# Thermal insulation characteristics of chemical protective clothing

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## Introduction

**Personal protective equipment (PPE)** against chemical/biological agents or radioactive materials is designed to provide perfect barrier between the user and harmful ambient environment aimed for effective elimination of the interaction of hazardous agents with the human body. However, the high level of protection significantly influences the **body heat exchange**. The use of protective clothing in combination with user's physical activity cause **physiologic strain** to the user, depending on ambient environmental conditions (temperature, air humidity and air velocity etc.) besides. Produced metabolic heat may lead to heat accumulation inside the body and subsequently to **heat stress** with undesired concequences to human physiology.

As a prevention countermeasure, thermal indices and **thermophysiological models** have been developed to estimate and predict maximum time limit of the stay in PPE. In our research, we intend to compare two prediction thermophysiological models, **Predicted Heat Strain (PHS) index** and **Fiala-based Thermophysiological Model (FMTK)** and check their usability for prediction of heat stress during wearing PPE. As input parameters, thermal characteristics of the protective ensembles and real data of induced physiologic strain on human probands had to be determined under defined ambient conditions.

**Thermal insulation** and **evaporative resistance** are substantial characteristics of the PPE affecting the body heat exchange of the PPE user. We measured those characteristics using **Newton thermal manikin** on four types of protective ensembles[1]. Besides chemical protective clothing and NBC suit we covered also fire-fighting garment as the heat stress risk is not limited to chemical protective clothing only.

The same types of protective ensembles were examined for induced **physiologic strain** with a group of probands performing physical activity in climatic chambre. The physiologic strain was evaluated using **Physiologic strain index (PSI)**[2] based on increase of heart rate (HR) and body core temperature (RT) during the real tests.

## Testing of the physiologic strain

The **tests of physiologic strain** were performed in a **climatic chamber** of National Institute for NBC Protection **with 10 volunteer probands** – 6 men and 4 women wearing the protective ensemble and performing defined physical activity (walking on a treadmill) under defined ambient conditions*. **Maximum exposure time achieved** in the test by each volunteer was determined, range and average is shown at fig. 1.

Each proband was measured for **anthropometric parameters** (body size, body mass index, fat percentage, waist-to-hip ratio) and their fitness (according to $VO_2$ max related to their age and gender). In relation to their individual results they were categorized to **fitness levels:** very good – good – poor – very poor.

**Testing of the physiologic strain with probands in PPE**:

- **Conditions in climatic chamber:** a) -10 °C/25 % rel. humidity, b) 5 °C/25 % rel. hum., c) 25°C/20 % rel. hum., d) 35 °C/20% rel. hum.; air velocity 0.2 m/s, walking on treadmill 4 km/h.
- **Monitored values:** heart rate (HR), body core temperature (RT), skin temperature (tsk) at 8 locations.
- **End of the test:** time limit 120 min or limit heart rate (220 – age) or limit body core temperature (38.5 °C) or proband' s demand (headache, unbearable hot, other discomfort).
- **Physiologic strain index (PSI):** the calculation is based on HR and RT increase[2], PSI numerical scale is 0–10 where 0 = no strain, 10 = very high strain.

