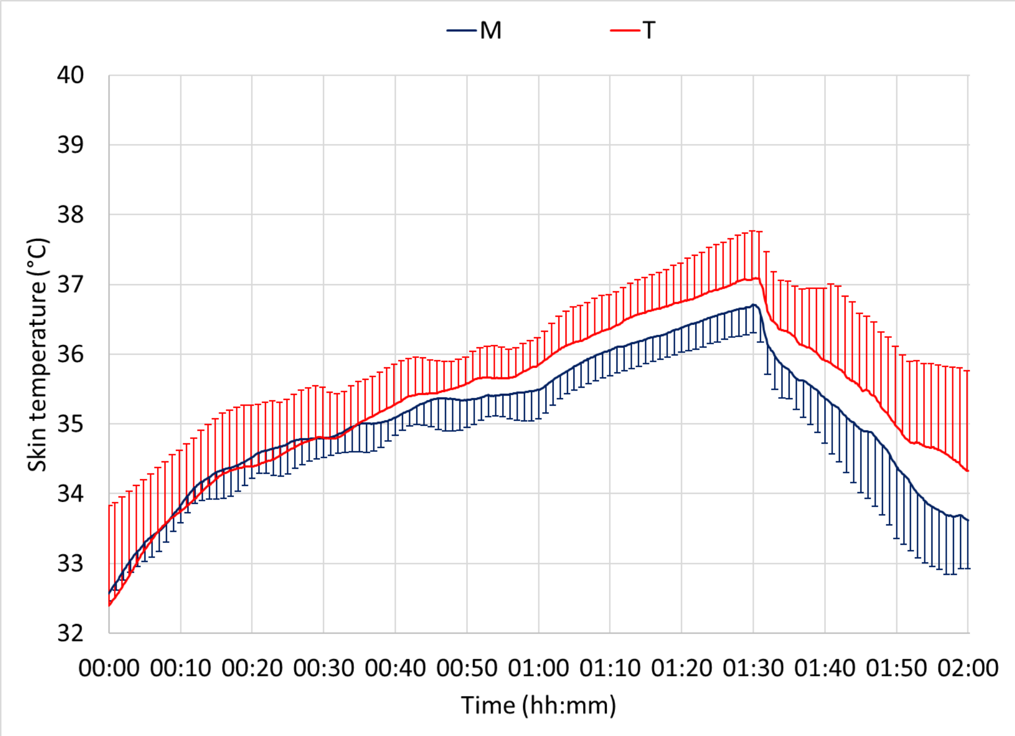
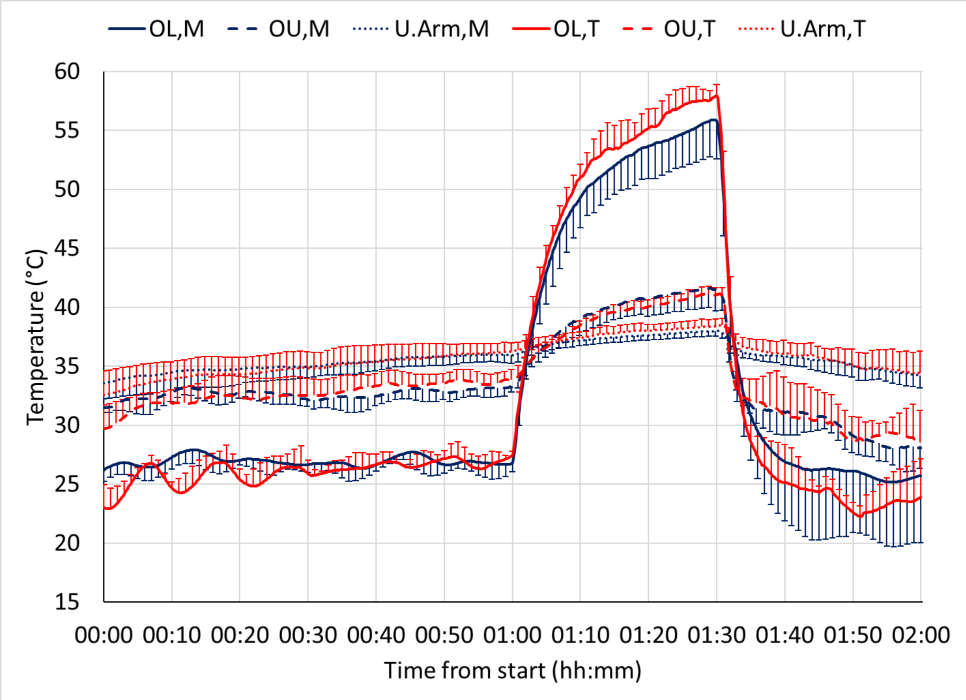


Figure 2.8 Mean skin temperatures for the TRW scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Upper arm temperatures and humidity of textile layers and skin surfaces
This wavy pattern is more clearly observable in the outer layer temperature at the upper arm (Figure 2.9), where due to high clothing insulation this temperature differed only minimally from the air temperature in the periods without radiation. At the onset of 1 kW/m^2 radiation the outer layer surface temperature increased by 15 °C in less than 5 minutes. After that, the surface temperature increase started slowing down and reached over 55 °C in the next 25 minutes. The outer layer surface temperature of Trad reached a couple of degrees higher than on Mod. This may have depended on the fact that on Mod, the sensor position was on a reflective tape and on most of ensembles Trad (see different outer layer design for Trad in Table 1.3) there was no reflective tape at that point on the upper arm.



OL = outer layer turnout suit; OU = Operational Uniform; u.arm = upper arm

Figure 2.9 Right upper arm skin surface and textile layers' temperatures during the TRW scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Starting from recovery, the outer layer temperature reflects the air temperature near the TPs as the jacket was removed and the sensor stayed hanging behind the backrest of the seated TPs.

The temperatures measured in between the layers, on top of the station wear (OU) stayed relatively similar in both Mod and Trad, while local skin temperature at the upper arm reached under radiation about 0.4 °C higher in Trad than in Mod (Figure 2.9). In any case, the local skin temperatures never reached above 39 °C.

Relative humidity (RH) between the layers started growing with the onset of the exercise and reached close to and in Mod even above 90 % at the onset of the radiation (Figure 2.10). Considering lower evaporative resistance (Table 1.3) and more sweating (= body weight loss, Figure 2.15) in Mod than in Trad, these results show a discrepancy that can only be explained by individual differences between the test person groups for Mod and Trad.

A small peak in RH after 1 hour walking and straight after (2-3 minutes) the onset of the radiation may indicate some additional evaporation from the outer layer that became warmer, causing vapour to reach humidity sensor on OU, or reduced moisture leaving from the system due to an increase of the absolute humidity at the inner side of the outer layer (Figure 2.11). With a continued increase of the OU temperature RH reduced, while the absolute humidity kept increasing until the end of the exercise in heat and the start of recovery when the jacket was removed (Figures 2.10 and 2.11). As the absolute humidity at the skin and between the layers during radiation both stayed above or close to 6 kPa and in the environment around 1.5 kPa, no vapour movement towards skin could be expected, but only out through the clothing system, towards the environment.

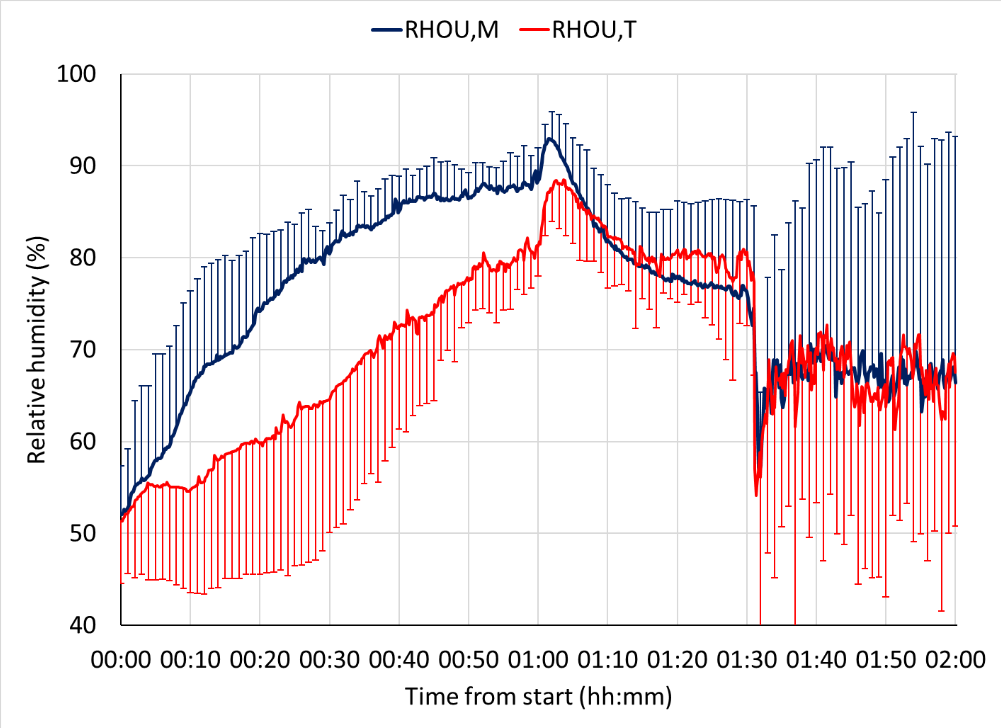


Figure 2.10 Relative humidity between the clothing layers at the right upper arm during the TRW scenario: M – modular clothing system Mod; T – traditional clothing system Trad

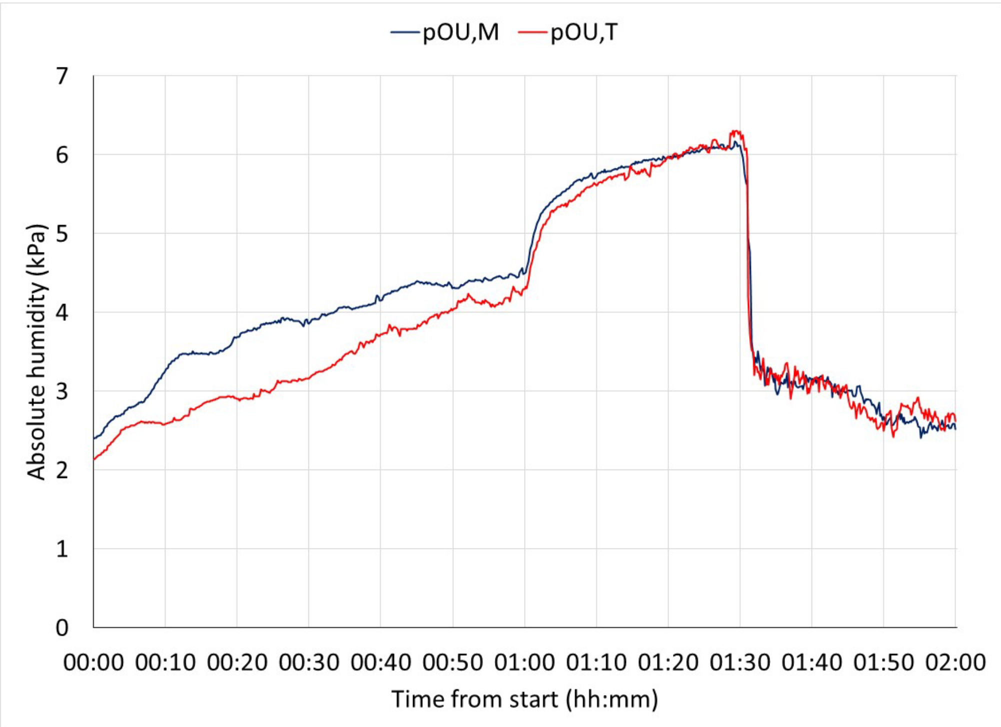


Figure 2.11 Absolute humidity as water vapour partial pressure between the clothing layers at right upper arm measured on OU during the TRW scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Rectal and mean body temperature

Figure 2.12 shows the dynamics of the rectal temperature development and Figure 2.13 in mean body temperatures. Starting from the same temperature level, the differences between Mod and Trad increased with time, showing a quicker rise in Trad, and the differences being the largest at the end of recovery. It can be observed that the maximal rectal temperature is reached only after about 5 minutes into recovery (Figure 2.12) in both clothing sets. This can be explained by the fact that the heat is accumulated in the superficial body layers and muscles, and despite the increased evaporation from the skin when removing the jacket (see sharp drop in skin temperature at the start of the recovery in Figure 2.8), heat still continues moving towards the body central areas through tissue conductivity and blood circulation.

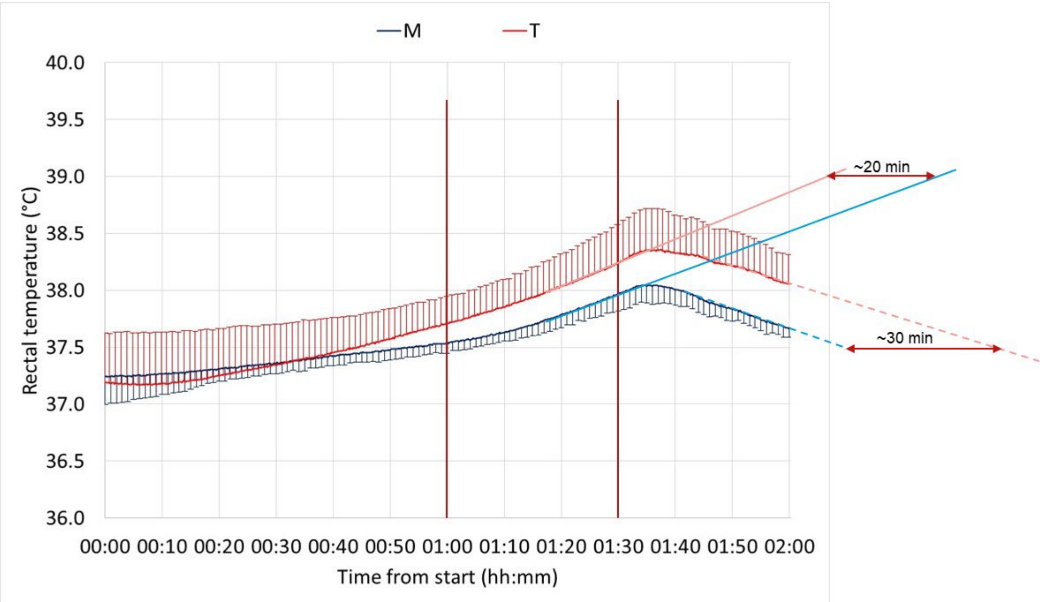


Figure 2.12 Rectal temperatures for the TRW scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Continued trendlines for the end of exposure and recovery indicate expected rectal temperature development until exposure termination (39 °C) and restoring normal core temperature before the start of the next work pass (37.5 °C) (M= Mod and T= Trad).

If a rectal temperature of 39 °C is considered an exposure termination criterion, and it is assumed that the latest measured workload and environmental conditions stay at the same level, the rescue workers could continue working 20 minutes longer in Mod than in Trad (Figure 2.12). The estimated recovery period required to reach a rectal temperature of 37.5 °C before the next work pass would be about 30 minutes shorter in Mod than in Trad. If in an emergency the rectal temperature of 38 °C would be selected as the aimed recovery temperature after which a next, preferably lighter, work pass can be started, then in Mod only a short 10-minute break for rehydration is needed, while in Trad the break must still be at least 30 minutes.

The mean body temperature increase (Figure 2.13) reflects the increase in body heat content. By the end of the exercise, the body heat content is on average about 16 % higher in Trad than in Mod and the body heat storage rate is also higher in Trad than in Mod by about 14 %. Although the temperatures start dropping soon after the recovery start, these differences between clothing systems increase up to about 45 and 39 % respectively, as the recovery is slower in Trad than in Mod.

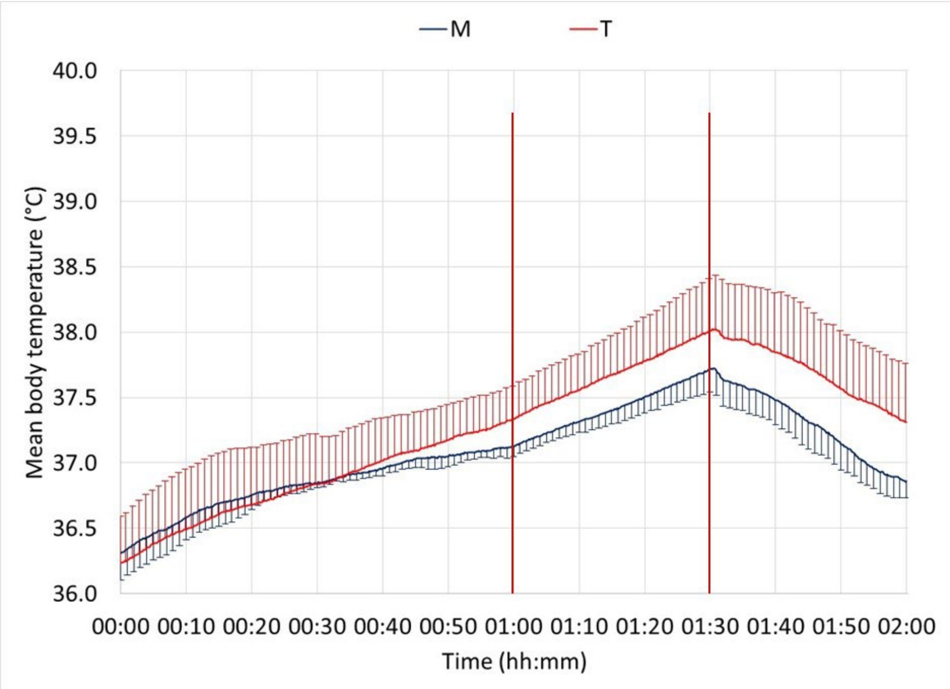


Figure 2.13 Mean body temperatures for the TRW scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Temperature changes

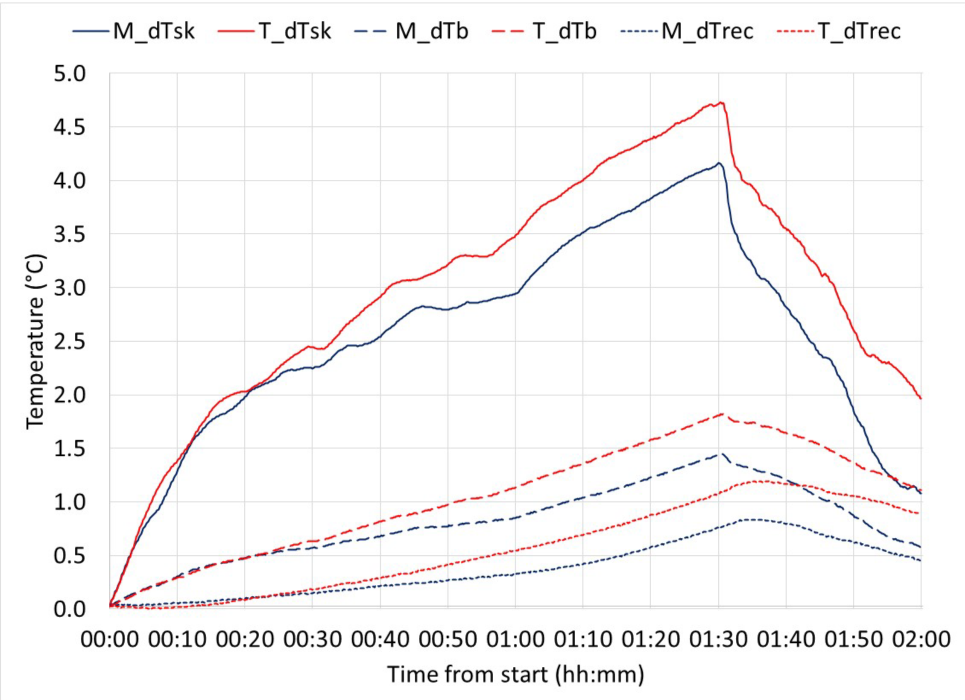


Figure 2.14 Change in critical temperatures for the TRW scenario: dTsk = change in mean skin temperature; dTb = change in mean body temperature; dTrec = change in rectal temperature; M – modular clothing system Mod; T – traditional clothing system Trad

The differences between Mod and Trad are even more clear when the temperature curves are adjusted to the same start point (Figure 2.14). They are practically the same up to about 25th minute and then start deviating, reaching to about 0.5, 0.4 and 0.3 °C by the end of the exercise, and to about 0.8, 0.6 and 0.5 °C by the end of the recovery for Tsk, Tb and Trec, respectively.

