# Comfort and Personal Protective Clothing

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**Abstract** Harsh thermal conditions directly affect human health, performance and comfort. The interaction between the human body and functional clothing, e.g. personal protective equipment (PPE), can be described by measurements of thermo physiological parameters. For PPE these parameters and performance requirements are given in standards such as DIN EN 469(1) for fire fighters or DIN EN ISO 11611(2) for welding and allied processes. First, PPE should protect the wearer from external influences such as fire, heat, weather and water. Also, it should protect from internal dangers such as overheating which can cause - in the worst case - cardiovascular failure or heat stroke. These important but minimalistic thermophysiological requirements are given in the standards and describe the insensitive sweating. Further it is desirable that PPE is comfortable, too. So, the sensible sweating state of a human body should be characterized more in detail for PPE.

With the Hohenstein Skin Model (sweating guarded hot plate) according to ISO 11092(3) the instationary buffering capacity of liquid sweat (buffering index $k_f$) can be measured(4). With this measurement a wear condition is comprehended where the wearer is sweating so heavily that there is liquid sweat on his skin. It could be shown that there is a huge difference between state-of-the-art fire fighter PPEs. Some show poor buffering capacities of liquid sweat with an $K_f$-value of 0.3 – 0.4. On the other hand, there exist fire fighter PPEs with higher (better) buffering capacities of liquid sweat with $k_f$-values between 0.75 – 0.88. By combining the fire fighter PPE with functional undergarments, the buffering capacity of liquid sweat could be improved.

Further studies deal with the influence of reprocessing and reimpregnation on the sweat management of PPE. By reprocessing of fire fighter suits contaminations of the PPE can be removed and the functional integrity of such PPE may be extended. Therefore, the usage of special laundry processes according to the manufacturer information is necessary. To preserve the water and oil repellent characteristics of the face of the outer shell fabric in long term an impregnation with perfluorocarbon during the last rinsing bath is recommended. It could be shown that such perfluorocarbon impregnations have a negative influence on the thermophysiological wear comfort of PPE.

**Keywords:** personal protective clothing, clothing physiology, comfort, sweating

## 1 Introduction

The main task of personal protection equipment (PPE) is the protection from external dangers. In case of fire fighters or welders this is fire, heat or extinguishing water. At the same time heat and moisture produced by the human body should be transferred through the PPE to the ambient and the mobility of the wearer should not be influenced by the PPE. These performance requirements are given in standards such as DIN EN 469(1) for fire fighters or DIN EN ISO 11611(2) for welding and allied processes.

During wearing the PPE gets dirty by different contaminations depending on the operation area and activity. In case of firefighting it could be soot or hazardous substances, at an emergency response blood or at technical aid mud, acid, brine and oil. Those contaminations are sometimes not visible for the human eye on the PPE. But if not removed the function of the PPE could be influenced. Soiled reflective stripes for example impair the visibility of the fire fighter. So, the contaminations should ne removed to obtain the function. One way, the expensive one is the replacement of the PPE. As an alternative the PPE could be reprocessed professional. Until now there is no guideline for reprocessing fire fighter PPE. There are only care instructions given by the PPE or detergent manufacturers. To guarantee the water repellent effect of fire fighter PPE a perfluorocarbon impregnation is recommended after every fifth reprocessing cycle. To activate this hydrophobic finish heat (ironing, tumbler, finisher) is necessary. Such a perfluorocarbon impregnation obtains the water and oil repellent effect of the outer fabric. The question arises if these perfluorocarbon impregnations within the last rinsing bath of reprocessing PPE influences other characteristics such as the clothing physiological parameters.

## 2 Materials and Methods

Five state of the art fire fighter suits were characterized about clothing physiological parameters in new state and after reprocessing cycles with and without perfluorocarbon impregnation. Table 1 shows the used fire fighter PPE in detail.