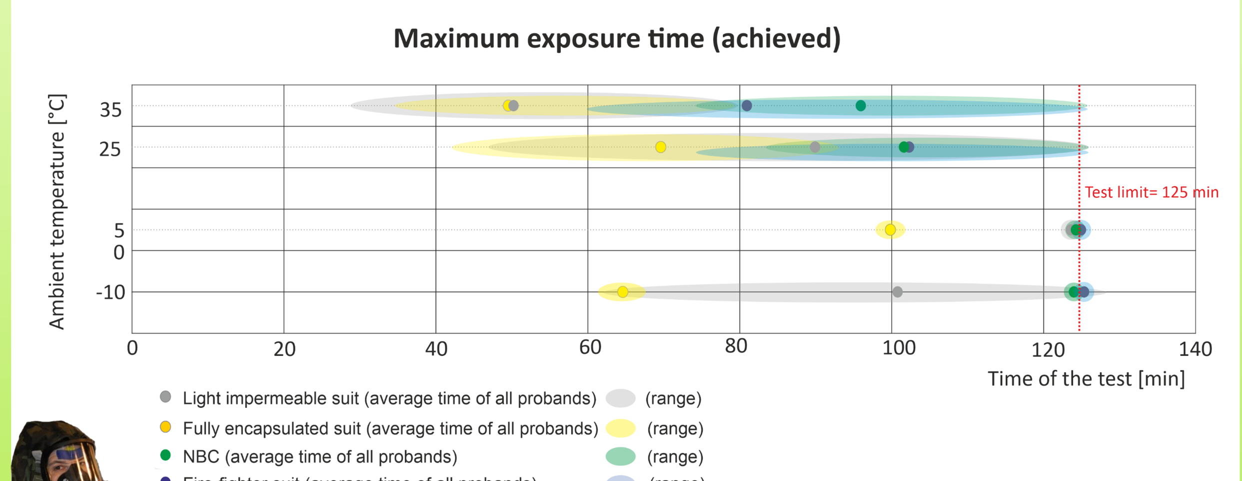
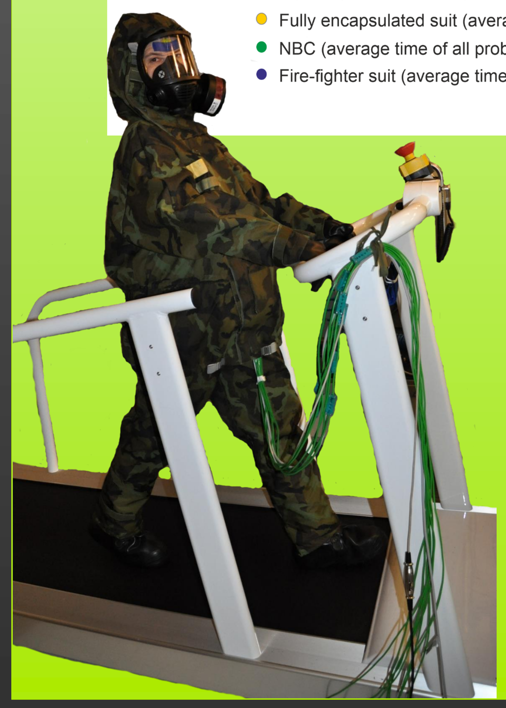



Figure 1: Maximum exposure time achieved by all probands



The monitored values (HR, RT, tsk) and calculated PSI are crucial inputs for thermophysiological models designed for the detail prediction of body heat strain. As an example, increase of RT (average of all probands) for one suit at one temperature is demonstrated on fig. 2.

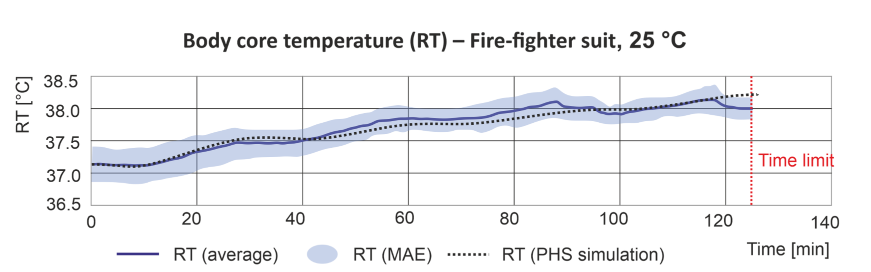



Figure 2: Fire-fighter suit at 25 °C – Increase of body core temperature (RT) – average value of all probands, RT mean absolute deviation (MAE) and prediction of RT – simulation using PHS index

## Evaluation of the clothing parameters on Newton thermal manikin

Thermal clothing properties of the four types of protective ensembles were measured by means of 34-zones **Newton thermal manikin** in climatic chamber at Brno University of Technology.

**Overall thermal resistance** $I_t$ as well as **local thermal resistance** $I_{t,i}$ were established for the four types of PPE according to procedures described in ISO 15831.

