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Testing and evaluation of light clothing properties used in fire and rescue service units

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Abstract
In the testing room for examination products of the Fire Engineering and Expert Institute (FEEI) of the Ministry of the Interior of the Slovak Republic in Bratislava, the Slovak National Accreditation Service SNAS has granted accreditation. Accredited testing room with identification number no. S-084 performs tests applied in the field of personal protective equipment. The goal is to specify, determine, and, above all, verify the selected characteristics for emergency clothing (light emergency clothing - LEC) used by firefighters and rescuers in the Fire and Rescue Service units to determine the conditions for procurement and quality control of the LEC supplied. The results obtained during the examination of the properties of light emergency clothing will be used in the next steps of the research of the Product Assessment Department (PAD) FEEI of the Ministry of the Interior of the Slovak Republic. In contrast, individual parameters can be used to design new LEC.
The basic meaning and purpose of any protective means are to protect a person who intervenes in a dangerous environment contaminated with chemical, biological or radioactive substances, for example, in industrial accidents connected with the release of dangerous substances (HAZMAT), in accidents of vehicles transporting HAZMAT and natural disasters or fires of various nature. Protecting from the external environment is one of the favourable inherent properties of personal protective work equipment (PPE).

Keywords
Fire, emergency clothing, testing

Introduction

Fires cause loss of life, property, and natural ecosystems every year, so it is important to study them to prevent or limit the occurrence of potential fires. The basic principle of fire prevention is to create and develop the conditions to ensure the effective protection of life and health of persons and property from fires, as well as their effective management, including the provision of assistance during such events. The area of fire prevention and the provision of basic fire prevention measures is currently addressed in a number of ways, particularly the roles, responsibilities, and competencies contained in fire protection legislation. Extinguishing fires, technical interventions, and interventions by members of fire brigades are considered to be one of the most dangerous professions, and they require intensive physical work in a dangerous and health-damaging environment. Firefighters, not only in Slovakia, are obliged to wear emergency clothing during their work, including emergency trousers, an emergency helmet, an emergency coat and shoes. In addition, depending on the type of intervention and according to the location of the intervention, they are also required to use respiratory protection means or unique means to protect the body surface, as shown in Figure 1 [Coca et al., 2010; Tomaskova et al., 2022].

More and more research and evidence indicate that firefighters have an increased risk of developing cancer and other diseases compared to the general population. This increased risk may be related to firefighters' occupational exposure to toxic fire fumes. Fires and firefighting interventions at fires represent a high cost to government budgets each year. They cause secondary damage that can be more severe than the direct consequences of fire, for example, by limiting infrastructure by closing off areas damaged by fire. [LeMasters et al., 2006; Hull et al., 2009; Wolffe et al., 2023)].

As for individual research, due to exposure to toxic combustion products, these hazardous substances remain not only on the PPE, but due to the use of only one emergency clothing during the performance of the service, these hazardous substances are transferred to the fire stations and finally to the surface of the firemen's body and thus also to an organism. These contaminants are receiving increasing attention worldwide, and they focus on decontamination procedures that aim to minimise the exposure of firefighters and thereby reduce the incidence of cancer [Stec a Hull, 2010; Demers et al., 2022; Horn et al., 2022].

Fig. 1. Emergency clothing (source: elaborated by authors)

Currently, there is no legal standard or legislation in force that requires PPE commonly used in response to protect against chemical or biological agents (meaning normal response clothing), which requires detailed research to lead to innovations in the field of protection of the body against carcinogenic, toxic, or biological substances. In addition to the classic effect of contaminants on firefighters during a fire, there are also other ways in which contaminants can affect firefighters, such as handling contaminated PPE, storing contaminated PPE, handling during individual cycles of decontamination and washing, etc. [Fent et al., 2020; Kirk et al., 2015; Mayer et al., 2019].

In the Slovak Republic, firefighting PPE consists of an emergency jacket, emergency trousers, emergency shoes, helmet, gloves, firefighter's hood, and an autonomous breathing apparatus with an open circuit – pressure relief, while depending on the type of danger during an intervention, the PPE may differ. In addition to this emergency clothing, station uniforms, such as T-shirts and trousers, are classically worn underneath. While the above PPE is designed to protect against several hazards (heat, cold, surface wetting, radiant heat, overheating, etc.), more and more research and literature question the effectiveness of this garment when it comes to exposure to toxic and carcinogenic substances, or a complex contaminant [Horn et al., 2022; Gill and Britz-McKibbin; 2020].