**Table 1.** Fire Fighter Materials.

| *Sample* | *Description* | *Structure* | *Grammage [g/m²]* | *Watervapor-permeability "breathability" $R_{et}$ [m²Pa/W]* |
|---|---|---|---|---|
| 1 | Outer fabric: Nomex<br>Moisture barrier: 2-layer laminate with PU-membrane<br>Thermoinsulation: quilted Nomex with $AR/CV_{FR}$ | liner;<br>membrane orientated to outer fabric | 660 | 25.68 |
| 2 | Outer fabric: Nomex<br>Moisture barrier with thermoinsulation:<br>2-layer laminate with PTFE-membrane and spacer dot<br>Lining material: $AR/CV_{FR}$ | liner;<br>membrane orientated to outer fabric | 495 | 28.98 |
| 3 | Outer fabric: AR/PBI/C<br>Moisture barrier with thermoinsulation:<br>3-layer laminate with PTFE-membrane and spacer dots | liner;<br>membrane orientated to skin | 570 | 17.97 |
| 4 | Outer fabric: Kermel<br>Moisture barrier: 2-layer laminate with PU-membrane<br>Lining material: AR | liner;<br>membrane orientated to skin | 595 | 21.53 |
| 5 | Outer fabric: Kermel/Belton<br>Moisture barrier: 2-layer laminate with PES-membrane<br>Thermoinsulation: quilted AR with $AR/CV_{FR}$ | liner;<br>membrane orientated to outer fabric | 660 | 24.65 |

### *2.1 Methods*

The reprocessing of fire fighter PPE is performed according an industrial laundry process (ISO 15797)(5). The developed washing procedure is named "contaminated with oil" and simulates a worst-case scenario for PPE soiled during a mission. During the process the washer extractor Kannegiesser Favorit Plus is used as well as Almesin as detergent and Mulan as detergent booster. Drying process A is used with an input temperature of 110°C and an exhaust air temperature of 80°C. Through each washing cycle the fire fighter PPE was impregnated with a perfluorocarbon.

For characterisation of the perfluorocarbon impregnation the Sorption speed of a water drop into the fabric (sorption index $i_B$). This sorption speed can be determined by a video film of a water drop of defined size falling from a burette 5 cm above the sample onto the fabric's inner surface. By crossing a light beam just before touching the fabric's surface the falling water drop triggers a video camera. which takes pictures of the water drop on the fabric's surface. Out of the time-pattern of the contact angle of the water drop the time lapse can be extrapolated, after which the water drop has been completely absorbed by the sample. This time lapse yields the sorption index $i_B$. Regarding its sensorial comfort a fabric must be judged the better, the smaller $i_B$. Particularly $i_B$ should be below 270.

The thermoregulatory model of human skin (Skin Model) simulates the dry as well as the sweating human skin. With the Skin Model the specific thermophysiological quantities of textiles as layers, relevant to physiological comfort, can be determined. Under “normal” or “stationary” conditions the moisture flux from the skin appears as water vapor (insensitive sweating). In this stationary case the water vapor resistance $R_{et}$ can be measured according ISO 11092(3). DIN EN 469 requires a water vapor resistance $R_{et}$ (stationary conditions) between 30 and 45 m² Pa/W for Level 1 PPE and $R_{et} \leq 30$ m² Pa/W for Level 2 PPE. Level 1 PPE is not water vapor permeable.

For the clothing physiological properties of textiles not only their stationary thermo-physiological properties are important but also the capacity to buffer sweat pulses which are occurring quite frequently in the practical use of textiles and clothing. Concerning the buffering capacity, it must be distinguished between two mechanisms:

Buffering capacity of water vapor (moisture regulation index $F_d$): This measurement describes the wear condition where the wearer is already sensibly sweating, but the sweat is still evaporating within the channels of the skin's sweat glands. In the clothes' microclimate an increased water vapor pressure is occurring but still no liquid sweat.

With the buffering capacity of liquid sweat (buffering index $K_f$) a wear condition is comprehended where the wearer is sweating so heavily that there is liquid sweat on his skin.

Like the stationary wear conditions, also the instationary conditions can be simulated with the Skin Model. A description of the test procedures is given in the Standard-Test Specification BPI 1.2(4, 6).