Body weight loss, evaporation and estimated accumulation in clothing system
Higher weight loss in Mod than in Trad was not expected (Figure 2.15) and can be related to the sweating capacity of the individuals in the Mod and Trad groups. Some contributing factors to mass loss are body size, sweat gland density and their sweating capacity, but also acclimatisation and fitness level/training habits. These factors were not controlled in this study. At the same time, the evaporation during exercise stayed equal in Mod and Trad. Higher evaporation in Mod than in Trad during recovery is logical, as after removing the helmet, gloves and jacket, there is more accumulated sweat in the clothing system, especially when the body weight loss is higher. Higher evaporation in Mod may also explain a quicker decrease in the mean skin temperature than in Trad (Figures 2.8 and 2.14). Also, for the same reason the accumulated sweat in Mod could be expected to be higher than in Trad, especially since the evaporation during exercise was similar in both clothing ensembles. However, equal evaporation was not expected in these sets as the evaporative resistance in Mod was lower than in Trad. This discrepancy needs to be studied closer and verified in the follow-up studies.

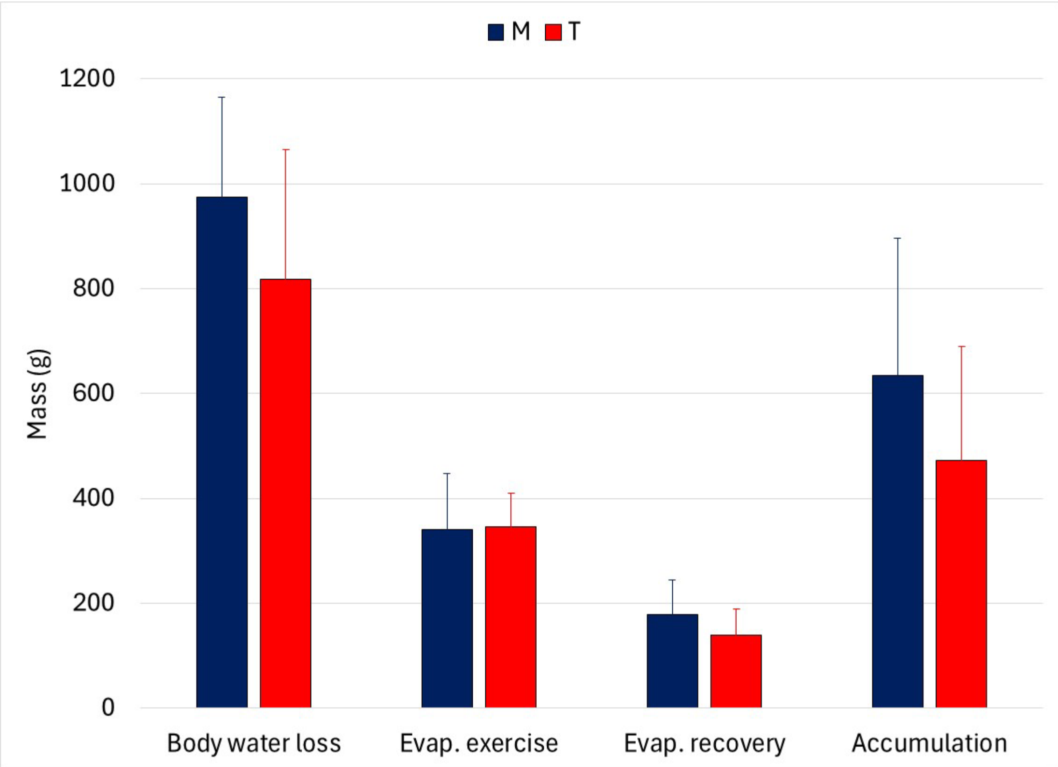


Figure 2.15 Weight loss, evaporation and estimated moisture accumulation in clothing in the TRW scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Subjective responses
The subjective responses followed the observed physiological temperatures and moisture to some extent, while the discrepancies can up to a certain degree be explained (Figure 2.16).

Mod provided lower thermal sensation and less discomfort until the onset of the radiation. After this and during recovery the differences were negligible, probably due to the IR-radiation and temperature increase in the clothing system leading to a relatively high heat load and discomfort in both systems. Possibly, the stronger increase of moisture in clothing Mod compared to Trad could have affected these responses. The skin moisture experienced on the other hand matched the increase in the measured weight loss and development of moisture accumulation well and showed stronger skin moisture sensation in Mod than in Trad. The perceived exertion in both clothing sets was quite similar and matched the minimal differences in metabolic rates (Figure 2.7).

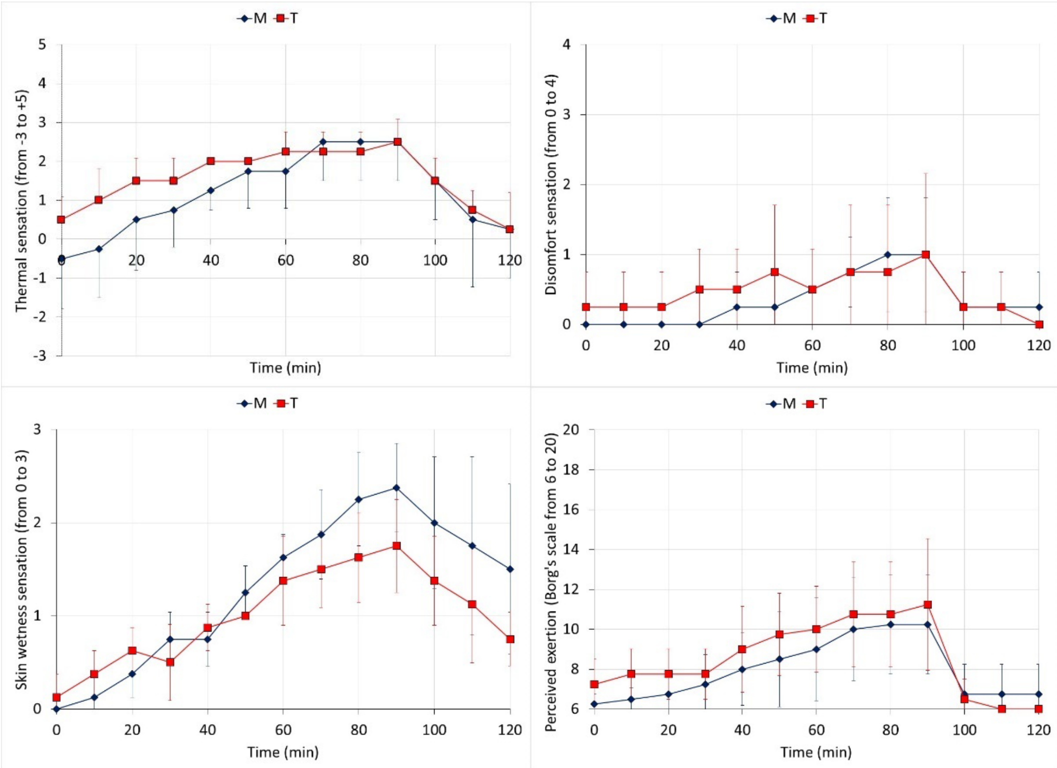


Figure 2.16 Subjective responses during the TRW scenario using modular (Mod) or traditional (Trad) turnout gear: M – modular clothing system Mod; T – traditional clothing system Trad

2.3.2 WLF

Heart rate and metabolic rate

Heart rate (HR) was only a bit lower for each activity level in Mod than in Trad (Figure 2.17). There were no statistically significant differences between Mod and Trad, except for the recovery, in which the mean difference increased to close to 20 beats/min, and was higher in Trad (Figure 2.17). The presented values are the mean HR and metabolic rate (Met) for the last minute of each activity. It should be kept in mind here that the metabolic rates did not differ significantly, although they were somewhat higher for persons wearing Mod. It is even more important to consider that the HR in Mod stayed only a bit lower than in Trad during the heat exposure and recovered quicker despite the significantly higher mean environmental temperatures for Mod (up to 4 °C in the middle of the heat exposure and close to 7 °C close to the end of the heat exposure, Table 2.2). This shows the importance of a lower evaporative resistance (Table 1.3) and possibly an improved pumping effect (ventilation) during body motion reflecting the impact of the clothing design.

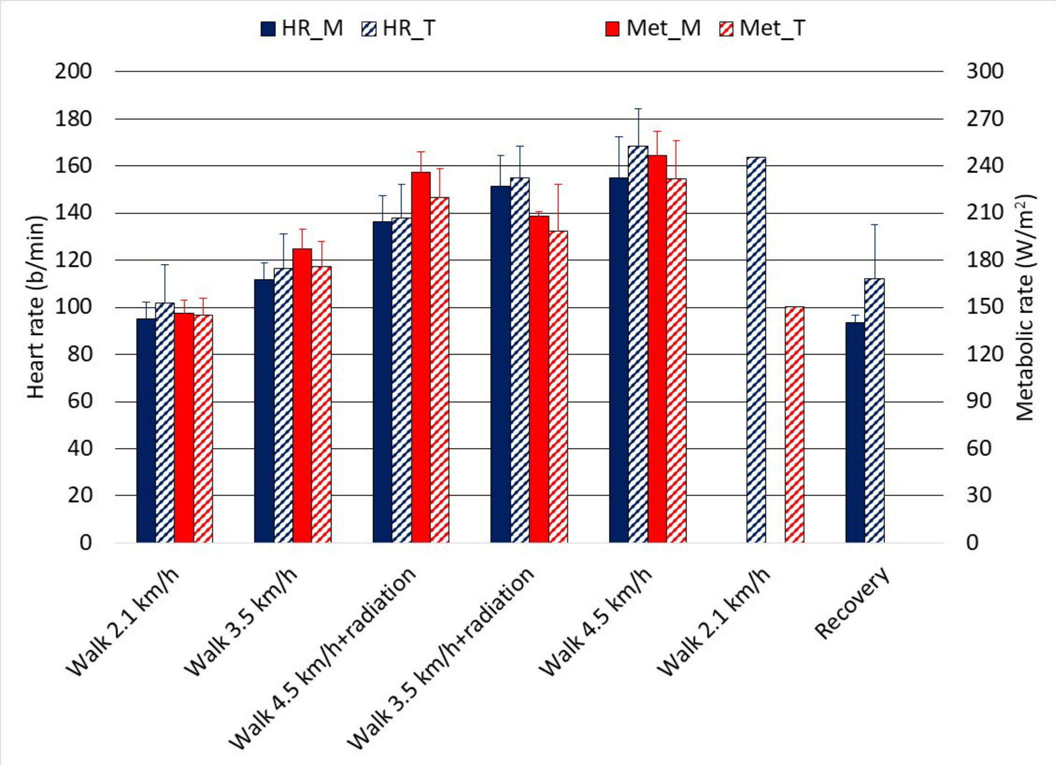
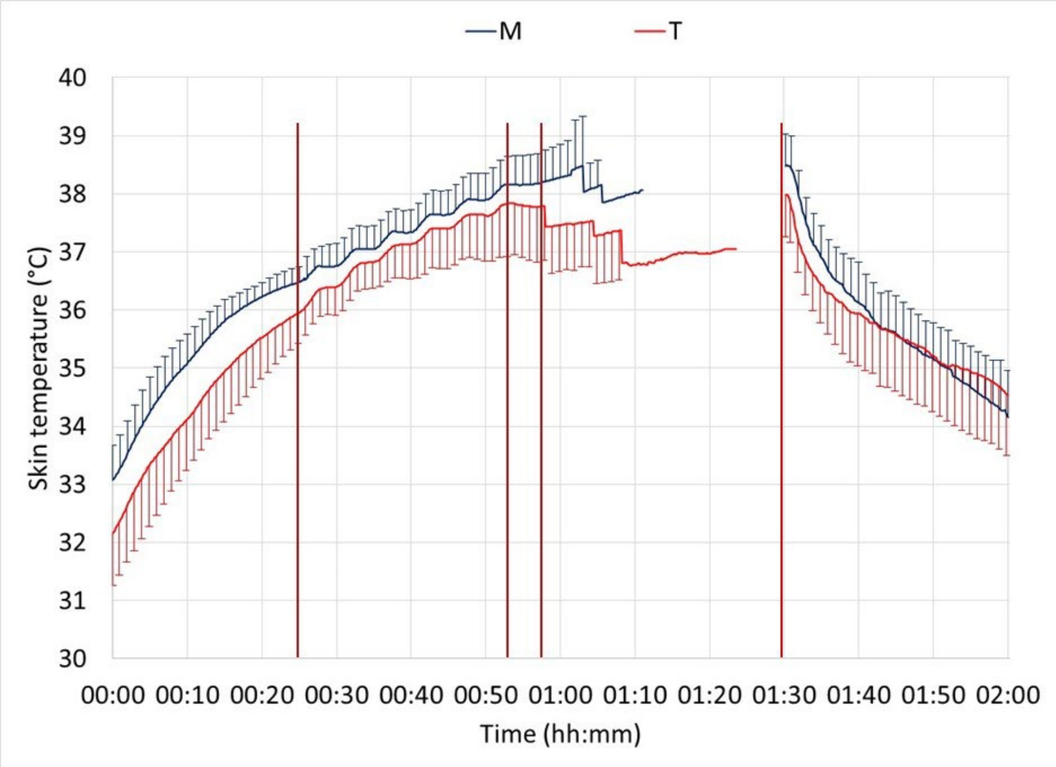


Figure 2.17 Heart and metabolic rates for the WLF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

In WLF it can be seen even more clearly than in TRW that Met stays similar independently from exposure time for the same activity, while the HR grows with time and heat stress development. During the seated recovery, the HR drops but is after 30 minutes still similar to the HR at the end of the first activity level. This preserved elevation of the HR clearly reflects the elevation in body temperatures and the increased heat stress.

Skin temperature

In the WLF scenario, the mean skin temperatures at the start of the exposure differed on average almost 1 °C with Trad, having lower T_{sk} than Mod (Figure 2.18). This can be related to the lower air temperature in the preparation area on some of the test days with Trad. The increase in skin temperatures in Mod and Trad is relatively similar until about the 15th minute of the heat exposure. Then, it slows down in Mod until the start of a stronger radiation period, after which the changes again follow the same pattern. After the end of the intensive intermittent radiation period, the differences start increasing again. However, as the test persons started dropping out soon after this, the further differences in mean skin temperatures until the recovery period are more difficult to explain. Although the temperatures in Mod and Trad overlap during the recovery period it can be observed that the temperature decrease in Mod is somewhat quicker than in Trad, when clothing sets during recovery were similar (REC in Table 1.3), despite the hotter mean exposure temperatures (Table 2.2). More sweating and accumulation of moisture in Mod and the related evaporation during recovery were most probably the cause (Figure 2.25). The spread of skin temperatures is large and therefore the differences were not statistically significant. The wavy pattern in the mean skin temperature reflects the intermittent radiant load shifting between 1 and 3 kW/m^2 (Table 1.4).



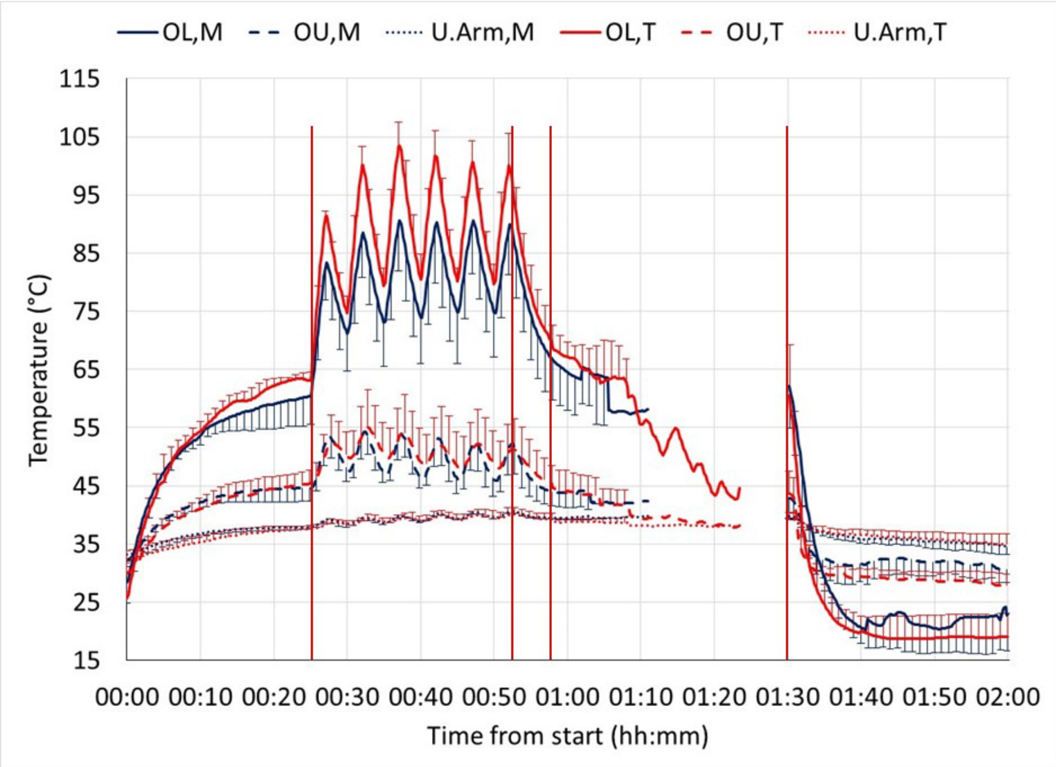
The first vertical red line marks the start of heat radiation of 3 kW/m², the second one the end of intermittent radiation, the third one the quitting of the first test person and the last one the start of the recovery period for all TPs, independent from heat exposure end time.

Figure 2.18 Mean skin temperatures for the WLF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Upper arm temperatures of textile layers and skin surfaces and humidity
The wavy pattern in skin and local clothing surface temperatures due to intermittent radiation is clearly observable in the measurements at the right upper arm (Figure 2.19). We can see that for this radiation load the minimum and maximum levels of outer layer and station wear (OU) temperatures stay more or less stable or show a minor reduction after the first couple of fluctuations, indicating a stable state has been reached.

The mean outer layer temperatures under radiation of 1 kW/m² reached on average close to 65 °C for Trad and to 60 °C for Mod in the first 25 minutes of exposure, and also dropped to approximately these levels after the intermittent radiation period. During the intermittent radiation period (2 minutes 3 kW/m² and 3 minutes 1 kW/m² for 30 minutes in total, i.e. six cycles), the temperatures in Mod shifted on average between 72 and 90 °C and in Trad between 80 and 100 °C during 1 kW/m² and 3 kW/m² radiation load, respectively (Figure 2.19). This can be related to that the sensor position on Mod was on a reflective tape and on most of ensembles Trad (see different outer layer design for Trad in Table 1.3) there was no reflective tape at that point on the upper arm.