**Evaporative resistance** $R_{eT}$ was established by non-standard pre-wetted skin method. The tight-fitting cotton „skin" blue underwear covering whole manikin body was wetted with 850±30 g of water and the manikin wearing the protective ensemble was placed inside the chamber. The evaporative resistance was calculated according to measured heat loss in the same manner as for the previous thermal insulation measurement.

Based on the $I_t$ and $R_{eT}$ measurement, the **static moisture index** $i_m$ was calulated[3] for the four types of PPE.

**Thermal insulation measurements:**
Manikin´s surface temperature: 34 ±0.1 °C
Ambient temperature: 19.0 ±0.1 °C
Air velocity: 0.4 ±0.1 m/s
Relative humidity inside the chamber: 30-60%

**Evaporative resistence measurements:**
Manikin´s surface temperature: 34 ±0.2 °C
Ambient temperature: 34 ±0.2 °C
Air velocity: 0.5 ±0.2 m/s
Relative humidity inside the chamber: <50%

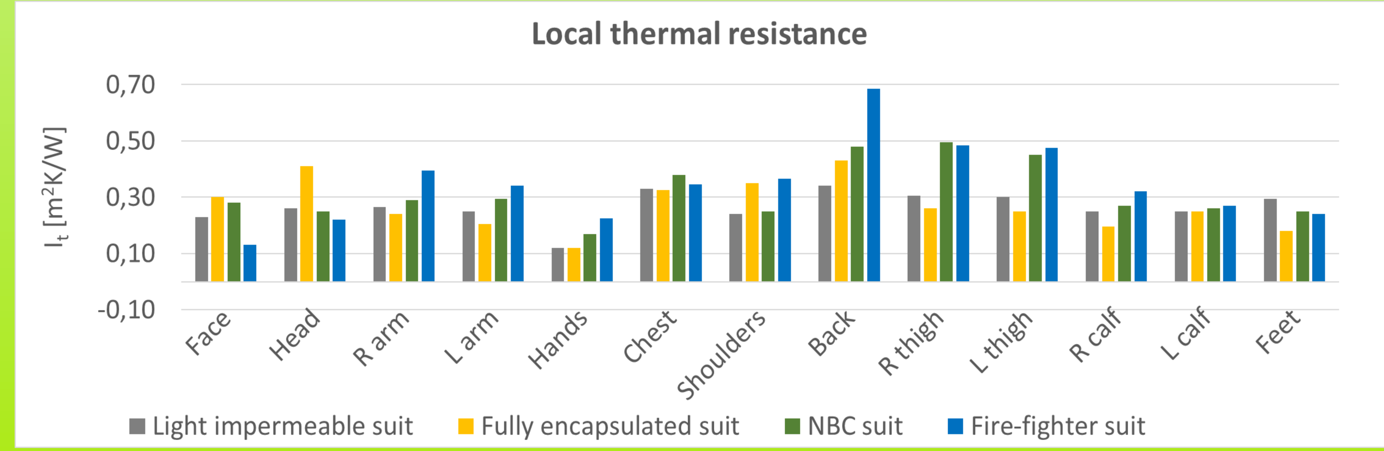



Figure 3: Local thermal resistances for four types of protective ensembles

| | Light impermeable suit Tychem® F, DuPont | Fully encapsulated suit OPCH90, Ecoprotect | NBC suit FOP96, B.O.I.S. - Filtry | Fire-fighter suit Tiger Plus, DEVA |
|---|---|---|---|---|
| **Thermal resistance** | | | | |
| $I_t$ [m²K/W] | 0,257 | 0,240 | 0,302 | 0,319 |
| $I_t$ [clo] | 1,66 | 1,55 | 1,95 | 2,06 |
| **Evaporative resistance** | | | | |
| $R_{eT}$ [kPa.m²/W] | 0,301 | 1,098 | 0,059 | 0,052 |
| **Static moisture index** | | | | |
| $i_m$ [-] | 0,052 | 0,015 | 0,310 | 0,372 |

## Results

Based on the $I_T$ and $R_{eT}$ measurements, the static moisture index[3] $i_m$ was calculated for the four types of PPE.