## 3 Results and Discussion

Fire fighter PPE was characterized about the thermophysiological comfort in new state and after reprocessing with and without perfluorocarbon impregnation. First the sorption index $i_B$ was determined. According this parameter the sorption characteristics of a textile can be described. During hard exercise like in case of a fire fighter mission the produced sweat should be absorb by the lining and transferred through the material combination to the ambient. If this is not the case heat and moisture accumulate in the clothing. Therefore, the concentration and performance of the fire fighter decreases. Regarding its sensorial comfort a fabric/clothing must be judged the better (hydrophilic), the smaller $i_B$. Particularly $i_B$ should be below 270.

Figure 1 shows the sorption index of the lining materials of fire fighter PPE in new state (blue), after reprocessing with (red) and without (green) perfluorocarbon impregnation during the last rinsing bad. In new state sample 1, 4 and 5 with AR quilted $AR/CV_{FR}$ as thermoinsulation or aramid fabric as lining have a sorption index of $i_B<60$. Except sample 3 all materials can be rated as hydrophilic.

After reprocessing with perfluorocarbon impregnation during the last rinsing bath all samples have a sorption index $i_B>600$ (Fig. 1, red bars). This means all samples are hydrophobic. Without perfluorocarbon impregnation (Fig. 1, green bars) sorption indices $i_B<60$ are measured. This shows that the hydrophobic effect residues from the perfluorocarbon impregnation. Sample 3 is an exception: in new state the lining shows a high sorption index. During reprocessing without perfluorocarbon impregnation, the sorption index increases. In this case an impregnation of the lining was performed during manufacturing and removed during reprocessing.

By perfluorocarbon impregnation during reprocessing of fire fighter PPE not only the outer fabric gets impregnated, but also the lining. Therefore, the liquid sweat, which occurs during exercise, could not be absorbed by the lining.

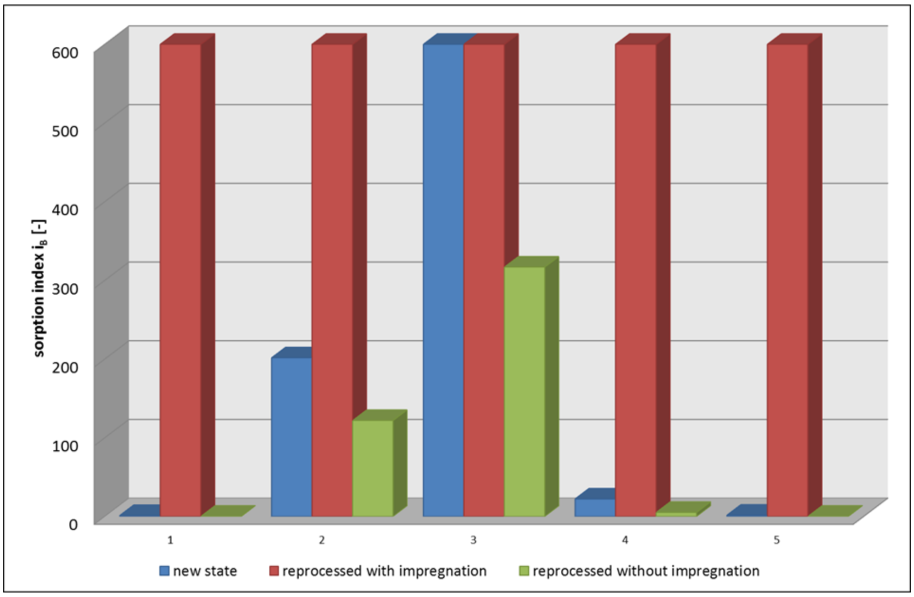


**Fig. 1.** Sorption index $_{iB}$ of lining material of fire fighter PPE new state (blue), after reprocessing with (red) and without (green) perfluorocarbon impregnation

In Case of fire fighter PPE, the watervaporpermeability $R_{et}$ is an important parameter required in DIN EN 469: it should be between 30 and 45 m² Pa/W for Level 1 PPE and $R_{et} \leq 30$ m² Pa/W for Level 2 PPE. Level 1 PPE is not water vapor permeable. This means that the PPE is only for temporary use. But all tested material combinations (MA1- MA5) showed a water vapor resistance beneath 30 m² Pa/W. Furthermore, it was shown that if the membrane is orientated to the lining or skin the $R_{et}$ is lower than if it is orientated to the outer layer (Table 1).