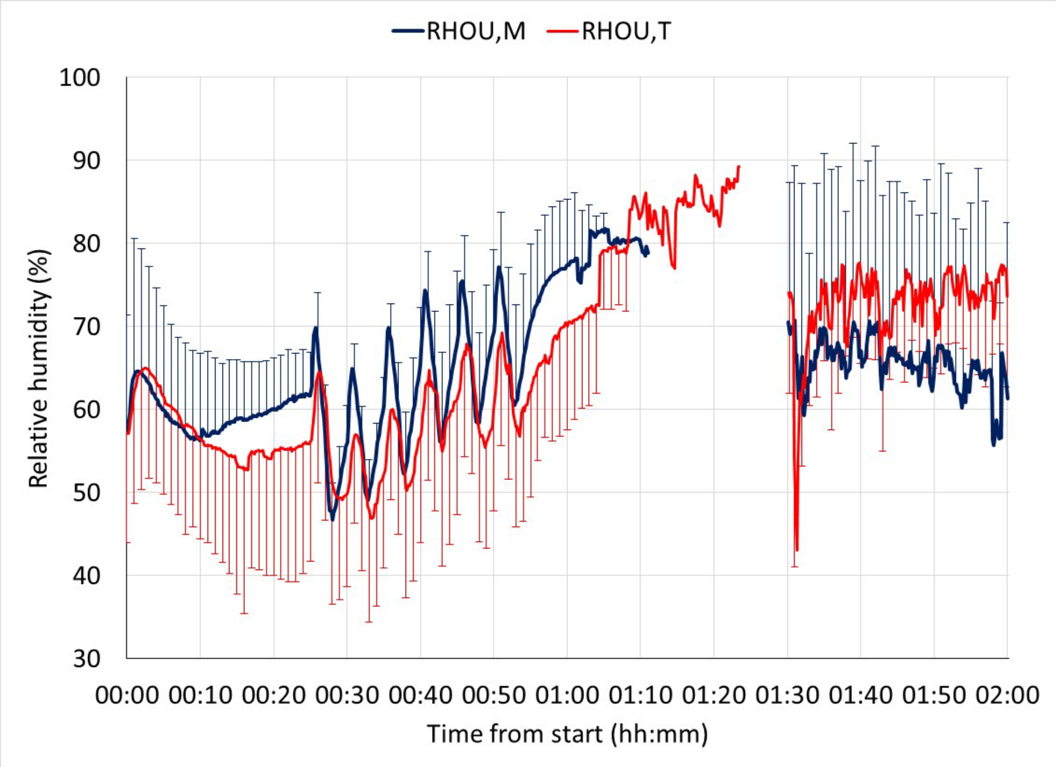
In WLF, the temperatures of the outer layer during 1 kW/m² were only slightly higher than in TRW exposure, and can be attributed to the ambient temperature that was over 5 °C higher in WLF (Figures 2.1 and 2.2, Tables 2.1 and 2.2). The temperature fluctuations between the clothing layers, on station wear, reached on average from 46 to 55 °C for Mod and from 47 to 55 °C for Trad at 1 and 3 kW/m^2, respectively (Figure 2.19). From this viewpoint, and considering the variability, there were no significant differences between Mod and Trad.



The first vertical red line marks the start of heat radiation of 3 kW/m^2, the second one the end of intermittent radiation, the third one the quitting of the first test person and the last one marks the start of recovery period that is independent from the heat exposure end time for all TPs.

Figure 2.19 Right upper arm skin surface and textile layers' temperatures during the WLF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

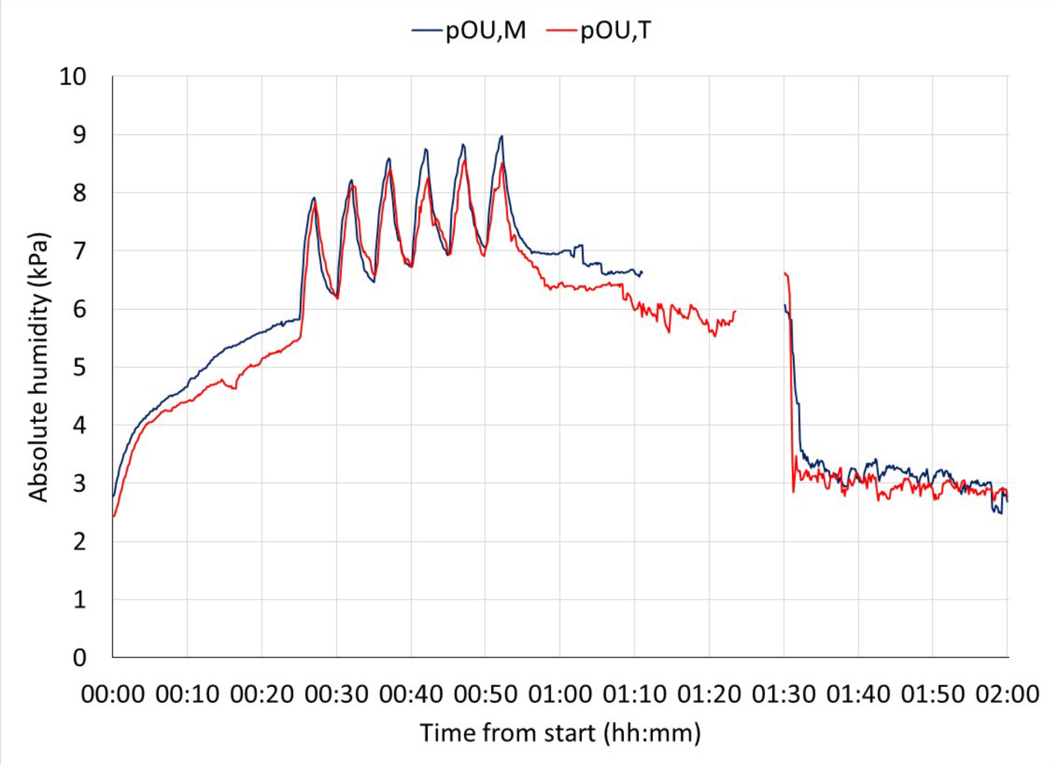
The fluctuations in skin temperature are observable while a general trend is still showing increase. The skin temperatures did not reach 43 °C in any of the exposures, but stayed always below 42 °C, i.e. about 3 °C higher than in TRW scenario. The slight decrease in clothing layer temperatures can be related to increased sweating, moisture transport in and evaporation from the layers (Figure 2.20).



Recovery period for all TPs starts independently from the heat exposure end time.

Figure 2.20 Relative humidity between the clothing layers at the right upper arm during the WLF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

At the same time, the evaporation from the skin did not increase drastically while the higher clothing temperatures continued contributing to skin temperature increase (Figure 2.19). Considering water vapour pressure between the clothing layers being 6.5-9 kPa (Figure 2.21) and skin temperatures during that period staying on average close to 40 °C and skin relative humidity at 100 % with resultant water vapour pressure at the skin of about 7.5 kPa, then we can expect that evaporation from the skin at the upper arm was minimal and could only work due to ventilation created by pumping air through clothing openings during walking. With continuation of similar intensity intermittent radiation load it could be estimated that skin temperature in some test persons could reach 43 °C and above within the next 10-15 minutes if the intermittent radiation exposure had continued. From this viewpoint there was no big difference between Mod and Trad. During recovery humidity and water vapour pressure on the station wear (OU) stayed at similar levels as in the TRW scenario (Figures 2.10, 2.11, 2.20 and 2.21).



The recovery period for all TPs starts independently from the heat exposure end time.

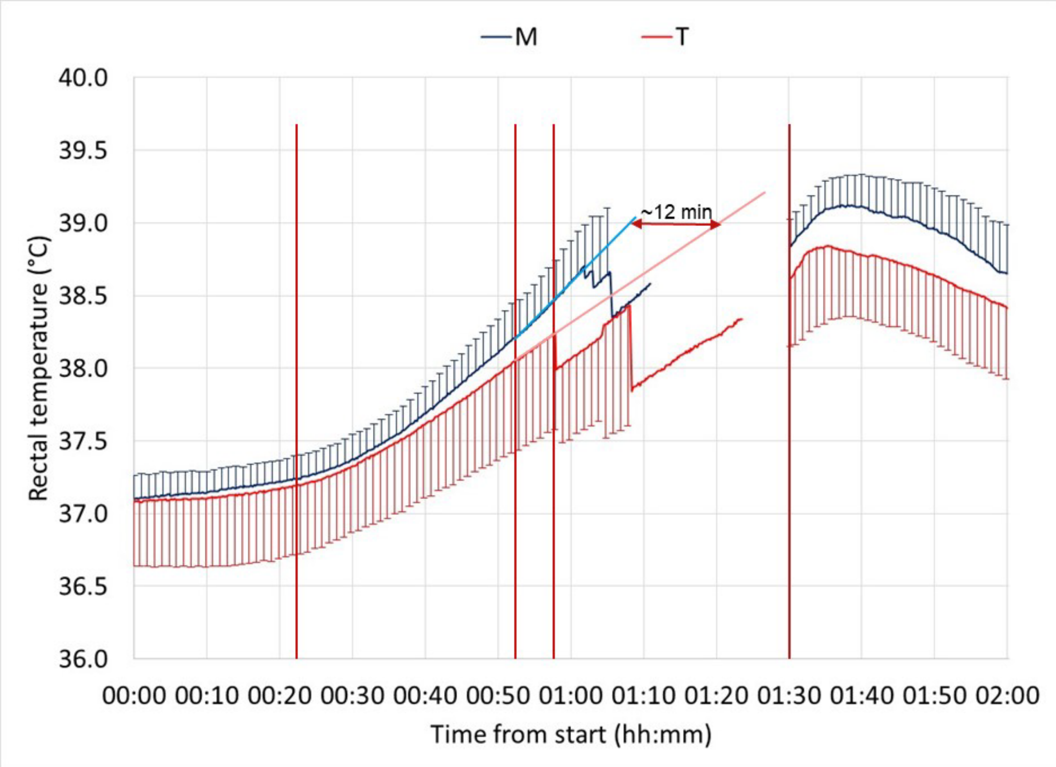
Figure 2.21 Absolute humidity as water vapour partial pressure between the clothing layers at the right upper arm measured on OU during the WLF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Rectal and mean body temperature

All TPs quitted the heat exposure before the intended time, either due to their own wish or because their rectal temperature reached 39.0 °C (Figure 2.22). The first dropout occurred at minute 58. By then, the air temperature for Mod was on average 3.3 °C higher than for Trad (Table 2.2). At the time of the last dropouts, the air temperature in the chamber for Mod was on average already about 6 °C higher than for Trad (see Table2.2). Both the first and the last dropout occurred in Trad.

The rectal temperatures in Mod and Trad started differing in the middle of the intermittent radiation period (around minute 40, Figure 2.22). However, the differences were not significant. Considering that the rectal temperature is a limiting parameter for heat exposure, and as up to the first dropout there were no statistically significant differences between clothing sets Mod and Trad, it can be said that in Mod one can manage over 3 °C higher ambient temperatures with the same activity level than in Trad. As insulation of Mod was slightly higher and evaporative resistance somewhat lower than of Trad (Figure 2.4), the better performance of Mod could be related to a lower evaporative resistance (moisture permeability index of Mod was 0.33 versus 0.25 for Trad).

Still, considering the rectal temperature curve rise before the first dropout in each clothing set, and assuming a rectal temperature of 39 °C as an exposure limit, we can see that in these conditions the exposure time could be 12 minutes longer in Trad than in Mod. Here it has to be noted that on average, the ambient temperature in the test room by the end of the exposures was over 6 °C warmer in Mod than in Trad (Table 2.2).

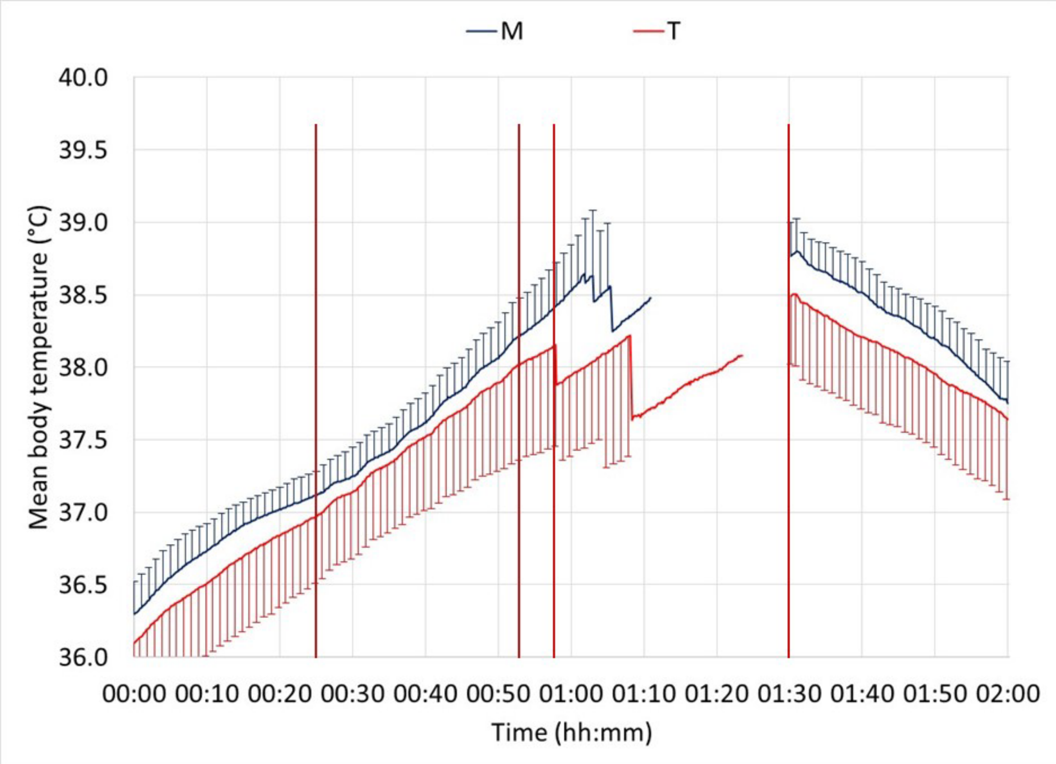


The first vertical red line marks the start of heat radiation of 3 kW/m^2, the second one the end of intermittent radiation, the third one the quitting of the first test person and the last one the start of the recovery period that is for all TPs independent from heat exposure end time.

Figure 2.22 Rectal temperatures for the WLF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Again, during recovery, a typical after-rise in rectal temperature can be seen for 5-10 minutes before it starts reducing (Figure 2.22). As the heat exposure was more severe, the after-rise was somewhat longer in WLF than it was in TRW (Figures 2.12 and 2.22). A somewhat quicker temperature decrease in Mod compared to Trad can be related to a slightly bigger temperature gradient between the body and the recovery room temperature, and to more accumulated moisture in clothing set Mod than in Trad (Figure 2.25).

The mean body temperature in Mod stayed somewhat above the values of Trad throughout the test (Figure 2.23). However, the changes in Mod and Trad were relatively similar (Figure 2.24), confirming that in clothing set Mod, the user could manage doing work at over 3 °C higher temperature environment than in Trad.



The first vertical red line marks the start of heat radiation of 3 kW/m², the second one the end of intermittent radiation, the third one the quitting of the first test person and the last one the start of recovery period that is for all TPs independent from heat exposure end time.

Figure 2.23 Mean body temperatures for the WLF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Temperature changes

The differences (skin temperature during heat exposure and recovery) and similarities (mean body temperature reflecting body heat content change) between Mod and Trad are presented clearer in Figure 2.24. The figure illustrates the discussions of the clothing impact on skin, rectal and mean body temperature in previous sections even better.

We see a quicker increase in skin temperature during heat exposure and a slower drop during recovery for Trad than for Mod, a more increasing rectal temperature for Mod from the middle of the heat exposure and a practically equal change of mean body temperature in both clothing systems despite the higher ambient temperature for heat exposure (increasing mean difference of 3-6 °C, Table 2.2) for Mod than with Trad. This shows that Mod enables to work at higher temperature with the equal heat strain level as Trad.

Again, it must be considered that the test groups were small and that individual differences, e.g. sweating capacity, could have influenced the outcome.

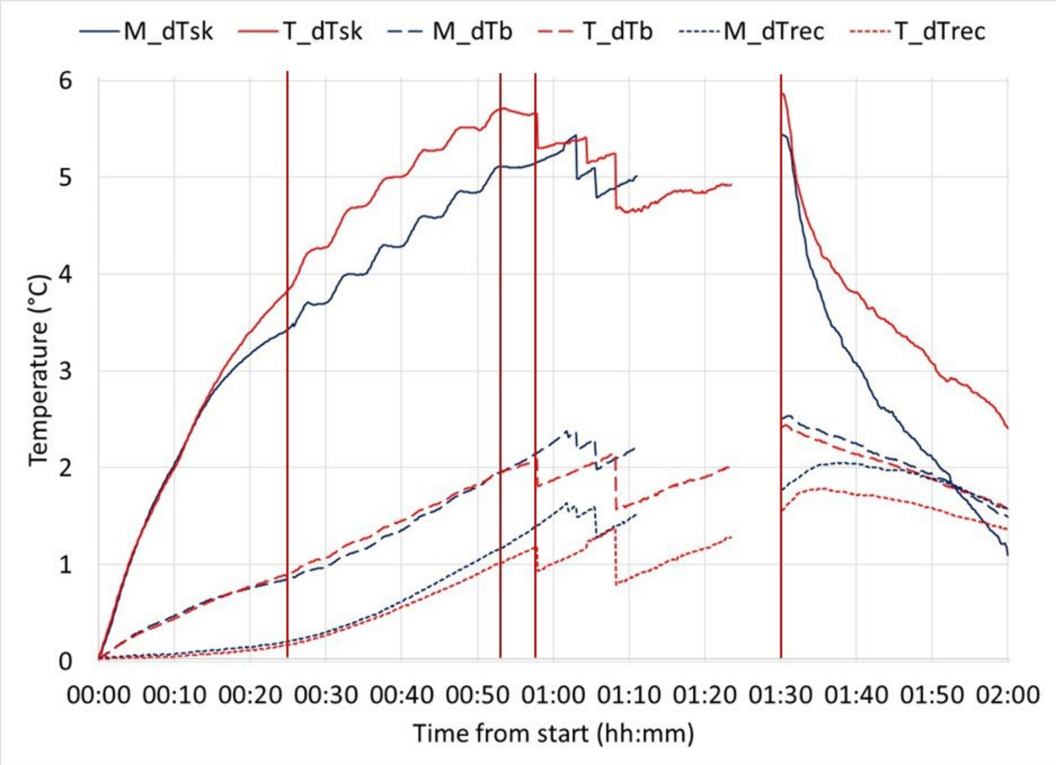


Figure 2.24 Change in critical temperatures for the WLF scenario: dTsk – change in mean skin temperature; dTb – change in mean body temperature; dTrec – change in rectal temperature; M – modular clothing system Mod; T – traditional clothing system Trad

Body weight loss, evaporation and estimated accumulation in clothing system
Sweating was significantly higher in Mod than in Trad, and as evaporation was relatively similar in both – and only a bit lower in Mod than in Trad – the moisture accumulation in clothing was also significantly higher in Mod than in Trad (Figure 2.25). Considering a higher environmental temperature and a higher relative humidity – and with this also a considerably higher absolute humidity (difference 400-600 Pa) – in Mod experiments compared to Trad experiments (Table 2.2), such an outcome could be expected.