All these elements of a firefighter's protective system have been designed to protect against multiple hazards, such as thermal hazards (e.g., exposure to flame and excessive heat), inhalation of toxic gases, and physical injury (e.g., cuts, collisions, punctures, slips, falls etc.). Until now, studies on the firefighter's protective system have focused mainly on thermal protection, which, combined with advances in material technology over the past decade, has significantly reduced burns. [Boorady et al., 2013; Adams a Keyserling; Hu et al., 2007].

However, studies show that the effort to improve thermal protection has inevitably increased the weight and volume of emergency clothing, thereby significantly endangering the mobility and comfort of firefighters [Li et al., 2020; Betuš et al., 2023].

Sobeih et al. and Dorman found that wearing heavy and bulky clothing restricted body movement, leading to many injuries to firefighters in hard-to-reach and inaccessible fire areas [Sobeih et al., 2006].

Coca et al. also identified decreased neck and ankle range of motion when wearing the intervention kit [Coca et al., 2010; Coca et al., 2008].

In addition, self-contained breathing apparatus and emergency footwear were also defined in studies as a deterioration of body balance and as a cause of musculoskeletal injuries. Using self-contained breathing apparatus (with an average weight of 9-13 kg) on the back disrupts the body balance of firefighters during movement by changing their centre of gravity, which is a significant contributor to fall injuries [Henelman et al., 1989].

Also, according to Park and Taylor, wearing heavy emergency clothing, which can weigh up to 4.4 kg, causes rapid fatigue, as evidenced by up to nine times the rate of metabolism per unit of weight compared to a self-contained breathing apparatus. A previous study by Neeves et al. concluded that wearing firefighting boots causes more physical strain due to less efficient foot movement during the intervention [Park et al., 2010; Taylor et al., 2011].

As for the emergency clothing itself, firefighter clothing is generally multilayered, which ensures the very safety of firefighters from hazards such as flame, chemicals, and radiant heat flow, and must also maintain thermal balance with the human body by preventing any possibility of fatal skin burns [Keiser and Rossi, 2008; Bajaj and Senqupta, 1992; Lawson, 1997; Nayak et al., 2014].

A firefighter's emergency clothing consists of an outer shell, a moisture barrier and a thermal barrier, as shown in Figure 2. The outer shell is made of materials that do not burn on contact with flame and heat, prevent ignition on contact with flame, and have water-repellence and thermal insulation properties [Jin et al., 2013; Tomaskova et al., 2022].

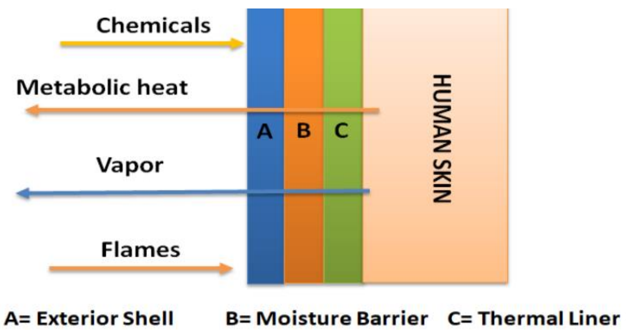

Fig. 2. Configuration of Firefighter clothing [Nayak et al., 2014; Jin et al., 2013]

The moisture barrier is a microporous membrane between the outer shell and the thermal barrier. This layer is permeable to water vapour but impermeable to liquid water. Its primary purpose is to protect the firefighter's body from liquefied chemicals [Song et al., 2010; Makinen, 2005].

A thermal barrier protects the human body by stopping ambient heat, and this layer usually uses flame-retardant fibres and their blends. It can be in the form of lining fabric, knitted fabric, non-woven fabric, stitched batting, laminated woven and spun [Song et al., 2010; Makinen, 2005].

The main function of emergency clothing is to ensure that the intervening firefighter's temperature escalation rate is reduced or slowed down. In this way, the firefighter has enough time at his disposal to carry out his duties effectively and minimise skin injuries. [Song et al., 2008; Ming et al., 2013; Chen et al., 2003; Celar et al., 2008; Fan et al., 1991].

This functionality of emergency clothing is expressed as thermal protection performance, which is considered the most critical performance factor of firefighter clothing. This performance means how well the intervening firefighter is protected from second-degree burns. Improving the protection of firefighter clothing extends the time firefighters can perform their work without sustaining severe injuries. As a result, firefighters can perform their work longer in a dangerous and health-damaging environment [Chung and Lee, 2005; Yang et al., 2012; Mah and Song, 2010; Holmer, 2006; Adolphe et al., 2000].