Further the hydrophobic effect of the perfluorocarbon impregnation on the sweat transport was investigated by measurements with the Skin Model in instationary case. For this purpose, the buffering capacity of liquid sweat $K_f$ of fire fighter PPE in new state (blue), after reprocessing with (red) and without (green) perfluorocarbon impregnation was investigated (Fig. 2). Fabrics with high buffering capacity of liquid sweat $K_f$ (high $K_f$ values) transport the liquid sweat better from the inside to the outside of clothing. In new state as well as reprocessing without perfluorocarbon impregnation the fire fighter PPE has higher $K_f$ values than reprocessing with perfluorocarbon impregnation. In addition, liquid sweat which is produced during high physical strain during fire fighters work cannot be absorbed by the lining material caused by the impregnation. Residual sweat on the skin poses a risk for the fire fighter and may end in circulatory collapse or scalding in case of flash over.

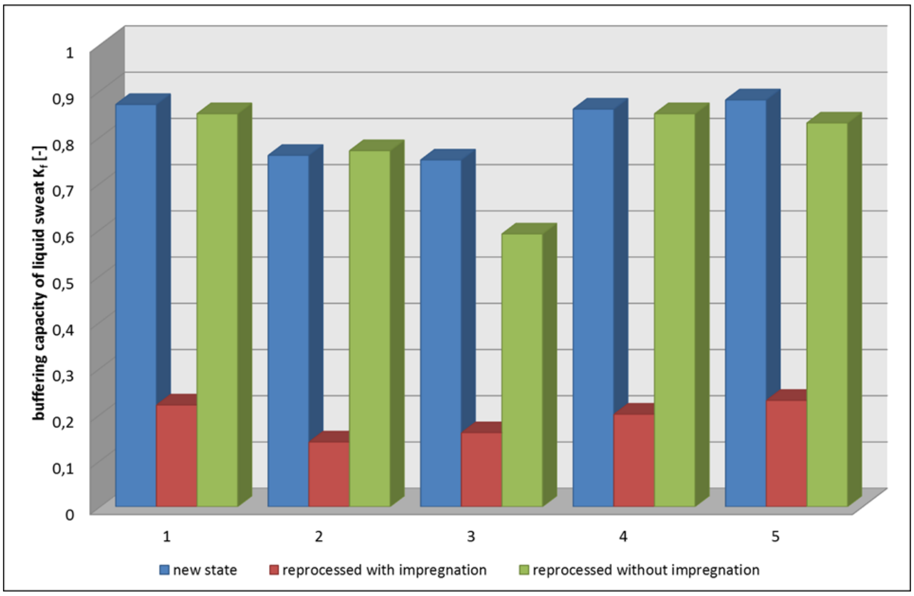


**Fig. 2.** Buffering capacity of liquid sweat $K_f$ of fire fighter PPE new state (blue), after reprocessing with (red) and without (green) perfluorocarbon impregnation

## 4 Conclusion

In conclusion it can be stated that reprocessing of fire fighter PPE is important to remove contaminations and to guarantee a long-time function of the PPE. Nowadays there is no standardized reprocessing process for such PPE.

The reprocessing with perfluorocarbon impregnation one hand has a positive effect on oil and water repellent characteristics of the face of outer shell fabric. But on the other hand, there is a negative effect on sweat absorption and sweat transport of fire fighter PPE. By reimpregnation via perfluorocarbon within the last rinsing bath during reprocessing the whole material combination of the fire fighter PPE is getting hydrophobic properties. Therefore, the clothing physiological characteristics including the sweat management deteriorate. The lining material of the PPE is no longer able to absorb from the human skin and transfer it trough the material combination.

An approach to receive the clothing physiological characteristics of fire fighter PPE after reprocessing with reimpregnation is a spray impregnation. In this process the perfluorocarbon impregnation is applied only on the outer fabric. So, the clothing physiological parameters of the inner textile layers are not affected by the impregnation. Further investigation dealing with this topic are ongoing.

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