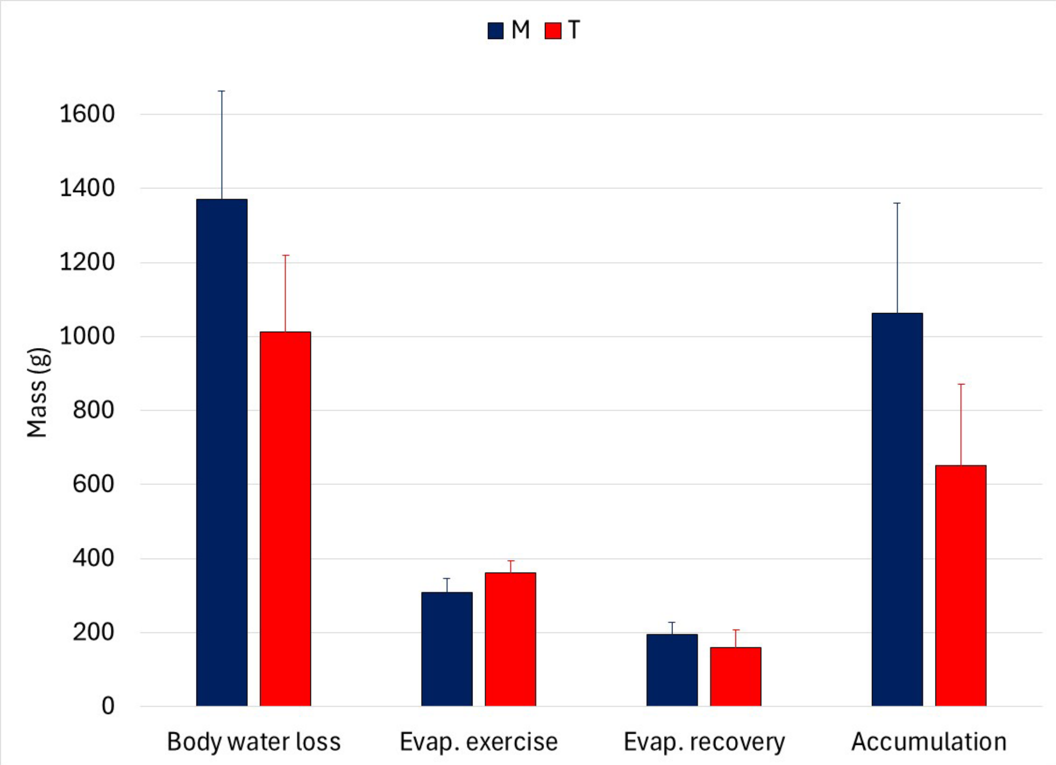


Figure 2.25 Weight loss, evaporation and estimated moisture accumulation in clothing in the WLF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

In addition, there could also be some individual differences present, as can be seen in the TRW scenario, where the environmental conditions stayed more similar (Table 2.1 and Figure 2.15). Another aspect to consider for weight loss differences in this exposure condition is different quitting times of heat exposure. Although one TP in Trad lasted the longest, most TPs in Trad quitted earlier than in Mod, see for example the jumps in the dTsk data in Figure 2.24 from the 58^{th} minute.

Due to many uncontrolled changes in the variables studied, it is difficult to draw specific conclusions, and only abovementioned assumptions can be made for WLF condition. These could be verified in follow-up studies.

Subjective responses

Similar to the TRW scenario, the subjective responses in WLF (Figure 2.26) also followed physiological changes reasonably well. The thermal sensations were relatively similar, while the difference increased during the recovery. The latter can be related to higher moisture accumulation in the clothes and somewhat higher evaporation during the recovery in Mod than in Trad. This is confirmed by the same skin wetness sensation and change during the recovery (Figure 2.26), but also by the relatively similar absolute humidity between the layers (Figure 2.21), as after the tests the clothing in both clothing ensemble types was soaked.

Thus, it can be expected that a somewhat higher discomfort sensation in Mod than in Trad (Figure 2.26) is related to a higher (increasing) heat load in conditions with Mod (Table 2.2) in combination with higher skin, rectal and body temperatures (Figures 2.18, 2.22 and 2.23) and more moisture in the clothing system (Figure 2.25).

The perceived exertion response (Figure 2.26) showed slightly higher values for Trad than for Mod and increasing difference towards the end of the heat exposure despite the thermal conditions for Trad were milder than for Mod (Table 2.2). At the same time, these responses matched with somewhat (yet insignificantly) higher measured heart rates in Trad than in Mod (Figure 2.17), although the metabolic rates were higher in Mod than in Trad (Figure 2.17). Therefore, the observed differences may mainly be related to individual variation. This is confirmed by the sharply increased differences after the 60th minute, when several TPs had quitted the study, and the perception of individual participants played an even larger role.

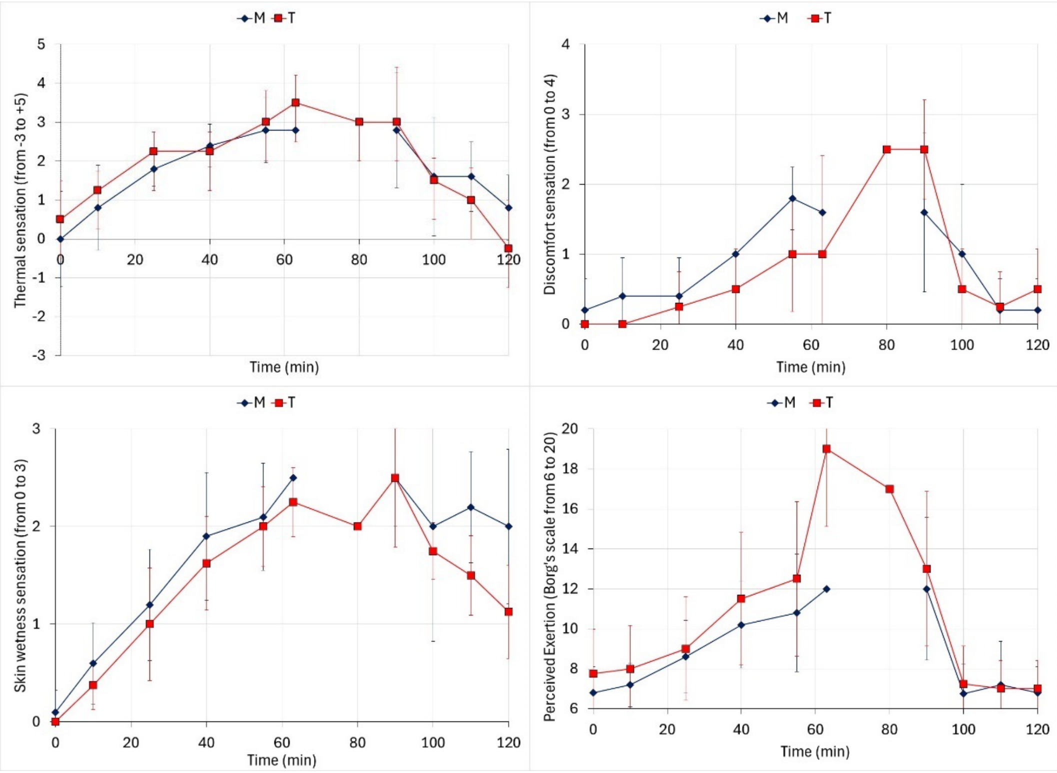


Figure 2.26 Subjective responses during the WLF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

2.3.3 SIF

Heart rate and metabolic rate

The conditions for SIF were most extreme, but the exposure was the shortest, so that all TPs completed the whole test protocol. In this scenario, clothing system Mod was used with double jackets. This seems to have affected the metabolic rates, which stayed higher in Mod than in Trad (Figure 2.27). The differences are bigger than in TRW (Figure 2.7) and are in a similar range as in WLF (Figure 2.17). At the same time, the average heart rate in Mod stayed up to about 10 beats/m lower than in Trad, indicating partly individual differences but partly higher heat stress as well. The differences in heart rates between Mod and Trad in scenario TRW were bigger, and in WLF they were comparable to scenario SIF.

Figure 2.27 clearly indicates the increase of the influence of heat stress on the heart rate: where similar metabolic rates at different time points stay the same, the heart rate increased by almost 20 beats/min, corresponding to a rectal temperature rise of 0.3-0.5 °C in 10 minutes, depending on the time point and clothing system (Figure 2.32). This can be compared to a rectal temperature rise of about 0.5 °C and a heart rate increase of 20 beats/min within 30 minutes in scenario TRW (Figures 2.7 and 2.12), and of about 1 °C per

30-35 beats/min heart rate increase within 30 minutes in scenario WLF (Figures 2.17 and 2.22). Individual fitness and time components certainly play a role, as well as the influence of previous exercise on the next one, but it can be roughly estimated that a core temperature rise of 1 °C increases the cardiovascular load by at least 30 beats/min during these medium heavy to heavy activity levels.

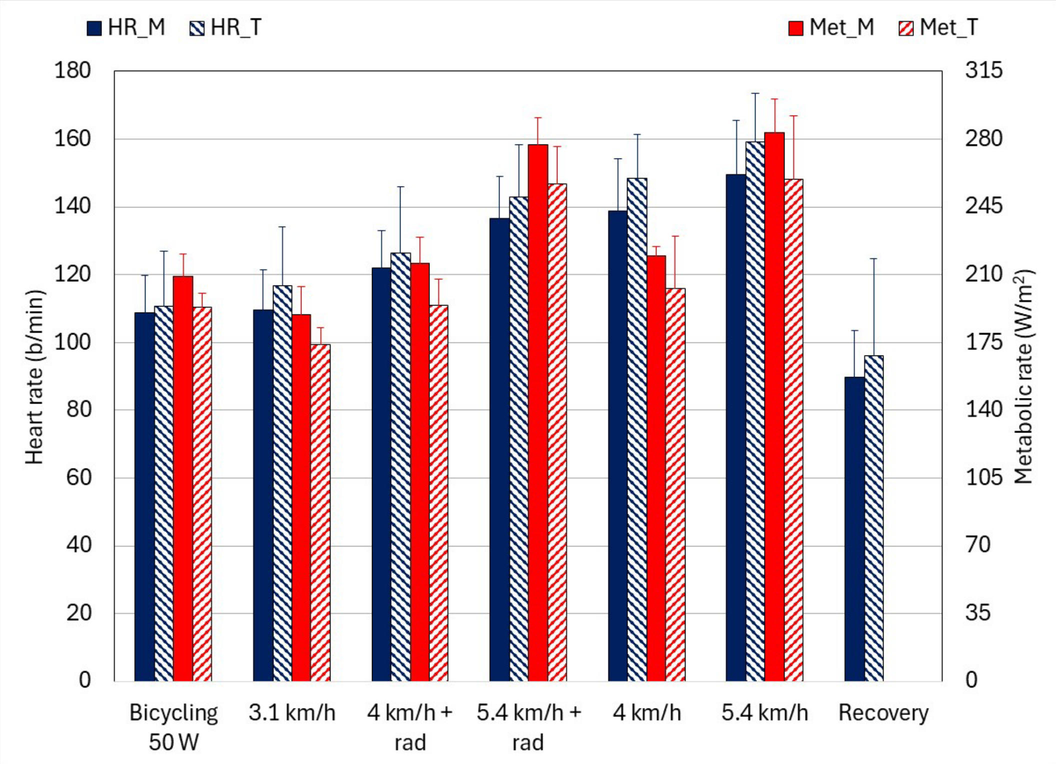
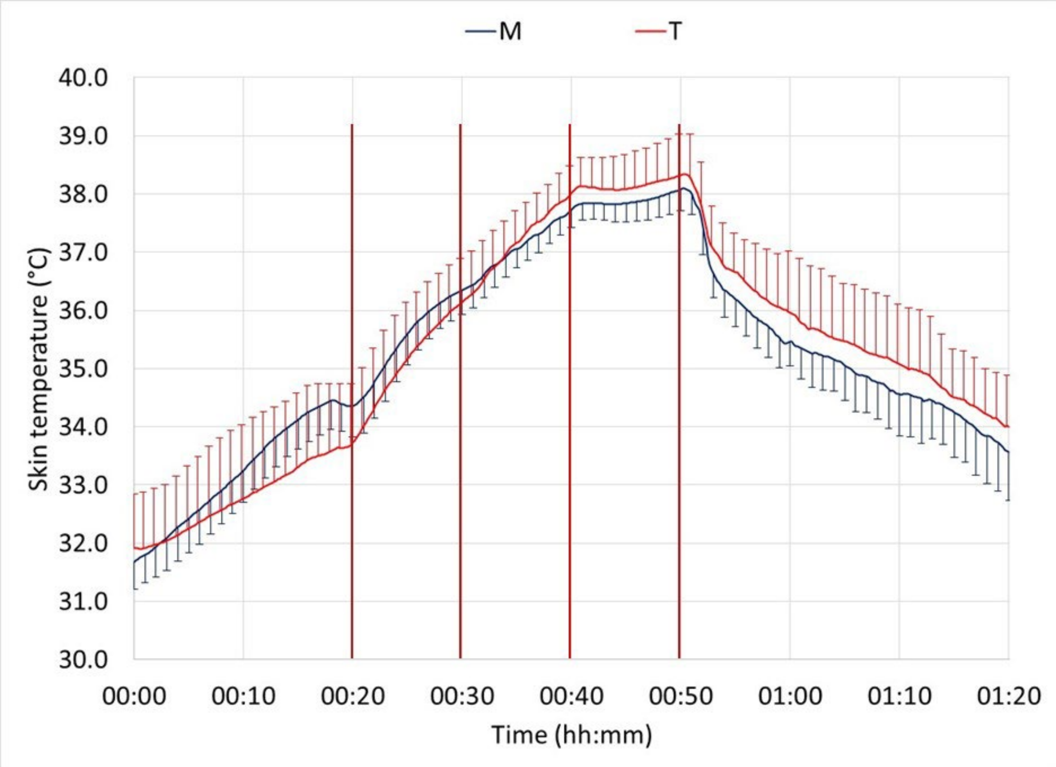


Figure 2.27 Heart and metabolic rates for the SIF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Skin temperature

In the SIF scenario, the mean skin temperatures at the start of the exposure were very similar (Figure 2.28), allowing to follow the physiological impact of different clothing on the user. During the prework outside the climate room (bicycling), the skin temperature increase in Mod (higher insulation on the body, see Table 1.3 and Figure 2.4) was quicker than in Trad. However, at entering the hot environment the differences decreased, and especially adding radiation made the skin temperatures develop quicker in Trad than in Mod. This shows the positive effect of thermal insulation on the protection against extreme heat and flames. After exiting the hot room and removing the jackets, the skin temperature reduction pattern is very similar in both clothing systems (Figures 2.28 and 2.34).

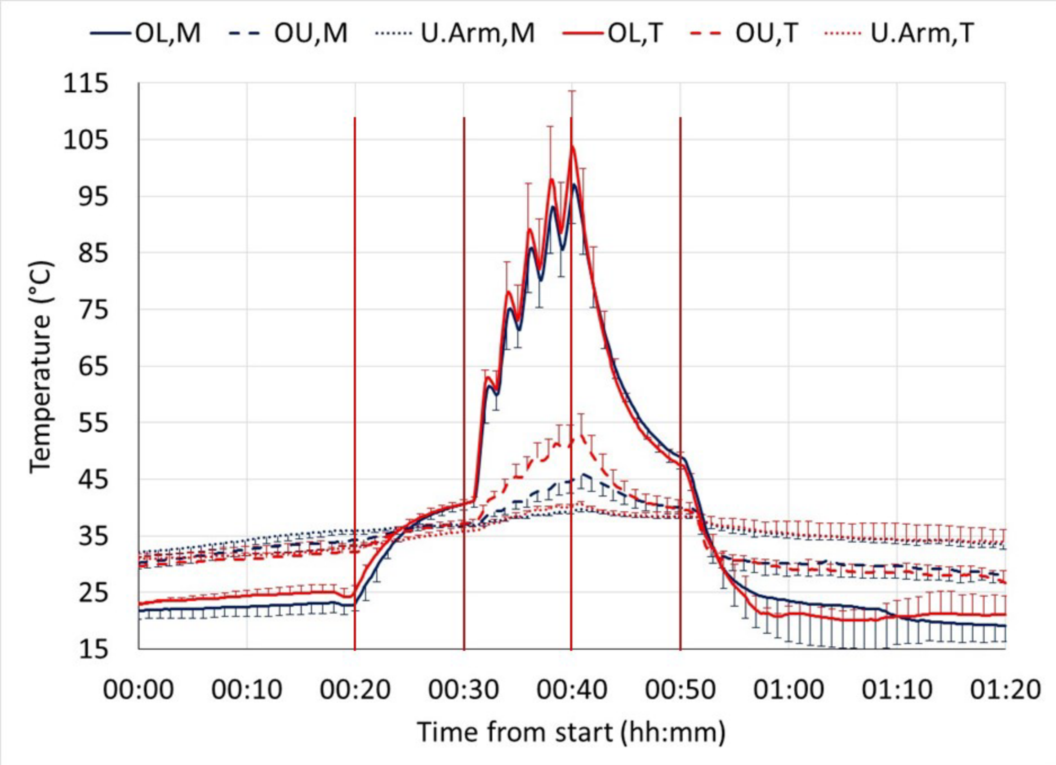


The first vertical red line marks entering the heat, the second one the start of intermittent heat radiation with 4 kW/m^2, the third one the end of intermittent radiation and the last one the end of the heat exposure and the start of recovery period.

Figure 2.28 Mean skin temperatures for the SIF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Upper arm temperatures of textile layers and skin surfaces and humidity
Differently from radiation in WLF (1 kW/m^2 continuously on and for a period shifting radiation load repeatedly to 3 kW/m^2 for 2 minutes, alternating with 1 kW/m^2 for 3 minutes, Figure 2.19, Table 1.4), in SIF (each second minute radiation of 4 kW/m^2 on and off during a 10 minute period, Figure 2.29) the highest clothing surface temperatures did not stabilize at a specific level, but kept increasing with each radiation period. Due to a shorter high radiation time in SIF than in WLF, the temperature fluctuation on the station wear (OU) and on the skin were less distinct than in the WLF scenario, while the temperatures did not show signs of stabilization and kept increasing until the end of the radiation exposure period. Still, no skin temperature reached above 43 °C, confirming that the initial assumptions and estimations for the study planning based on Heus and den Hartog (2017) and Heus et al. (2022) were correct. If the radiation exposure would have continued longer, in a few minutes the first TP would have reached a skin temperature of 43 °C at the upper arm.

Differently from TRW and WLF, the insulation and evaporative resistance at the upper arm were higher in SIF (Figures 2.5 and 2.6). While the outer layer surface temperatures developed relatively similar, with a final mean difference of about 7 °C with Mod having a lower temperature than Trad, this heat load was translated into a similar mean temperature difference on the OU with Trad reaching significantly higher temperatures between the layers than Mod. Also, the skin temperatures at the upper arm exposed to radiation were on average over 1 °C higher in Trad than in Mod (Figure 2.29).



The first vertical red line marks entering the heat, the second one the start of intermittent heat radiation with 4 kW/m^2, the third one the end of intermittent radiation and the last one the end of heat exposure and the start of the recovery period.

Figure 2.29 Right upper arm temperatures of the textile layers and skin surfaces and humidity during the SIF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Relative humidity (RH) between the layers started growing with the onset of the exercise and reached close to, and in Mod above, 90 % with the onset of the radiation (Figure 2.30). Considering a higher total insulation and an only slightly lower total evaporative resistance of the whole clothing system (Table 1.3) and more sweating (= body weight loss, Figure 3.35) in Mod than in Trad throughout the experimental period as well, these results confirm the beforementioned discrepancy for TRW, which largely can be explained by individual differences between the TP groups for Mod and Trad.

The relative humidity on the OU was lower in Trad than in Mod, only because the OU temperature in Trad was considerably higher than in Mod (Figure 2.29). This means a higher absolute humidity between the layers in Trad than in Mod during the radiation periods (Figure 2.31). During the radiation-off periods, the absolute humidity dropped to similar levels in both clothing systems, and in other periods outside the intermittent radiation levels, the absolute humidity in Trad was on average lower than in Mod. This higher absolute humidity in Trad during intermittent radiation period may have created a high enough water vapour pressure gradient between the inner layers and the skin (~2.5 kPa), leading to additional wet heat transfer from the clothing layers towards the skin. This could explain the sharper local (Figure 2.29) and mean (Figure 2.28) skin temperature rise in Trad.