The thermal protection test itself helps to determine how the emergency clothing and individual layers protect the firefighter from burns, while the thermal performance is evaluated by several tests, where individual properties such as resistance to water vapour, thermal conductivity, etc. [Onofrei et al., 2014; Huand, 2006; Roguski et al., 2016; ISO 6942:2022].

Materials and Methods

The current state of the issue

The examination and research related to improving the protection of the intervening firefighters against the effects of external sources during interventions include several research and tests of the emergency clothing of firefighters. It is possible to improve the characteristics of the emergency clothing:

- by increasing the thickness of the firefighter's emergency clothing [Min et al., 2007; Venkataraman et al., 2016] - the thickness of the fabric has a significant effect on the thermal behaviour of the textile substrate, which may be because the increase in the textile substrate's thickness affects the fabric's porosity due to the subsequent increase of the fabric. However, if the increase in thickness can cause significant increases in the corresponding weight of the textile substrate, this can make heat protection counter-productive [Stabkovic et al., 2008; Sombatsompop and Wood, 1997; Jin et al., 2018; Barr et al., 2010],
- by increasing the air gaps between different layers of emergency clothing [Fu et al., 2013; Li et al., 2007]: another approach is to increase the thickness of the air gap to a certain extent to increase the thermal protection ability of the firefighter's emergency clothing due to good thermal insulation. However, the size limit of the air gap between the layers is critical. Otherwise, it can lead to natural or emergency convection, which can reduce the thermal insulation properties of the emergency clothing [Li et al., 2007; Ghazy and Bergstrom, 2012],
- application of materials with phase change (Phase Change Material) to the thermal barrier of firefighter's clothing [Shaid et al., 2015; Noel et al., 2022] - in recent years, researchers have been using thermal barrier phase change materials to enhance the protection of emergency clothing, where these materials passively provide inward heat protection by absorbing heat from the external heat flow [Ali and Mohamed, 2015; Mehling and White, 2023],
- applying aluminium foil to the surface of the emergency clothing - this application causes better thermal stability and better protection on the outer surface of the emergency clothing, especially if the intervening firefighters are exposed to a high radiant heat flow. However, this, on the other hand, can cause problems with the breathability of emergency clothing [Yoldas et al., 2000; Tomaskova et al., 2022].

Methodology of the work

Regarding their barrier properties, the personal protective work equipment against the external impact of firefighters must meet the conditions given by ISO and EN standards. In parallel, however, some standards determine and evaluate thermal load and several other parameters that do not directly apply only to anti-chemical clothing but generally to protective clothing, load and environment. In practice, the minimum functional requirements for emergency clothing used for a long time during firefighting activities in an open space are thus established. In case of these requirements, it is necessary to define terms such as ageing and cleaning of clothing [STN EN ISO 13688:2013; STN EN 469:2021; STN EN 469:2021; EN 13688; Won and Yun, 2011].

Ageing is a change in product properties over time during use or storage. Ageing is generally a combination of many factors, such as exposure to visible and/or ultraviolet UV/VIS, high or low temperature, excessive humidity, wear and tear, maintenance, cleaning and disinfection. Ageing also inherently includes some different factors, such as:

- chemical nature - the influence of chemicals,
- biological nature - the presence of bacteria, funguses, insects and pests,
- mechanical damage - abrasion, pressure and stretching,
- contamination - the influence of dirt, oils, and molten metals [ISO 6942:2022; STN EN ISO 13688:2013].

Cleaning removes various impurities and contamination, after which the emergency clothing is again usable and/or satisfactory from a hygienic point of view. Directly related to cleaning is also the cleaning cycle, which is a cycle of washing and drying or dry cleaning, followed by ironing or other finishing if required [STN EN ISO 13688:2013; Krzeminska and Szewczynska, 2022].

Test samples must represent the material or combination used in the personal emergency clothing being tested. The number and size of the required test samples must be per the provisions of the relevant test methods. In all tests of material surfaces, only their outer surface – the exposed surface – is tested. The exposed surface also includes retroreflective and fluorescent material, or combined functional material, which must be attached to the outer surface of the emergency clothing. It must be visible from all sides by at least one belt encircling the clothing's arms, legs and torso area [STN EN 469:2021; EN 13688].

The goal is to specify, determine and verify the selected characteristics for light emergency clothing used by firefighters in the Fire and Rescue Service units to determine the conditions for the procurement and quality verification of the supplied emergency clothing.