Two prediction thermophysiological models – **Predicted Heat Strain (PHS)** based on analytical approach as described in ISO 7933[6] and **Fiala-based Thermophysiological Model (FMTK)**[4,5] were compared to determinate their applicability for prediction of the increase of body core temperature and related maximum exposure time for work in PPE. The FMTK model is based on numerical solution of heat transfer in the human body regarding the individual anthropometric data to predict the physiologic response of the human considering the ambient environmental conditions and thermal characteristics of the clothing.

The simulation results were compared to real data from the climatic chamber experiments under various conditions, as demonstrated on fig. 2, 4, 5. The results show that PHS index is well usable for clothing with higher value of $I_t$ (even exceeding the validity given in ISO 7933, i. e. 0.1 – 1.0 clo), but the prediction results strongly depend on the static moisture index $i_m$ value. For clothing with moderate $i_m$ (0.3-0.4) the simpler PHS index gives satisfactory results under various ambient temperatures. However, for impermeable protective ensembles with low $i_m$ (under 0.1) the PHS index gives unrealistic predictions. A more complex FMTK model showed to produce more realistic values.

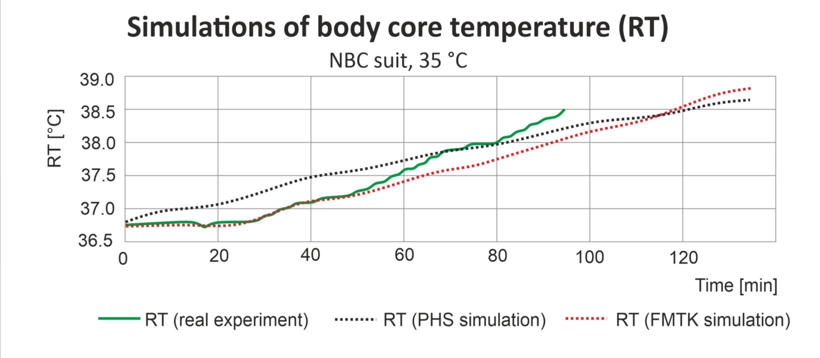



Figure 4: Increase of body core temperature (RT) – comparison of real experiment data with simulations using 2 thermophysiological models – PHS index a FMTK model for air-permeable NBC suit ($im$ = 0.31) at 35 °C.

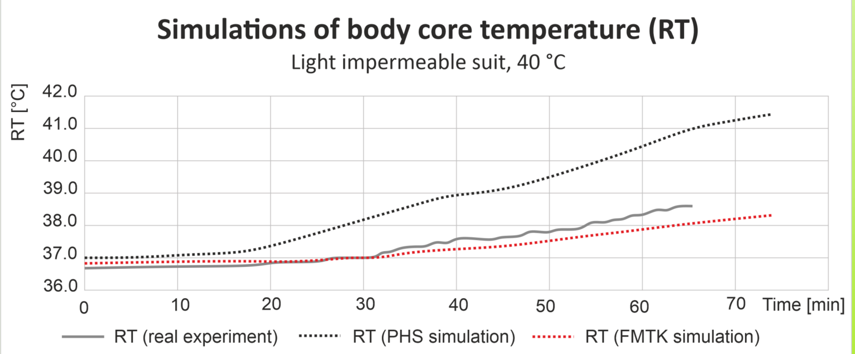



Figure 5: Increase of body core temperature (RT) – comparison of real experiment data with simulations using 2 thermophysiological models – PHS index a FMTK model for light impermeable suit ($im$ = 0.052) at 40 °C.

The study is going on to obtain more data to be used as input for more detailed optimization of the thermophysiological mathematical models[4,5] intended for prediction of human body response to staying in CBRN protective ensembles.

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* Tests in climatic chamber are ongoing (namely at low temperatures) to get the complete set of the tests

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