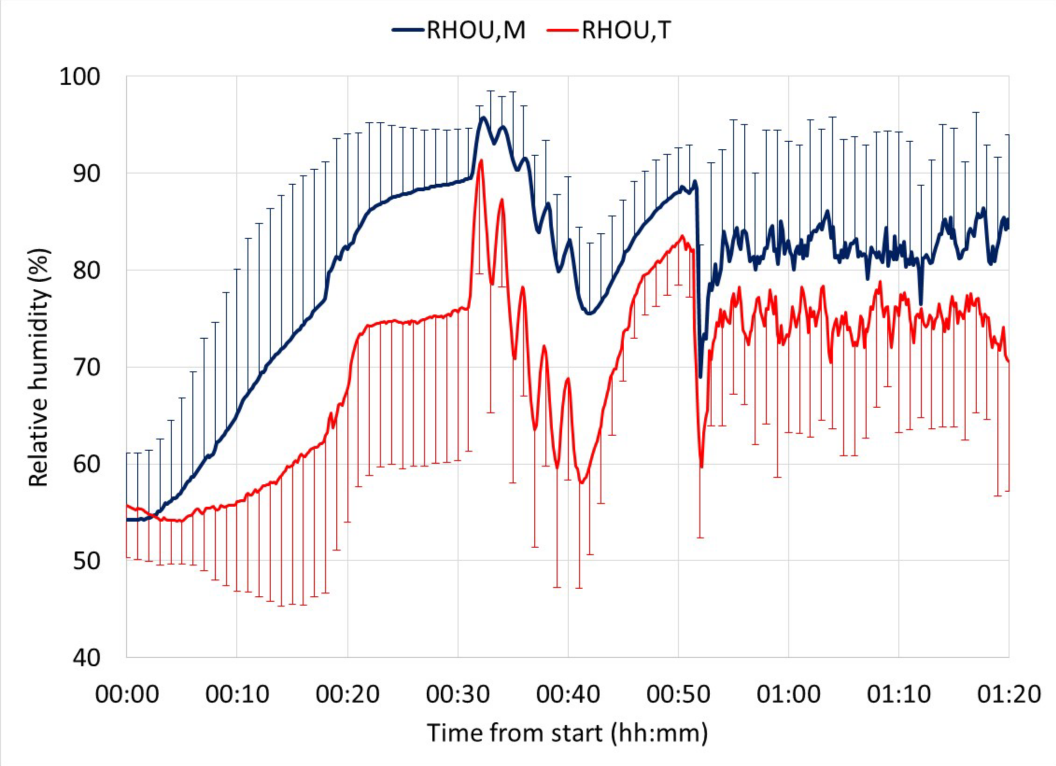


Figure 2.30 Relative humidity between clothing layers at the right upper arm during the SIF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

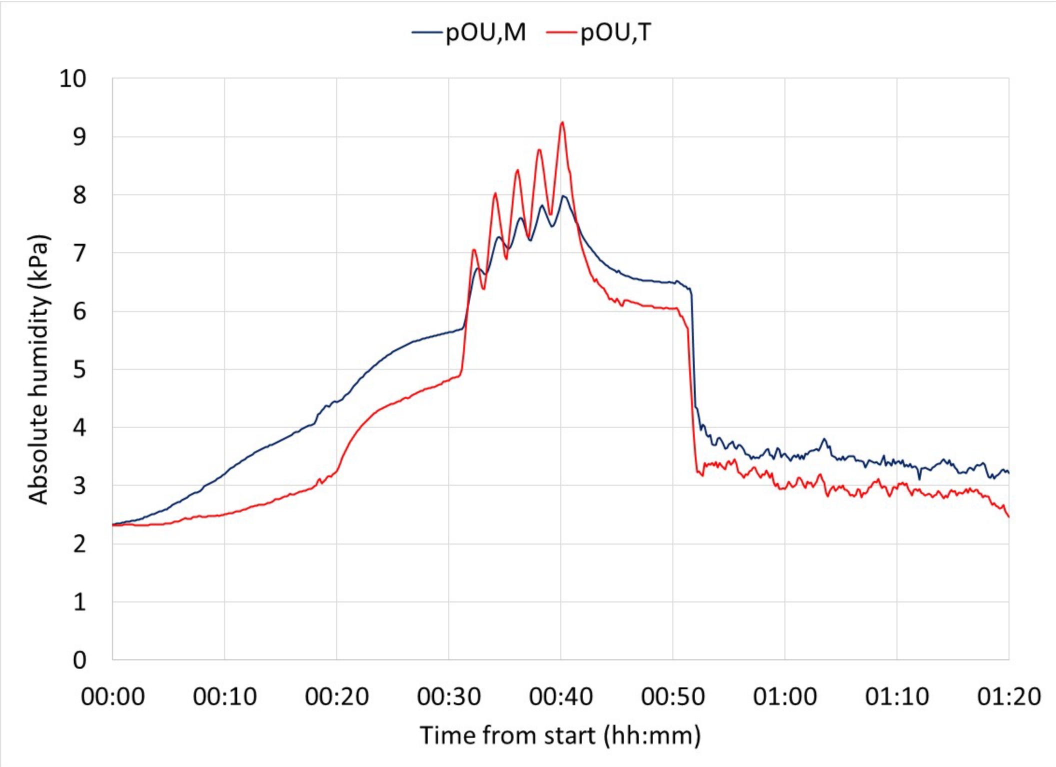
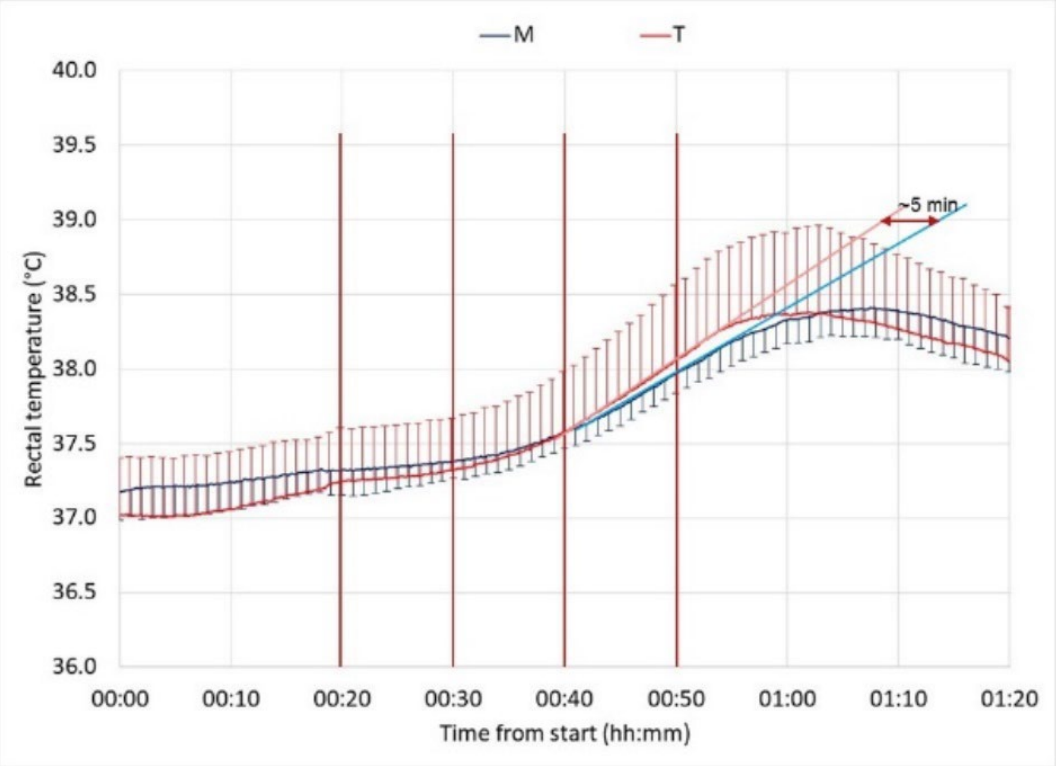


Figure 2.31 Absolute humidity as water vapour partial pressure between the clothing layers at the right upper arm measured on OU during the SIF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Rectal and mean body temperature

Figure 2.32 shows the dynamics of the temperature development in rectal temperatures, and Figure 2.33 in the mean body temperatures. The rectal temperature in Mod started on average at about 0.2 °C higher than in Trad, and it stayed higher during the whole prework period outside the chamber (the first 20 minutes), although the differences start to diminish from about the 10th minute. No differences nor changes, however, were significant. The average rectal temperatures were very similar during the first 10 minutes of the heat exposure with the rectal temperature in Trad staying slightly lower than in Mod. With the onset of the intermittent radiation, this started changing and the rectal temperature increase was quicker in Trad. By the end of the heat exposure, the rectal temperature in Trad was a bit higher than in Mod.



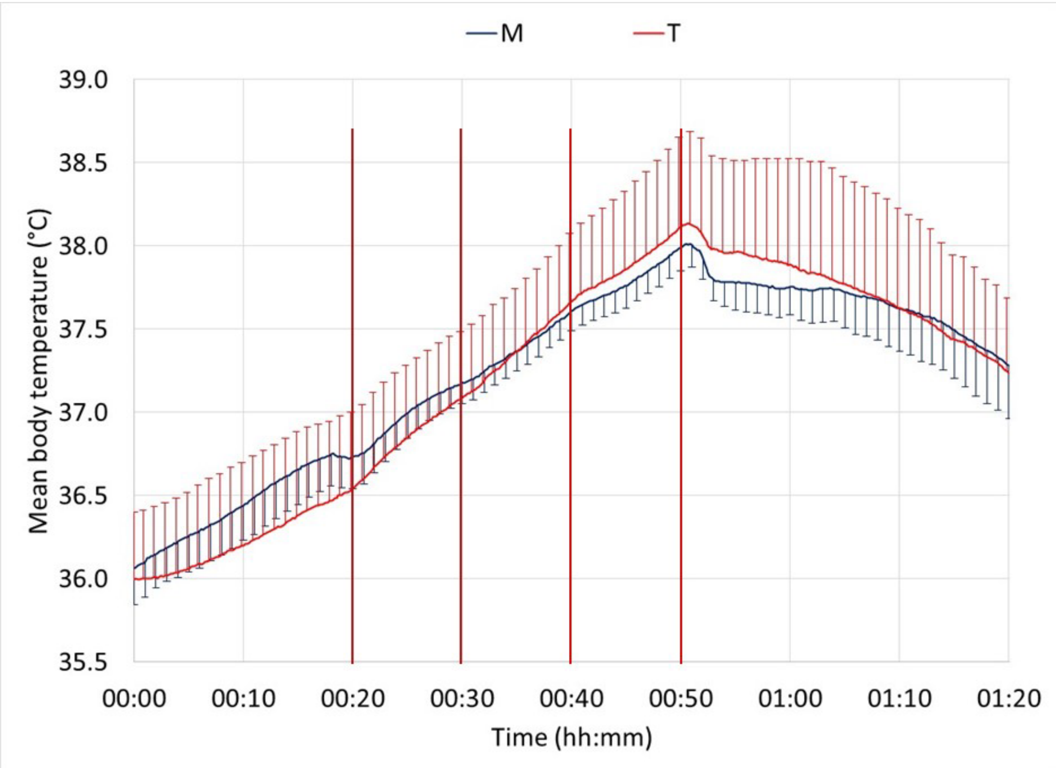
The first vertical red line marks entering the heat, the second one the start of intermittent heat radiation with 4 kW/m^2, the third one the end of intermittent radiation and the last one the end of the heat exposure and the start of the recovery period.

Figure 2.32 Rectal temperatures for the SIF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

If to consider a rectal temperature of 39 °C as an exposure termination criterion, and assuming the latest workload and environmental conditions stay at the same level, the rescue workers could continue working for 5 minutes longer in Mod than in Trad (Figure 2.32). At the same time, it can be observed that the maximal rectal temperature in Trad is reached only after about 10-12 minutes and in Mod after about 18 minutes into recovery (Figure 2.32) before it started reducing. This indicates that more heat was accumulated in the body when using clothing system Mod. The difference is partly related to the somewhat higher temperatures in Mod already at the start of the exposure.

Despite the shorter heat exposure, this after-rise of the rectal temperature in SIF is considerably longer than in TRW (Figure 2.12) and WLF (Figure 2.22). This can be explained by more heat during this extreme exposure being accumulated in the body superficial layers and muscles. Despite the increased evaporation from the skin when removing the jacket (see the sharp drop in skin temperature at the start of the recovery in Figure 2.28), heat still continues moving towards the body central areas by tissue conductivity and blood circulation. On average, the recovery time to reach a core temperature of 37.5 °C can be estimated to be over 1 hour in both cases, while the expected recovery time either to 37.5 or 38 °C seems to be considerably longer in Mod than in Trad. However, if we look at Figure 2.34 at temperature changes from the beginning and where the influence of different rectal start temperatures is eliminated, the exposure length in Mod can on average be even up to 10 minutes longer than in Trad, while the recovery trend is relatively similar in both systems. At the same time, we must consider that, in practice, if one dresses in more insulating clothes at the fire station then the body temperature will rise already before reaching the incident site.

The mean body temperature increase (Figure 2.33) reflects the increase in body heat content, and despite some differences between Mod and Trad the mean change is similar. This is also confirmed by the mean body temperature change (Figure 2.34).

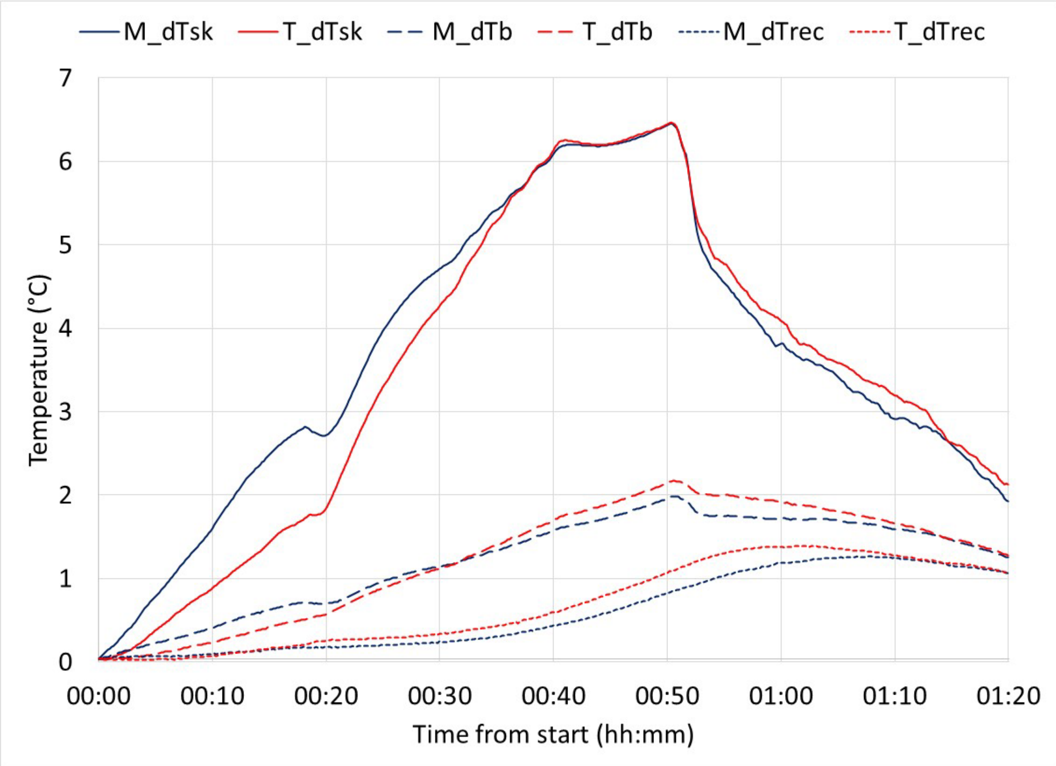


The first vertical red line marks the entering of heat, the second one the start of intermittent heat radiation with 4 kW/m^2, the third one the end of intermittent radiation, and the last one the end of heat exposure and the start of the recovery period.

Figure 2.33 Mean body temperatures for SIF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Temperature changes

Figure 2.34 shows the differences between Mod and Trad. Both the rectal and the mean body temperatures clearly show that Mod and Trad behave relatively similar, while the skin temperature development is quicker in Mod during prework at room temperature. This trend is reversed during exposure to extreme heat, showing better protection for Mod, especially under radiation load. The temperature development for the last part of the heat exposure is practically identical. Under recovery, the temperature differences between Mod and Trad in Tsk, Tb and Trec stay practically negligible.



dTsk – change in mean skin temperature; dTrec – change in rectal temperature; dTb – change in mean body temperature.

Figure 2.34 Change in critical temperatures for SIF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Body weight loss, evaporation and estimated accumulation in clothing system

As in TRW and WLF, the body weight loss and moisture accumulation in clothing in SIF was also higher in Mod than in Trad (Figure 2.35). Evaporation during pre-work outside the climate room was similar in both clothing combinations: in heat it was higher in Mod and during recovery higher in Trad. The high standard deviations in weight loss, moisture accumulation and in both highest evaporation values refer to big individual variation. Most likely, these significant differences can be related to the sweating capacity of the individuals in the groups of Mod and Trad.

The higher evaporation in Mod than in Trad during heat exposure is logical, as there is more moisture in the system. Yet, a clear discrepancy in evaporation is seen during recovery: Mod has a lower evaporation than Trad despite higher sweating and more moisture accumulation in the clothing layers. The only explanation could be that a large part of moisture was accumulated in the outer layers of Mod (double jacket, helmet and gloves). Unfortunately, the individual items were not weighed in this study. Therefore, some dedicated studies should look at this discrepancy closer.

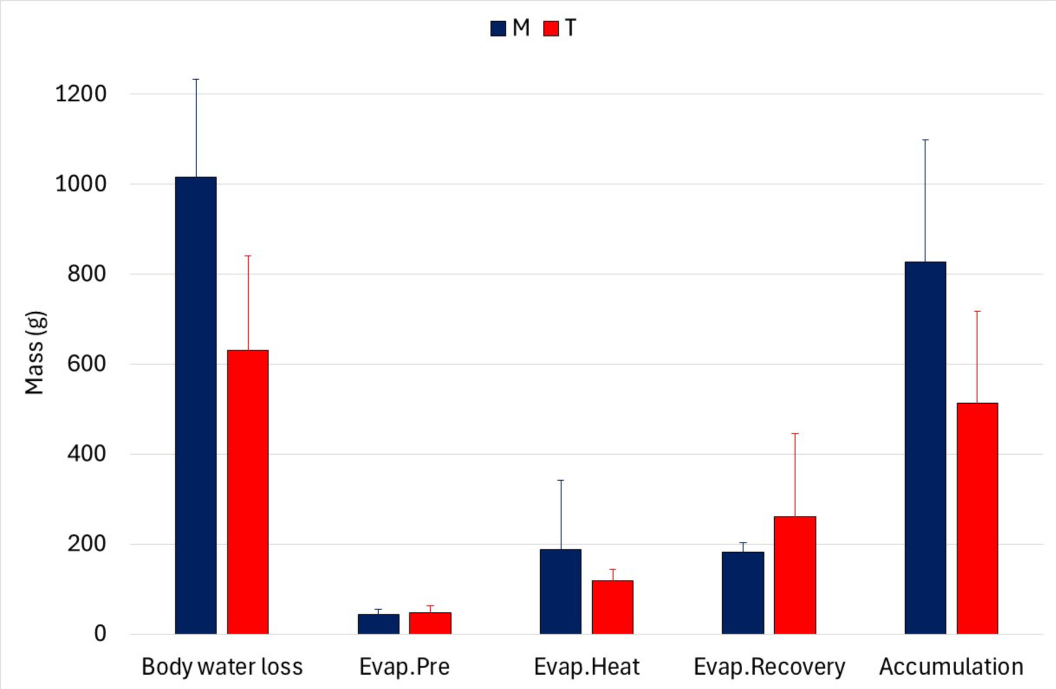


Figure 2.35 Weight loss, evaporation and estimated moisture accumulation in the clothing in the SIF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

Subjective responses

The thermal sensation was relatively similar in both clothing sets, with an increasing difference during the recovery period, where Mod was experienced to be warmer than Trad (Figure 2.36). This is confirmed by the comfort sensation, which became more different already in the middle of the heat exposure. The skin wetness sensation was higher in Mod than in Trad already from the start and increased significantly during recovery. In this way it confirmed the weight loss, evaporation and moisture accumulation data (Figure 2.35). At the same time, the perceived exertion in both clothing sets was similar (Figure 2.36), while in TRW (Figure 2.16) and WLF (Figure 2.26) the perceived exertion was somewhat higher in Trad. This indicates a similar load from the protective system, such as moving restrictions from clothes and the higher proportion of carrying the SCBA system.

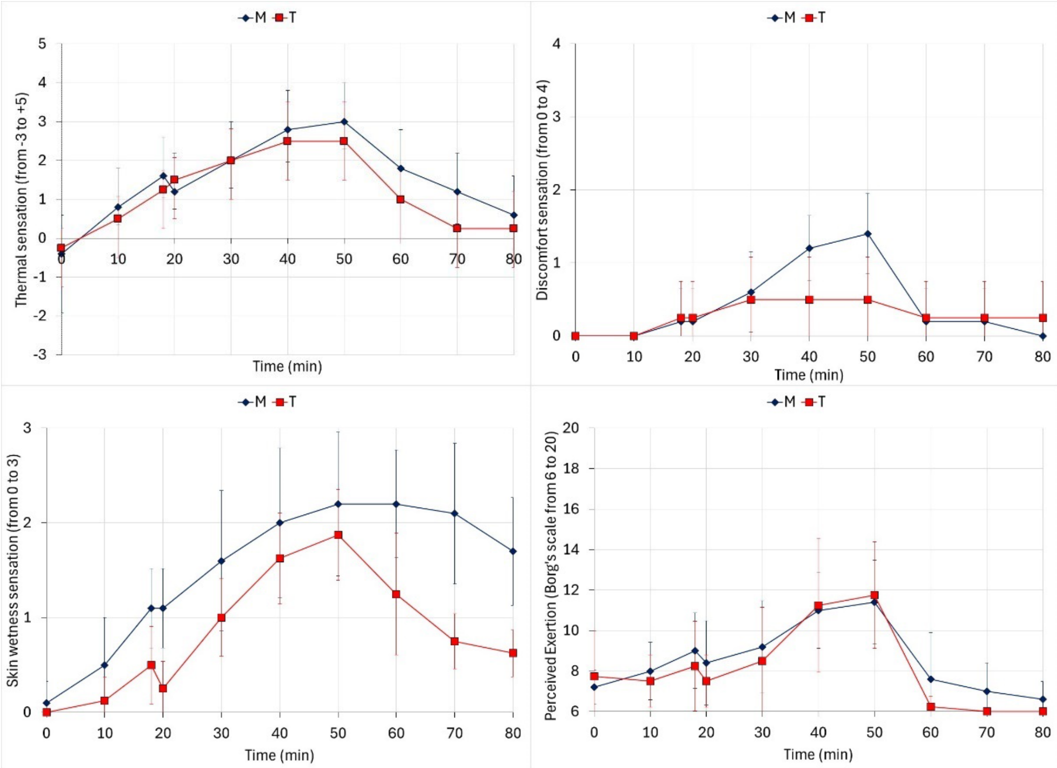


Figure 2.36 Subjective responses during the SIF scenario: M – modular clothing system Mod; T – traditional clothing system Trad

2.4 Usability of models

The collected data covered a wide range of exposure conditions and clothing combinations, making it a good base for validation of thermo-physiological prediction models. Three models were evaluated up to now of which the results are included in the annex of this report:

> Two versions of PHS (ISO 7933):
  – Lund University based modified online PHS (Annexes 1 and 5, Jacobs 2024, Jacobs et al. 2025a, Jacobs et al. 2025b, Kuldmäe 2025, Kuldmäe et al. 2025)
  – FAME Lab online PHS (Appendixes 2 and 5, Klomp 2024, Klomp et al. 2025a, Klomp et al. 2025b, Kuldmäe 2025, Kuldmäe et al. 2025)

> TAITherm™ from Thermoanalytics (Page et al. 2025a, Page et al. 2025b).

The PHS model is relatively simple to use. However, PHS predictions did sometimes follow TP data, but sometimes not. As PHS has been developed and validated for industrial use, and does not cover extreme exposures, high insulation and evaporative resistance of protective gear, a good enough match was not achieved between the conditions of the tests and PHS – where tasks are performed at human physiological limits. However, this study created a base for improving the PHS method to cover more extreme exposures. Thus, in order to use a PHS type of model for rescue service needs, it has to be modified or extended with specific algorithms that are matched to the incident scenarios.

TAITherm™ showed closer predictions but needs some adjustments too. For example, when clothing and equipment mass and related thermal inertia were considered, the predictions improved. However, the model input is more detailed and complex for random users. Thus, here a more simple or automatized input of clothing properties, environment and work-related parameters is needed. This requires access and automatic connection to detailed clothing properties' values from manikin measurements (see Kuklane et al. 2022 and 2024a), local weather data (similar to ClimApp, see Kingma et al. 2021) and input from incident development models.

3 Conclusions

3.1 Use of clothing system

This study examined two different clothing systems under three different conditions. The clothing systems consisted of the standard turnout suit with the operational uniform underneath (the traditional system, Trad) and a modular system consisting of the operational uniform with two layers over it. The first layer could be used for wildfire and technical rescue, with a second layer for interior firefighting (the modular system, Mod). Work was carried out with these two systems under simulated conditions, namely a technical rescue, a wildfire scenario, and an interior fire scenario. Heat buildup and evaporation resistance were measured for both clothing systems under these conditions.

No statistically significant differences in these parameters were observed between the two clothing systems during these experiments. This means that in this study no difference in heat strain was measured between the traditional suit and the modular clothing system in these three scenarios. However, a few caveats can be noted, which allows us to conclude that the modular system performs better and, moreover, allows for scaling up or down the layers depending on the task.

During the experiments, it was found that the ambient temperature during the measurements of the modular system in the climate chamber (during the wildfire scenario) was unintentionally 6 °C higher than during the experiments with the traditional system. Furthermore, due to circumstances, the study was unintentionally conducted with fewer subjects (8 instead of 10), resulting in a greater spread in the results, and the differences not always statistically significant. The following observations are important for interpreting the results:

- In the technical rescue scenario, work could be carried out longer in the modular system with lighter protection than in the traditional system.
- In the wildfire scenario, despite the more severe conditions (a higher ambient temperature of 6 °C), comparable heat stress was measured between the two systems.
- In the interior firefighting scenario, a combination of clothing layers with evaporation resistance comparable to that of the traditional system was worn in the modular system. This resulted in a comparable heat load.

3.2 Findings on physiological impact

- The individual variation was high. The data is good for modelling purposes, but does not allow for easy comparison of the clothing combinations as:
  - different persons wore different clothing systems (Mod versus Trad),
  - the number of test persons was low for such comparison (only 4 per system), and
  - the climate-controlled room and the preparation/recovery area conditions varied due to weather change and sudden problems with the climate room regulation close to the end of the test series.

- Local skin temperature at the upper arm did not exceed 43 °C in any exposure.
  - It is possible to estimate exposure times based on available studies when knowing clothing insulation.
  - Further analysis of these data is needed to settle the specific relationships between radiation power, local insulation and exposure duration.
- All test persons (TP) did quit the wildfire scenario. Some exposures were stopped because TP rectal temperature reached the set safety limit of 39 °C, and some because of TP request: the selected conditions in combination with the radiation load were leading to the individual tolerance limits.
  - The conditions were selected based on the preliminary modelling of the incidents and briefly adjusted according to the in literature reported field exposures. The used simplistic PHS model did work in some cases but not always.
- It can be roughly estimated that core temperature rise by 1 °C increases cardiovascular load by about 30 beats/min during medium heavy to heavy activity levels in heat.

3.3 Use of models

Three models were evaluated. Two models are relatively simple to use, but the predictions were not good enough because specific algorithms for incident scenarios of rescue workers are missing to get close predictions. One model showed more close predictions but also needs adjustments to give better predictions and the model is complicated to use.

Annex 1. PHS validation based on Lund University version

Jacobs, L. Validation of the modified predicted heat strain model for intermittent firefighter activities. BSc thesis report, VU Amsterdam, **2024**, pp. 43.

Abstract

Firefighters wear highly protective clothing to protect them against extremely warm conditions and dangerous situations. When combined with heavy physical activity, this can result in the development of heat stress. Heat stress prediction models can estimate the possible risk of heat-related illness in workers. A frequently used model is the Predicted Heat Strain (PHS) model. However, this model is not designed for firefighters with varying activity levels and high clothing thermal insulation values. This study aimed to investigate the validation of the modified PHS model for intermittent firefighting tasks during Technical Rescue Warm (TRW), Wildland Firefighting (WLF), and Structural Indoor Firefighting (SIF) scenarios. Four firefighters participated in this study. They underwent three different measurements with firefighter scenarios in a climate chamber. Total water loss (*TWL*), rectal temperature (*Trec*), and skin temperature (*Tsk*) were measured. Furthermore, the clothing of the firefighters was tested on a thermal manikin, to measure clothing properties. Both data were needed for the PHS model predictions. Before using the PHS model, the model was modified to make the input of intermittent activity and higher clothing insulation values possible. The experimental data was compared to the predicted data. The result was that the modified PHS model accurately predicted both *Trec* and *Tsk* in the SIF scenario (RMSD < SD). For the TWL, the model gave a good prediction in the TRW and WLF scenarios compared to the experimental data ($p > 0.05$). The PHS model does not provide accurate predictions in all scenarios. Therefore, the modified PHS model is not valid and suitable for individual firefighters.

Keywords: PHS model, heat stress, firefighters, protective clothing, intermittent activity, clothing thermal insulation

Annex 2. PHS validation based on FAME Lab version

Klomp, M.H. Predicted heat strain model validation for intermittent firefighter activities. BSc thesis report, VU Amsterdam, **2024**, pp. 48.

Abstract

Background: Firefighters face hazardous conditions that can induce negative physiological and psychological responses, leading to heat strain. The FAME Lab predicted heat strain model (PHSFL) enables the determination of heat strain while considering clothing properties.
Purpose: To validate the PHSFL model for three intermittent firefighter scenarios: Technical Rescue Warm (TRW), Wildland Firefighting (WLF), and Structural Indoor Firefighting (SIF).
Methods: Four firefighters (mean age 39 ± 14 years) performed three intermittent firefighter tasks with highly insulated clothing under varying hot environmental conditions. Rectal temperature (*Trec*), skin temperature (*Tsk*), and body water loss were measured, with clothing thermal insulation determined using a thermal manikin. PHSFL model predictions were compared with measured data.
Results: The PHSFL model underestimated *Trec* and *Tsk* in all scenarios and overestimated water loss for SIF. The discrepancies increased over time and were the largest for *Tsk*. Significant differences (mean ± SD) were observed at the end of exertion between measured and predicted *Trec*: TRW (38.23 ± 0.34 °C vs. 37.25 ± 0.27 °C), WLF (38.50 ± 0.58 °C vs. 37.23 ± 0.08 °C) and SIF (38.04 ± 0.51 °C vs. 37.52 ± 0.39 °C); and measured and predicted *Tsk*: TRW (34.06 ± 0.09 °C vs. 35.51 ± 0.10 °C), WLF (37.90 ± 0.85 °C vs. 36.03 ± 0.40 °C) and SIF (38.29 ± 0.72 °C vs. 36.05 ± 0.31 °C). SIF's predicted body water loss (1078 ± 269 g) exceeded significantly measured body water loss (630 ± 209 g). Root mean square deviation (RMSD) showed unacceptable predictions for TRW and WLF, while there was alignment for *Tsk* during SIF.
Conclusion: The PHSFL model is not valid for intermittent firefighter activities. A new ISO standard is necessary to prevent heat strain in firefighters. Adjustments to the PHSFL model are crucial for realistic predictions under specific initial conditions.

Keywords: firefighters, intermittent activities, physiological measurements, clothing ensembles, PHSFL model, validation PHSFL, thermal manikin

Annex 3. A study in structural firefighting scenario with different clothing and without radiation

Ambo, E. Thermo-physiological suitability of rescuer´s protective clothing. MSc thesis report, Estonian University of Life Sciences, **2024**, pp. 46.

Abstract

The aim of this master's thesis was to determine whether it is more optimal, from the perspective of reducing a firefighter's heat load, to go on a call-out in the station wear (strategy 1) and add protective clothing according to the nature of the call or to go on a call-out in protective clothing worn over the special clothing (strategy 2). To accomplish this task, an experiment simulating a building fire scenario was conducted, during which comparable thermo-physiological parameters were collected using the Estonian firefighter's station wear and protective clothing "TAURUS." Knowing the properties of clothing sets is crucial because, in addition to functionality, the clothing must be safe for the wearer and as optimal as possible. By understanding how the clothing affects the wearer, it is possible to prevent and reduce the risk of heat stress caused by the clothing. To achieve the goal, prior scientific literature was reviewed, and practical knowledge was gathered by conducting experiments with firefighters in the Netherlands. The experiment involved physical exertion, starting with pre-work on a bicycle ergometer at $T_a = 23 \pm 2$ °C with a relative humidity of $\varphi = 33 \pm 5\%$. Exposure to heat took place in a climate chamber while walking on a treadmill at $T_a = 45 \pm 1$ °C and a relative humidity of $\varphi = 26 \pm 5$ %. The air movement speed in the climate chamber during the experiment was 0.12 to 0.13 m/s. The experiment concluded with recovery, sitting on a chair at $T_a = 23 \pm 2$ °C with a relative humidity of $\varphi = 33 \pm 5\%$. A total of eight volunteer subjects participated in the experiments, n = 8. Data were collected through skin temperature, rectal temperature, heart rate, and weighing the individuals/clothing. An important finding was that upon exiting the heat, the rectal temperature does not start to drop immediately, as the heat begins to accumulate internally, and it can rise to a critical 39 °C within 20 minutes of exposure to heat. Detailed weighing of the clothing revealed that the most fluid accumulates in the special clothing jacket and sweatpants. The results indicate that with strategy 1, the firefighter's performance improves by 1,5 times that is reflected in possible longer exposure to the heat, shorter time for recovery etc. Therefore, it is recommended to do pre-work in station wear and add protective clothing along with the necessary equipment when entering a hot environment. During recovery, as many clothes as possible should be removed, but care must be taken to avoid cold-related illnesses.

Keywords: firefighters, heat stress, climatic chamber, hot environment, building fire, smoke diving

Annex 4. A study in wildland firefighting scenario with different clothing and without radiation

Kaaver, S. Physiological impact of Estonian rescue workers´ protective clothing on heat strain development during simulated wildland firefighting activities. MSc thesis report, Estonian University of Life Sciences, **2025**, pp. 97.

Abstract

Wildland firefighting presents significant physiological challenges due to extreme environmental conditions and prolonged operations. Working for extended periods in hot environments while wearing protective clothing induces heat stress and increases the risk of occupational injuries. Protective clothing also affects cardiovascular function and is associated with changes in metabolic processes, which in turn influence physical endurance and performance. The aim of this master’s thesis was to assess the impact of protective clothing systems used by Estonian firefighters (Red Fox RF-504 and Taurus), both compliant with the EN 469 standard, as well as the undergarments worn beneath them (station wear), on firefighters’ physiological responses and work capacity during a wildland firefighting simulation.

Methods. The experiment was conducted in a climate-controlled chamber at the Institute of Sports Sciences and Physiotherapy, University of Tartu. The experimental group consisted of male professional firefighters (n = 12), who participated in the trial wearing two different protective clothing systems: Taurus (n = 6) and Red Fox RF-504 (n = 6). The tests were conducted with two types of protective clothing configurations: in the “heavy” series, participants wore underwear shorts, a T-shirt, and station wear (blouson and sweatpants) underneath the protective clothing, and in the “light” series, they wore only underwear shorts and a T-shirt provided by the employer under the turnout gear. Heat exposure took place at an ambient temperature (Ta) of 35,9 ± 0,3 ºC and relative humidity (φ) of 36,0 ± 1,8 %, followed by a recovery phase outside the chamber at Ta = 23,3 ± 0,2 ºC and φ = 41,9 ± 1,9 %. Air velocity (va) remained below 0,15 m/s throughout the trial. The test protocol consisted of continuous treadmill walking at varying speeds: 2,1 km/h (0–10 min), 3,5 km/h (10–25 min), 4,5 km/h (25–40 min), 3,5 km/h (40–55 min), 4,5 km/h (55–70 min) and 2,1 km/h (70–80 min). After exiting the heat, the test persons removed their gloves, helmet, baclava and firefighting jacket. During the recovery period (80–110 min), they were seated. The recorded data included heart rate, rectal (representing body core temperature), and skin temperature, and based on these the mean body temperature was calculated, subjective ratings were collected and sweat evaporation and fluid loss were assessed by weighing the test persons with and without clothes. Skinfold thickness was measured for calculation of body fat percentage, and body mass index (BMI) was calculated. Aerobic and anaerobic work capacity was measured in these test persons who agreed to do the maximal capacity test (n = 9).

The analysis of the results showed that protective clothing systems with the station wear (heavy) caused greater increases in rectal, body, and skin temperatures, longer recovery times, and greater fluid loss compared to light one ($p < 0,05$). In contrast, light protective clothing systems were associated with lower measured temperatures and subjective ratings indicated greater comfort. The results confirmed that, in hot environmental conditions, lighter protective clothing should be preferred, and that reducing the number of clothing layers during the recovery phase is advisable to promote more efficient body cooling. It is important to note that the higher number of test terminations in the protective clothing conditions with station wear suggests that the additional clothing layers caused greater discomfort and earlier cessation during heat exposure, likely hindering heat dissipation.
Keywords: wildland firefighting, protective clothing, heat strain, thermal insulation, physiological strain

Annex 5. PHS validation based on the conditions without radiation

Kuldmäe, G. Validation on the Predicted Heat Strain model (PHS) for assessing firefighters' heat stress in wildland and structural fire situations. MSc thesis report, Estonian University of Life Sciences, **2025**, pp. 86.

Abstract

The aim of this research was to evaluate the validity of the Predicted Heat Strain model (PHS) based on the experimental results performed in a simulated wildland and structural fire scenario by comparing measured and modelled physiological parameters. Methodology: During the validation, two online versions of the heat strain model, PHS-LU and PHS-FL, were utilized while considering the effects of so called light and heavy (without and with station wear) combinations of the Red Fox and Taurus protective clothing systems. These two turnout gear systems were used with and without the use of station wear in wildland firefighting scenario, and with and without the use of turnout gear during the simulated prework in structural firefighting scenario. The subjects' rectal and skin temperatures, body fluid loss, and evaporation were compared. In the event of a structural fire, the situation was considered “light” (Strategy 1) if, during the preparatory work, the person was wearing station wear, including a T-shirt and underwear. In the case of a “heavy” condition (Strategy 2), firefighter protective clothing – i.e., turnout gear – was worn on top of the station wear already during prework simulation. Results: In simulated wildland firefighting scenario, the PHS-FL model consistently underestimated the rectal temperature increase and fluid loss of a rescue worker. The PHS-LU model was more accurate for higher physical exertion, especially for Red Fox heavy and Taurus heavy conditions, where no significant differences appeared between the actual and projected values. However, there was a noticeable underestimation of the rectal and skin temperatures in Taurus light condition. The simulated structural firefighting scenario showed a similar trend as the wildland firefighting scenario. The PHS-FL model predicted that the rectal temperature of the rescue worker would be significantly lower and that it would stabilize earlier in time compared to measured under experimental conditions where it did not stabilize during heat exposure. In terms of skin temperature, the predictions of both models were significantly lower than the actual values of the test subjects. Also, the PHS-FL model significantly underestimated the body's fluid loss. The PHS-LU model was once again more accurate in the conditions of structural fire scenario in both Red Fox and Taurus heavy conditions. However, there was an underestimation in the light condition while using this protective clothing system, especially during the recovery period. The models were unable to realistically reflect the evaporation of the body. The PHS-LU model predicted evaporation to be systematically lower than it was actually measured in test subjects. Because the results showed that neither model was able to predict physiological changes in the body with sufficient accuracy under the observed conditions, then both model versions should be improved. The dynamics of the physiological parameters of the rescue worker while acting at the fire incident site must be taken into account in order to prevent excessive values of rectal and skin temperatures and fluid loss (evaporation) indicators. The combination of protective clothing (light, heavy) depending on

the fire scenario plays an important role. Conclusions: Both model versions (PHS-LU and PHS-FL) need improvements in order to predict the dynamics of the physiological parameters of the firefighters while performing their tasks, in order to prevent the organism from exceeding the thresholds of physiological parameters in different rescue scenarios. The use of station wear under protective clothing layers (light, heavy) is important to consider, as it is vital for the occupational safety of rescue workers.
Keywords: fire scenario, predicted heat stress model, ISO 7933, protective clothing, rescue worker

Publications and presentations related to work with modular protection concept

Ambo, E. Thermo-physiological suitability of rescuer´s protective clothing. MSc thesis report, Estonian University of Life Sciences, **2024**, pp. 46, http://hdl.handle.net/10492/9280.

Ambo, E., Reinvee, M., Purge, P., Kuklane, K. Heat stress in simulated structural firefighting scenarios utilizing two types of dressing strategies. Eds. Kutlu, B., Kartal, G.E., Türkoğlu, G.C. Proceedings of the 11th European Conference on Protective Clothing, Kuşadası - Aydın, Turkey, May 20-23, **2025**, p. 79-82, https://doi.org/10.5281/zenodo.17472264.

Bröde, P.; Kuklane, K.; Havenith, G. Requirements for benchmarking the ergonomics of PPE systems. 9th European Conference on Protective Clothing, online, Stuttgart, Germany, May 10-12, **2021**, 106-107, https://es-pc.eu/media/attachments/2022/11/24/9th-ecpc.pdf.

Eggeling, J.; Toma, R.; Kuklane, K. A new approach to estimate Ret values. Eds. Kuklane, K., Mertens, C. Proceedings of the 10th European Conference on Protective Clothing, Arnhem, Netherlands, May 9-12, **2023**, p. 66-67, https://nipv.nl/wp-content/uploads/2023/05/20230508-NIPV-ESPC-Proceedings-of-the-10th-European-Conference-on-Protective-Clothing.pdf.

Heus, R.; Catoire, M. Compatibility and ergonomic standards for personal protective clothing and other PPE. ECPC preceding webinar nr. 3, casted online, Netherlands, December 14, **2022**.

Heus, R.; Kingma, B.R.M.; van Berlo, B.M.A.; Mol, D.; Daanen, H.A.M.; Kuklane, K. The protective performance of process operators' protective clothing and exposure limits under low thermal radiation conditions. *Biology* **2022**, *11*, 1222, https://doi.org/10.3390/biology11081222.

Heus, R.; Kingma, B.R.M.; Mol, D.; Kuklane, K. Protection of process operators against heat radiation. 9th European Conference on Protective Clothing, online, Stuttgart, Germany, May 10-12, **2021**, 170-171, https://es-pc.eu/media/attachments/2022/11/24/9th-ecpc.pdf.

Heus, R.; Kuklane, K. Beschermende kleding brandweer. Deel 1 kledingeigenschappen. NIPV rapport. Nederlands Instituut Publieke Veiligheid (NIPV), p. 50, **2025**, https://nipv.nl/wp-content/uploads/2025/09/20250818-NIPV-Beschermende-kleding-brandweer-deel-1-kledingeigenschappen.pdf.

Jacobs, L. Validation of the modified predicted heat strain model for intermittent firefighter activities. BSc thesis report, VU Amsterdam, **2024**, pp. 43.

Jacobs, L.M.G., Klomp, A.M.H., Daanen, H.A.M., Kuklane, K. Heat stress prediction for simulated wildland firefighting. ThermoNED, Delft, Netherlands, April 11, **2025**a.

Jacobs, L.M.G., Klomp, A.M.H., Daanen, H.A.M., Kuklane, K. Heat stress prediction for simulated wildland firefighting. Editors: Olt, J., Kikas, T., Meneses, L. Book of Abstracts. 15th International Conference on Biosystems Engineering, May 7-9, **2025**b, Tartu, Estonia, p.34, http://hdl.handle.net/10492/9611.

Kaaver, S. Physiological impact of Estonian rescue workers´ protective clothing on heat strain development during simulated wildland firefighting activities. MSc thesis report, Estonian University of Life Sciences, **2025**, pp. 97, http://hdl.handle.net/10492/9994.

Kaaver, S., Kuklane, K. Physiological impact of rescue workers' protective clothing on heat stress development during simulated wildland firefighting activities. University master students conference, Estonian University of Life Sciences, Tartu, Estonia, April 24, **2025**.

Kaaver, S., Purge, P., Kuklane, K. Physiological impact of rescue workers' protective clothing on heat stress development during simulated wildland firefighting activities. . Eds. Kutlu, B., Kartal, G.E., Türkoğlu, G.C. Proceedings of the 11th European Conference on Protective Clothing, Kuşadası - Aydın, Turkey, May 20-23, **2025**, p. 83-86, https://doi.org/10.5281/zenodo.17472264.

Kingma, B.R.M.; Steenhoff, H.; Toftum, J.; Daanen, H.A.M.; Folkerts, M.A.; Gerrett, N.; Gao, C.; Kuklane, K.; Petersson, J.; Halder, A.; Zuurbier, M.; Garland, S.W.; Nybo, L. ClimApp – integrating personal factors with weather forecasts for individualised warning and guidance on thermal stress. *Int. J. Environ. Res. Public Health* **2021**, *18*, 11317. https://doi.org/10.3390/ijerph182111317.

Klomp, M.H. Predicted heat strain model validation for intermittent firefighter activities. BSc thesis report, VU Amsterdam, **2024**, pp. 48.

Klomp, A.M.H., Jacobs, L.M.G., Daanen, H.A.M., Kuklane, K. Heat stress prediction for simulated technical rescue activities. Eds. Kutlu, B., Kartal, G.E., Türkoğlu, G.C. Proceedings of the 11th European Conference on Protective Clothing, Kuşadası - Aydın, Turkey, May 20-23, **2025**a, p. 39-42, https://doi.org/10.5281/zenodo.17472264.

Klomp, A.M.H., Jacobs, L.M.G., Daanen, H.A.M., Kuklane, K. Heat stress prediction for simulated structural firefighting. Proceedings of the 13th International Manikin & Modelling Meeting (I3M) and The Clothing and Textile Sciences Research Meeting, Wilson College of Textiles, NC State, Raleigh, USA, Oct. 15-17, **2025**b, p. 121-131, https://doi.org/10.52750/825607.

Krause, R.; Kuklane, K.; Kemmeren, M.; Gries, T. Europäische nutzerumfrage zu smarter persönliche schutzausrüstung für feuerwehreinsatzkräfte. *Crisis Prevention* **2021**, *3*, 34-39 (in German).

Kuklane, K. EN ISO 15831 Clothing — Physiological effects — Measurement of thermal insulation by means of a thermal manikin. Invited lecture at European Commission workshop on EN ISO 15831:2004, Study on the inclusiveness of anthropometrics in European harmonised standards, Etterbeek, Belgium, October 13, **2023**.

Kuklane, K. Firefighter clothing database: preliminary modelling and exposure predictions. In eds. Kuklane, K., Mertens, C. Proceedings of the 10th European Conference on Protective Clothing, Arnhem, Netherlands, May 9-12, **2023**, p. 48-49, https://nipv.nl/wp-content/uploads/2023/05/20230508-NIPV-ESPC-Proceedings-of-the-10th-European-Conference-on-Protective-Clothing.pdf.

Kuklane, K. Modular protection concept for firefighter protective clothing system. Invited lecture at FITI, Seoul, Republic of Korea, June 10, **2024**.

Kuklane, K. Modular protection concept – starting up the work with future protective clothing for Dutch firefighters. ECPC preceding webinar nr. 2, casted online from Zoetermeer, Netherlands, May 25, **2022**.

Kuklane, K. New guidelines for selection, use, care and maintenance of smart garments protecting against heat and flame. 9th European Conference on Protective Clothing, online, Stuttgart, Germany, May 10-12, **2021**, 92-93, https://es-pc.eu/media/attachments/2022/11/24/9th-ecpc.pdf.

Kuklane, K. The climatic conditions at work: Ergonomics of the protective clothing. Invited lecture on World Ergonomics Day, Estonian University of Life Sciences, Tartu, Estonia, October 21, **2022**.

Kuklane, K. Thermal manikin measurements – the effect of size and fit on thermal performance of clothing. Invited lecture at European Commission workshop on EN ISO 15831:2004, Study on the inclusiveness of anthropometrics in European harmonised standards, Etterbeek, Belgium, October 13, **2023**.

Kuklane, K.; Eggeling, J.; Kemmeren, M.; Heus, R. A database of static thermal insulation and evaporative resistance values of Dutch firefighter clothing items and ensembles. *Biology* **2022**, *11*, 1813, https://doi.org/10.3390/biology11121813.

Kuklane, K.; Eggeling, J.; Kemmeren, M.; Heus, R. Local effects of printed logos and reflective striping fixed to firefighter clothing material packages under low radiation exposure. *Ind. Health* **2022**, *61*(5), https://doi.org/10.2486/indhealth.2022-0126.

Kuklane, K.; Kemmeren, M.; Kistemaker, L.; Heus, R. Physiological and subjective responses during fire training. 9th European Conference on Protective Clothing, online, Stuttgart, Germany, May 10-12, **2021**, 90-91, https://es-pc.eu/media/attachments/2022/11/24/9th-ecpc.pdf.

Kuklane, K.; Kemmeren, M.; Kistemaker, L.; Heus, R. Skin temperature measurements and subjective responses during flue gas cooling experiment. *The Catalyst* **2022**, *Q4*, 42-45, https://fliphtml5.com/hglao/eyne/2022_-_Catalyst_Q4/.

Kuklane, K.; Klomp, A.M.H.; Jacobs, L.M.G.; Heus, R. A size smaller accessory on top of firefighter protective clothing leads to higher risks. CLOTECH 2024, 15th Joint International Conference on Innovation in Clothing, Dresden, Germany, September 5-6, **2024**.

Kuklane, K.; Klomp, A. M.; Jacobs, L. M.; Heus, R. Thermal protective properties of a firefighter turnout gear with and without an accessory on top of turnout jacket. *Communications in Development and Assembling of Textile Products* **2024**, *5*(2), 242–254. https://doi.org/10.25367/cdatp.2024.5.p242-254.

Kuklane, K.; Levels, K.; de Weerd, M.; Teunissen, L.; Eggeling, J.; Kemmeren, M. Comparison of clothing measurements on 2 manikins in the light of size and fit. Eds. Kuklane, K., Mertens, C. Proceedings of the 10th European Conference on Protective Clothing, Arnhem, Netherlands, May 9-12, **2023**, p. 60-61, https://nipv.nl/wp-content/uploads/2023/05/20230508-NIPV-ESPC-Proceedings-of-the-10th-European-Conference-on-Protective-Clothing.pdf.

Kuklane, K.; Levels, K.; de Weerd, M.; Teunissen, L.; Eggeling, J.; Kemmeren, M. Thermo-physiological properties of Dutch firefighters' clothing systems – comparison of results from 2 manikins. ThermoNED, Soesterberg, Netherlands, April 1, **2022**.

Kuklane, K.; Levels, K.; Kistemaker, L.; Mol, E.; Tanck, I.; Heus, R. Firefighters' skin temperatures in three simulated incident scenarios: A comparison of 4- and 8-point based mean skin temperature calculations. ThermoNED, Nijmegen March 1, **2024**.

Kuklane, K.; Levels, K.; Kistemaker, L.; Mol, E.; Tanck, I.; Heus, R. Heat stress prediction for simulated rescue activities. Eds. Lee, J.-Y., Kim, D.-H. Proceedings of the 20th International Conference on Environmental Ergonomics, Jeju, Republic of Korea, June 3-7, **2024**, p. 145-146, https://ndownloader.figstatic.com/files/47045731.

Kuklane, K., Levels, K., Kistemaker, L., Tanck, I., Mol, E., Kemmeren, M., Heus, R. Heat stress under simulated technical rescue activities. Eds. Kutlu, B., Kartal, G.E., Türkoğlu, G.C. Proceedings of the 11th European Conference on Protective Clothing, Kuşadası - Aydın, Turkey, May 20-23, **2025**, p. 51-54, https://doi.org/10.5281/zenodo.17472264.

Kuklane, K.; Toma, R. Common clothing area factor estimation equations are inaccurate for highly insulating (Icl>2 clo) and non-western loose-fitting clothing ensembles. *Ind. Health* **2021**, *59*, 107-116. https://doi.org/10.2486/indhealth.2020-0209.

Kuklane, K.; Toma, R. Validation of ISO 9920 clothing item insulation summation method based on an ambulance personnel clothing system. *Ind. Health* **2021**, *59*, 27-33, https://doi.org/10.2486/indhealth.2020-0208.

Kuldmäe, G. Validation on the Predicted Heat Strain model (PHS) for assessing firefighters' heat stress in wildland and structural fire situations. MSc thesis report, Estonian University of Life Sciences, **2025**, pp. 86, http://hdl.handle.net/10492/9990.

Kuldmäe, G., Kuklane, K., & Merisalu, E. Kuumastressi mudeli valideerimine päästetööde tarbeks simuleeritud kliimakambri katsete baasil. (Validation of a heat strain model for assessing rescue activities based on climate chamber tests.) In Estonian. University master students conference, Estonian University of Life Sciences, Tartu, Estonia, April 24, **2025**.

Levels, K.; Kuklane, K.; Mol, E.; Kistemaker, L.; Tanck, I.; Heus, R. Validity of the heart rate-based ECTemp algorithm to estimate core temperature during simulated firefighting scenarios. Eds. Lee, J.-Y., Kim, D.-H. Proceedings of the 20th International Conference on Environmental Ergonomics, Jeju, Republic of Korea, June 3-7, **2024**, p. 149-150, https://ndownloader.figstatic.com/files/47045731.

Page, S.C., Hepokoski, M.A., Golubev T., Kuklane, K. Predicting the effectiveness of technical rescue gear with thermal modelling software. Eds. Kutlu, B., Kartal, G.E., Türkoğlu, G.C. Proceedings of the 11th European Conference on Protective Clothing, Kuşadası - Aydın, Turkey, May 20-23, **2025**a, p. 59-62, https://doi.org/10.5281/zenodo.17472264.

Page, S.C., Hepokoski, M.A., Golubev T., Kuklane, K. Predicting the effectiveness of structural internal firefighting gear using computational thermal modeling. Proceedings of the 13th International Manikin & Modelling Meeting (I3M) and The Clothing and Textile Sciences Research Meeting, Wilson College of Textiles, NC State, Raleigh, USA, Oct. 15-17, **2025**b, p. 14, https://doi.org/10.52750/825607.

Van Harten, T. Ergonomic and performance differences between firefighter protective clothing systems. MSc thesis report, VU Amsterdam, **2023**, pp. 53.

Van Harten, T; Kuklane, K.; Heus, R.; Daanen, H.A.M. Ergonomic and performance differences between firefighter protective clothing systems. Eds. Kuklane, K.; Mertens, C. Proceedings of the 10th European Conference on Protective Clothing, Arnhem, Netherlands, May 9-12, **2023**, 154-155, https://nipv.nl/wp-content/uploads/2023/05/20230508-NIPV-ESPC-Proceedings-of-the-10th-European-Conference-on-Protective-Clothing.pdf

References

Aljaroudi, A.M.; Bhattacharya, A.; Strauch, A.; Quinn, T.D.; Williams, W.J. Effect of cooling on static postural balance while wearing firefighter's protective clothing in hot environment. *Int. J. Occup. Saf. Ergon.* **2022**, *29*(4), 1460–1466, https://doi.org/10.1080/10803548.2022.2138142.

Ambo, E., Reinvee, M., Purge, P., Kuklane, K. Heat stress in simulated structural firefighting scenarios utilizing two types of dressing strategies. Eds. Kutlu, B., Kartal, G.E., Türkoğlu, G.C. Proceedings of the 11th European Conference on Protective Clothing, Kuşadası - Aydın, Turkey, May 20-23, **2025**, p. 79-82, https://doi.org/10.5281/zenodo.17472264.

Borg, G. Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise* **1982**, *14*(5), 377–381.

Carballo-Leyenda, B.; Ferreiro-González, M.; Aliaño-González, M.J. (2022). Perceptions of Heat Stress, Heat Strain and Mitigation Practices in Wildfire Suppression across Southern Europe and Latin America. International Journal Of Environmental Research And Public Health, 19(19), 12288, https://doi.org/10.3390/ijerph191912288.

Carballo-Leyenda, B.; Villa, J.G.; López-Satué, J; Rodríguez-Marroyo, J.A. Impact of different personal protective clothing on wildland firefighters' physiological strain. *Frontiers in physiology* **2017**, *8*, 618, https://doi.org/10.3389/fphys.2017.00618.

Chaui-Berlinck, J.G.; Alves Monteiro, L.H.; Navas, C.A.; Bicudo, J.E.P.W. Temperature effects on energy metabolism: A dynamic system analysis. *Proceedings of the Royal Society B: Biological Sciences*, **2002**, *269*(1486), 15–19, https://doi.org/10.1098/rspb.2001.1845.

De Freitas, C.R.; Grigorieva, E.A. A comprehensive catalogue and classification of human thermal climate indices. *International Journal of Biometeorology* **2014**, *59*(1), 109–120, https://doi.org/10.1007/s00484-014-0819-3.

Dorman, L.E. The effects of protective clothing and its properties on energy consumption during different activities. *Doctoral Thesis*, Loughborough University, Loughborough, UK, March **2007**.

Dorman, L.E.; Havenith, G. The effects of protective clothing on energy consumption during different activities. *European Journal of Applied Physiology*, **2009**, *105*, 463–470.

Durnin, J.V.G.A.; Womersley, J. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br J Nutrition* **1974**, *32*, 77-97.

Eggenberger, P.; MacRae, B.A.; Kemp, S.; Bürgisser, M.; Rossi, R.M.; Annaheim, S. Prediction of core body temperature based on skin temperature, heat flux, and heart rate under different exercise and clothing conditions in the heat in young adult males. *Frontiers in Physiology* **2018**, *9*, https://doi.org/10.3389/fphys.2018.01780.

EN 17528:2022 Clothing - Physiological effects - Measurement of water vapour resistance by means of a sweating manikin. European Committee for Standardization: Brussels, Belgium.

EN 17558:2023 Ergonomics – Ergonomics of PPE ensembles. European Committee for Standardization: Brussels, Belgium.

EN 469:2020 Protective clothing for firefighters — Performance requirements for protective clothing for firefighting activities. European Committee for Standardization: Brussels, Belgium.

Esfahani, B.H.; Li, R.; Zhang, M.; Eike, R.; Etemadzadeh, M.; Song, G. Enhancing firefighter hoods: innovations, challenges, and future directions in PPE design. *Textile Progress* **2025**, *57*(2), 73–116. https://doi.org/10.1080/00405167.2025.2528501

Færevik, H.; Reinertsen, R. E. Effects of wearing aircrew protective clothing on physiological and cognitive responses under various ambient conditions. *Ergonomics* **2003**, *46*(8), 780–799. https://doi.org/10.1080/0014013031000085644

Fullagar, H.; Schwarz, E.; Richardson, A.; Notley, S. R.; Lu, D.; Duffield, R. Australian firefighters perceptions of heat stress, fatigue and recovery practices during fire-fighting tasks in extreme environments. *Applied Ergonomics* **2021**, *95*, 103449. https://doi.org/10.1016/j.apergo.2021.103449

Gagge, A.P.; Nishi, Y. Heat exchange between human skin surface and thermal environment. *Comprehensive physiology* **1977**, 69-92.

Gebhardt, H.; Müller, B.H.; Hettinger, T.; Pause, B. *Physiologische Bewertung von Strahlungsheizungen*. [Physiological assessment of infrared radiators], in German. Bremerhaven, Germany: Wirtschaftsverlag N. W. Verlag für neue Wissenschaft, **1995**.

Givoni, B.; Goldman, R.F. Predicting metabolic energy cost. *Journal of Applied Physiology* **1971**, *30*(3), pp. 429–433.

Havenith, G.; Fiala, D. Thermal indices and thermophysiological modeling for heat stress. *Comprehensive Physiology Wiley Online Library*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, **2016**, *6*, 255–302. https://doi.org/10.1002/cphy.c140051.

Havenith, G.; Heus, R. A test battery related to ergonomics of protective clothing. *Appl. Ergon*. **2004**, *35*, 3–20. https://doi.org/10.1016/j.apergo.2003.11.001.

Heus R. Exposure to smoke. An overview report of the studies to exposure routes, contamination and cleaning of turn-out gear and the skin barrier function. Arnhem, Instituut Fysieke Veiligheid, **2018**, pp. 50

Heus, R.; den Hartog, E. Maximum allowable exposure to different heat radiation levels in three types of heat protective clothing. *Ind. Health* **2017**, *55*, 529–536, https://doi.org/10.2486/indhealth.2017-0137

Heus, R.; Kingma, B.R.M.; van Berlo, B.M.A.; Mol, D.; Daanen, H.A.M.; Kuklane, K. The protective performance of process operators' protective clothing and exposure limits under low thermal radiation conditions. *Biology* **2022**, *11*, 1222, https://doi.org/10.3390/biology11081222.

Heus, R.; Kuklane, K. Beschermende kleding brandweer. Deel 1 kledingeigenschappen. NIPV rapport. Nederlands Instituut Publieke Veiligheid (NIPV), p. 50, **2025**, https://nipv.nl/wp-content/uploads/2025/09/20250818-NIPV-Beschermende-kleding-brandweer-deel-1-kledingeigenschappen.pdf.

Holmér, I.; Kuklane, K.; Subzero project group. Subzero project: validation of IREQ predictions with results from wearer trials and manikin measurements. In: 2nd European Conference on Protective Clothing (ECPC) and NOKOBETEF 7: Challenges for Protective Clothing. Montreux, Switzerland [CD-ROM]. St. Gallen, Switzerland: EMPA; **2003**, https://es-pc.eu/media/attachments/2022/11/24/ecpc2_2003challprotclo.pdf.

Holmér, I.; Kuklane, K.; Gao, C. Test of firefighter's turnout gear in hot and humid air exposure. *International Journal of Occupational Safety and Ergonomics* **2006**, *12*(3), 297-305.

Ioannou, L.G., Tsoutsoubi, L., Mantzios, K., Flouris, A.D. A free software to predict heat strain according to the ISO 7933:2018. *Industrial Health* **2019**, 57(6), 711–720, https://doi.org/10.2486/indhealth.2018-0216.

ISO 11999 series. PPE for firefighters — Test methods and requirements for PPE used by firefighters who are at risk of exposure to high levels of heat and/or flame while fighting fires occurring in structures. International Organization for Standardization, Geneva, Switzerland.

ISO 10551:2019 Ergonomics of the physical environment – Subjective judgement scales for assessing physical environments. International Organization for Standardization, Geneva, Switzerland

ISO 11079:2007 Ergonomics of the thermal environment – Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects. International Organization for Standardization, Geneva, Switzerland.

ISO 15384:2018 Protective clothing for firefighters — Laboratory test methods and performance requirements for wildland firefighting clothing. International Organization for Standardization, Geneva, Switzerland.

ISO 15831:2004 Clothing – Physiological effects – Measurement of thermal insulation by means of a thermal manikin. International Organization for Standardization, Geneva, Switzerland.

ISO/TS 20141:2022 Personal safety — Personal protective equipment — Guidelines on compatibility testing of PPE. International Standards Organisation, Geneva, Switzerland.

ISO 7726:1998 Ergonomics of the thermal environment – Instruments for measuring physical quantities. International Organization for Standardization, Geneva, Switzerland.

ISO 7933:2004 Ergonomics of thermal environment – analytical determination and interpretation of thermal stress using calculation of predicted heat strain. International Organization for Standardization, Geneva, Switzerland.

Jacobs, L.M.G., Klomp, A.M.H., Daanen, H.A.M., Kuklane, K. Heat stress prediction for simulated wildland firefighting. ThermoNED, Delft, Netherlands, April 11, **2025**a.

Jacobs, L.M.G., Klomp, A.M.H., Daanen, H.A.M., Kuklane, K. Heat stress prediction for simulated wildland firefighting. Editors: Olt, J., Kikas, T., Meneses, L. Book of Abstracts. 15th International Conference on Biosystems Engineering, May 7-9, **2025**b, Tartu, Estonia, p.34, http://hdl.handle.net/10492/9611.

Jones, B.H.; Toner, M.M.; Daniels, W.L.; Knapik, J.J. The energy cost and heart-rate response of trained and untrained subjects walking and running in shoes and boots. *Ergonomics* **1984**, *27*(8), 895–902.

Teitlebaum, A.; Goldman, R.F. Increased energy cost with multiple clothing layers. *Journal of Applied Physiology* **1972**, *32*(6), 743–44.

Kaaver, S., Kuklane, K. Physiological impact of rescue workers' protective clothing on heat stress development during simulated wildland firefighting activities. University master students conference, Estonian University of Life Sciences, Tartu, Estonia, April 24, **2025**, http://hdl.handle.net/10492/9994.

Kaaver, S., Purge, P., Kuklane, K. Physiological impact of rescue workers' protective clothing on heat stress development during simulated wildland firefighting activities. Eds. Kutlu, B., Kartal, G.E., Türkoğlu, G.C. Proceedings of the 11th European Conference on Protective Clothing, Kuşadası - Aydın, Turkey, May 20-23, **2025**, p. 83-86, https://doi.org/10.5281/zenodo.17472264.

Kingma, B.R.M.; Steenhoff, H.; Toftum, J.; Daanen, H.A.M.; Folkerts, M.A.; Gerrett, N.; Gao, C.; Kuklane, K.; Petersson, J.; Halder, A.; Zuurbier, M.; Garland, S.W.; Nybo, L. ClimApp–integrating personal factors with weather forecasts for individualised warning and guidance on thermal stress. *Int. J. Environ. Res. Public Health* **2021**, *18*, 11317, https://doi.org/10.3390/ijerph182111317.

Klomp, A.M.H., Jacobs, L.M.G., Daanen, H.A.M., Kuklane, K. Heat stress prediction for simulated technical rescue activities. Eds. Kutlu, B., Kartal, G.E., Türkoğlu, G.C. Proceedings of the 11th European Conference on Protective Clothing, Kuşadası - Aydın, Turkey, May 20-23, **2025**a, p. 39-42, https://doi.org/10.5281/zenodo.17472264.

Klomp, A.M.H., Jacobs, L.M.G., Daanen, H.A.M., Kuklane, K. Heat stress prediction for simulated structural firefighting. Proceedings of the 13th International Manikin & Modelling Meeting (I3M) and The Clothing and Textile Sciences Research Meeting, Wilson College of Textiles, NC State, Raleigh, USA, Oct. 15-17, **2025**b, p. 121-131, https://doi.org/10.52750/825607.

Králík, L.; Lunerová, K.; Vaněk, J.; Weisheitelová, M.; Castulik, P.; Chrastek, J.; Serakova, M.; Kozeluh, J. Structural integrity of firefighter suits and protection against combustion products. Eds. Kutlu, B., Kartal, G.E., Türkoğlu, G.C. Proceedings of the 11th European Conference on Protective Clothing, Kuşadası - Aydın, Turkey, May 20-23, **2025**, p. 150-153, https://doi.org/10.5281/zenodo.17472264.

Kuklane, K.; Eggeling, J.; Kemmeren, M.; Heus, R. A database of static thermal insulation and evaporative resistance values of Dutch firefighter clothing items and ensembles. *Biology* **2022**, *11*(12), 1813, https://doi.org/10.3390/biology11121813.

Kuklane, K.; Gao, C.; Holmér, I.; Giedraitytė, L.; Bröde, P.; Candas, V.; den Hartog, E.; Meinander, H.; Richards, M.; Havenith, G. Calculation of clothing insulation by serial and parallel methods: effects on clothing choice by IREQ and thermal responses in the cold. *International Journal of Occupational Safety and Ergonomics* **2007**, *13*(2), pp.103-116, https://doi.org/10.1080/10803548.2007.11076714.

Kuklane, K.; Klomp, A. M.; Jacobs, L. M.; Heus, R. Thermal protective properties of a firefighter turnout gear with and without an accessory on top of turnout jacket. *Communications in Development and Assembling of Textile Products* **2024a**, *5*(2), 242–254. https://doi.org/10.25367/cdatp.2024.5.p242-254

Kuklane, K.; Levels, K.; de Weerd, M.; Teunissen, L.; Eggeling, J.; Kemmeren, M. Comparison of clothing measurements on 2 manikins in the light of size and fit. Eds. Kuklane, K., Mertens, C. Proceedings of the 10th European Conference on Protective Clothing, Arnhem, Netherlands, 9-12 May **2023**, p. 60-61, https://nipv.nl/wp-content/uploads/2023/05/20230508-NIPV-ESPC-Proceedings-of-the-10th-European-Conference-on-Protective-Clothing.pdf

Kuklane, K.; Levels, K.; Kistemaker, L.; Mol, E.; Tanck, I.; Heus, R. Heat stress prediction for simulated rescue activities. Eds. Lee, J.-Y., Kim, D.-H. Proceedings of the 20th International Conference on Environmental Ergonomics, Jeju, Republic of Korea, June 3-7, **2024b**, p. 145-146, https://ndownloader.figstatic.com/files/47045731.

Kuldmäe, G., Kuklane, K., & Merisalu, E. Kuumastressi mudeli valideerimine päästetööde tarbeks simuleeritud kliimakambri katsete baasil. (Validation of a heat strain model for assessing rescue activities based on climate chamber tests.) In Estonian. University master students conference, Estonian University of Life Sciences, Tartu, Estonia, April 24, **2025**.

Lee, H.; Kim, S.; Kim, D.; Kim, D.; Lee, J. Requirements of improvement on personal protective equipment and experiences exposed to accidently high risk circumstance while firefighting - a questionnaire study. *Journal of the Korean Society of Living Environmental System* **2017**, *24*(5), 549–561, https://doi.org/10.21086/ksles.2017.10.24.5.549.

Lei, Y.; Wang, F.; Yang, J. An extended model for analyzing the heat transfer in the skin–microenvironment–fabric system during firefighting. *Materials* **2023**, *16*(2), 487, https://doi.org/10.3390/ma16020487.

Levels, K.; Kuklane, K.; Mol, E.; Kistemaker, L.; Tanck, I.; Heus, R. Validity of the heart rate-based ECTemp algorithm to estimate core temperature during simulated firefighting scenarios. Eds. Lee, J.-Y., Kim, D.-H. Proceedings of the 20th International Conference on Environmental Ergonomics, Jeju, Republic of Korea, June 3-7, **2024**, p. 149-150, https://ndownloader.figstatic.com/files/47045731.

Lunerová, K.; Králík, L.; Vaněk, J.; Mašín, M.; Weisheitelová, M.; Fišer, J.; Pokorný, J. Testing of functional characteristics of NBC and firefighter protective clothing. Eds. Kutlu, B., Kartal, G.E., Türkoğlu, G.C. Proceedings of the 11th European Conference on Protective Clothing, Kuşadası - Aydın, Turkey, May 20-23, **2025**, p. 212-215, https://doi.org/10.5281/zenodo.17472264.

Malchaire, J. Occupational Heat Stress Assessment by the Predicted Heat Strain Model. *Industrial Health* **2006**, *44*(3), 380–387, https://doi.org/10.2486/indhealth.44.380.

Malchaire, J.; Piette, A.; Kampmann, B.; Mehnert, P.; Gebhardt, H.; Havenith, G.; den Hartog, E.; Holmer, I.; Parsons, K.; Alfano, G.; Griefahn, B. Development and validation of the predicted heat strain model. *Annals of Occupational Hygiene* **2001**, *45*(2), 123–135, https://doi.org/10.1093/annhyg/45.2.123.

McCarthy, A.; Wills, J.A.; Fuller, J.T.; Cassidy, S.; Nindl, B.C.; Doyle, T.L. Predicting maximal military occupational task performance from physical fitness tests using machine learning. *Medicine and Science in Sports and Exercise* **2025**, *57*(9), 1877-1885, doi: 10.1249/MSS.0000000000003727.

McLellan, T. M.; Daanen, H. A. M.; Cheung, S. S. Encapsulated environment. *Comprehensive Physiology* **2013***,* 1363-1391.

Moran, D. S.; Pandolf, K.B.; Shapiro, Y.; Laor, A.; Heled, Y.; Gonzalez, R. R. Evaluation of the environmental stress index for physiological variables*. Journal of Thermal Biology* **2003**, *28*(1), 43–49, https://doi.org/10.1016/s0306-4565(02)00035-9.

Page, S.C., Hepokoski, M.A., Golubev T., Kuklane, K. Predicting the effectiveness of technical rescue gear with thermal modelling software. Eds. Kutlu, B., Kartal, G.E., Türkoğlu, G.C. Proceedings of the 11th European Conference on Protective Clothing, Kuşadası - Aydın, Turkey, May 20-23, **2025**a, p. 59-62, https://doi.org/10.5281/zenodo.17472264.

Page, S.C., Hepokoski, M.A., Golubev T., Kuklane, K. Predicting the effectiveness of structural internal firefighting gear using computational thermal modeling. Proceedings of the 13th International Manikin & Modelling Meeting (I3M) and The Clothing and Textile Sciences Research Meeting, Wilson College of Textiles, NC State, Raleigh, USA, Oct. 15-17, **2025**b, p. 14, https://doi.org/10.52750/825607.

Parsons, K. *Human thermal environments*. 3rd ed.; Taylor & Francis Group: Boca Raton, FL, USA, **2014**.

Pandolf, K.B.; Burse, R.L.; Givoni, B.; Soule, R.G.; Goldman, R.F.; Pandolf, K.B. Effects of dehydration on predicted rectal temperature and heart rate during work in the heat. *Medicine & Science in Sports & Exercise* **1977**, *9*(1), 51.

Périard, J. D.; Eijsvogels; T. M. H.; Daanen, H. Exercise under heat stress: thermoregulation, hydration, performance implications, and mitigation strategies. *Physiological Reviews* **2021**, *101*(4), 1873–1979, https://doi.org/10.1152/physrev.00038.2020.

Petersson, J.; Kuklane, K.; Gao, C. Is there a need to integrate human thermal models with weather forecasts to predict thermal stress? *Int. J. Environ. Res. Public Health* **2019**, *16*, 4586. https://doi.org/10.3390/ijerph16224586.

Petruzzello, S.J.; Gapin, J.I.; Snook, E.M.; Smith, D.L. Perceptual and physiological heat strain: Examination in firefighters in laboratory- and field-based studies. *Ergonomics* **2009**, *52*(6), 747–754, https://doi.org/10.1080/00140130802550216.

Ramanathan, N.L. A new weighting system for mean surface temperature of the human body. *Journal of Applied Physiology* **1964**, *19*(3), 531-533.

Rathour, R.; Das, A.; Alagirusamy, R. Studies on the influence of process parameters on the protection performance of the outer layer of fire-protective clothing. *Journal of Industrial Textiles* **2021**, *51*(5_suppl), 8107S-8126S, https://doi.org/10.1177/15280837211054582.

Renberg, J.; Lignier, M.J.; Wiggen, Ø.N.; Færevik, H.; Helgerud, J.; Sandsund, M. Heat tolerance during uncompensable heat stress in men and women wearing firefighter personal protective equipment. *Applied Ergonomics* **2022**, *101*, 103702. https://doi.org/10.1016/j.apergo.2022.103702.

Sandsund, M.; Aamodt, E.; Renberg, J. Heat strain in professional firefighters: physiological responses to a simulated smoke dive in extremely hot environments and the subsequent recovery phase. *Industrial Health* **2024**, *62*(5), 312-323, https://doi.org/10.2486/indhealth.2023-0151.

Sköldström, B. Physiological responses of fire fighters to workload and thermal stress. *Ergonomics* **1987**, *30*(11), 1589–1597. https://doi.org/10.1080/00140138708966049.

Son, S.Y.; Muraki, S.; Tochihara, Y. Exploring the appropriate test methods to examine the effects of firefighter personal protective equipment on mobility. *Fash. Text.* **2022**, *9*, 22, https://doi.org/10.1186/s40691-022-00295-8.

Taylor, N.A.; Lewis, M.C.; Notley, S.R.; Peoples, G.E. A fractionation of the physiological burden of the personal protective equipment worn by firefighters. *European journal of applied physiology* **2012**, *112*, pp.2913-2921, https://doi.org/10.1007/s00421-011-2267-7

Tochihara, Y.; Lee, J.-Y.; Son, S.-Y.; Bakri, I. Heat strain of Japanese firefighters wearing personal protective equipment: a review for developing a test method. *Ergonomics* **2022**, *66*(5), 676–689, https://doi.org/10.1080/00140139.2022.2113150.

Underwood, C.R.; Ward, E.J. The solar radiation area of man. *Ergonomics* **1966**, *9*(2), 155–168, https://doi.org/10.1080/00140136608964361.

Van Harten, T. Ergonomic and performance differences between firefighter protective clothing systems. MSc thesis report, VU Amsterdam, **2023**, pp. 53

Van Harten, T; Kuklane, K.; Heus, R.; Daanen, H.A.M. Ergonomic and performance differences between firefighter protective clothing systems. Eds. Kuklane, K.; Mertens, C. Proceedings of the 10th European Conference on Protective Clothing, Arnhem, Netherlands, May 9-12, **2023**, 154-155, https://nipv.nl/wp-content/uploads/2023/05/20230508-NIPV-ESPC-Proceedings-of-the-10th-European-Conference-on-Protective-Clothing.pdf.

Wang, F.; Gao, C.; Kuklane, K.; Holmér, I. Effects of various protective clothing and thermal environments on heat strain of unacclimated men: the PHS (predicted heat strain) model revisited. *Industrial Health* **2013**, *51*(3), 266-274, https://doi.org/10.2486/indhealth.2012-0073.

Wang, S.; Park, J.; Wang, Y. Cross-cultural comparison of firefighters' perception of mobility and occupational injury risks associated with personal protective equipment. *Int. J. Occup. Saf. Ergon.* **2021**, *27*, 664–672, https://doi.org/10.1080/10803548.2019.1607027.

Xu, X.; Rioux, T.P.; Gonzalez, J.; Hansen, E.O.; Castellani, J.W.; Santee, W.R.; Karis, A.J.; Potter, A.W. Development of a cold injury prevention tool: The cold weather ensemble

decision aid (CoWEDA). In USARIEM Technical Report No. T19-06; March **2019**, Natick, MA, USA.
Xu, X.; Rioux, T.P.; Gonzalez, J.; Hansen, E.O.; Castellani, J.W.; Santee, W.R.; Karis, A.J.; Potter, A.W. A digital tool for prevention and management of cold weather injuries–Cold Weather Ensemble Decision Aid (CoWEDA). *Int. J. Biometeorol.* **2021**, *65*, 1415–1426, https://doi.org/10.1007/s00484-021-02113-0.
Xu, X.; Rioux, T.P.; Potter, A.W. Fabric Thermal resistance and ensemble thermal resistances are two different concepts. *Journal of Occupational and Environmental Hygiene* **2014**, *11*(11), D187–D188, https://doi.org/10.1080/15459624.2014.946517.
Yung, M.; Du, B.; Gruber, J.; Hackney, A.; Yazdani, A. Fatigue measures and risk assessment tools for first responder fatigue risk management: A scoping review with considerations of the multidimensionality of fatigue. *Safety Science* 2022, *154*, 105839, https://doi.org/10.1016/j.ssci.2022.105839.