Experiment procedure

The provider ensured the modernisation of the equipment, including the provision of sensing, recording and evaluation technology for evaluating the selected, tested characteristics of light emergency clothing used in the fire and rescue service units (F&RS units). The provider conducted the testing at the Fire Engineering and Expertise Institute of the Ministry of the Interior of the Slovak Republic. The provider supplied the ALMEMO modular system for obtaining and registering measured data with software, verified calibrated temperature sensors and a figurine for testing light emergency clothing. In cooperation with the Presidium of the Fire and Rescue Service, ten light emergency clothing were loaned for testing. As part of modernising the equipment, the provider also supplied a washing machine and a dryer with four types of cleaning agents. Individual types of cleaning agents were labelled:

- F3 - microemulsion detergent with decontaminating effect,
- F4 - means for cleaning reflective elements,
- F5 - detergent with disinfectant effect,
- F6 - detergent with disinfectant effect.

After the provider verified and trained FEEI members of the Ministry of the Interior of the Slovak Republic, light emergency clothing (LEC) was tested. In the individual steps of the research, parameters related to the wearing of the LEC, the colour fastness of the LEC, damage to the seams, the resistibility of the reflective elements, or the durability of the reflective elements were recorded. In this part of the research, there was a partial analysis of the wearing of the LEC due to mechanical stress on the LEC itself and the reflective elements of the given LEC, as well as detailed photo-documentation of the laboratory examination of the LEC. LEC testing using a washing machine and dryer, where regular wearing was simulated by washing according to the manufacturer's data on the LEC label during specific washing and drying cycles. The washing was carried out on samples of highly polluted LEC by petroleum substances, combustion products and other mineral oils.

Experience from the intervention of fire and rescue service units (F&RS units) indicates that the ideal way is to have directly mixed and prepared solutions in the concentration necessary and determined for decontamination. The manufacturer also provides ideal conditions for end users. In the research process, three types of cleaning agents were successively applied. In the first step, a detergent marked F3 was used, intended for degreasing firefighting clothing and other textile components of the equipment. It is intended for machine washing of emergency clothing soiled with petroleum substances, natural fats, or other substances of synthetic origin, where initial cleaning occurs in the presence of anionic and non-ionic surfactants.

The main goal is to avoid serious diseases due to long-term and repeated contact with dangerous and carcinogenic substances. The model is based on the basic thesis "from one intervention to another intervention". It summarizes the cyclical activity of firefighters during their service. [Nomeir and Doina-Abou; 1985; Brandmän, 2015].

The basis is that all equipment aimed at intervention is clean and free of toxic and dangerous substances. They belong here:

- personal protective work equipment,
- vehicle interior;
- means for body protection;
- means for respiratory protection;
- material and technical equipment located in the vehicle [Cavillo et al., 2019].

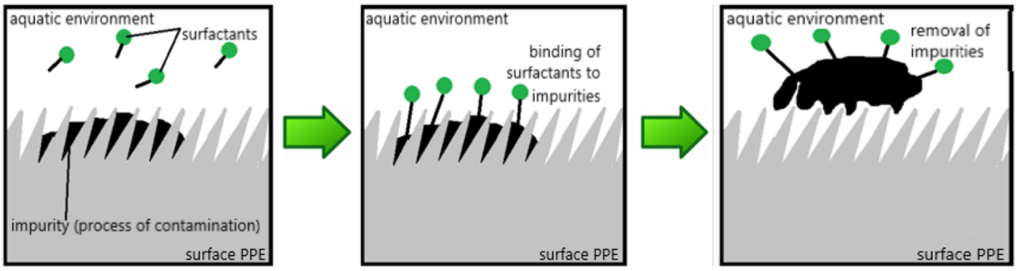

Fig. 3. A model picture of the sequence of continuous events from the initial contamination to binding and removal of the impurity (source: elaborated by authors)

The next step was the application of F4 preparation. A detached agent is a liquid cream with a micro-ground soft abrasive for pre-cleaning reflective PPE elements contaminated with soot and combustion emissions before washing in the washing machine. The composition and effect of the cleansing cream paste are based on anionic, non-ionic and amphoteric surfactants.

In the final stage, a combination of detergents marked F5 and F6 was applied. Detergent F5 is used for washing firefighting and emergency clothing with a decontamination effect. It is a liquid concentrate intended for washing and wet cleaning in a washing machine from a bath temperature of 15°C. The detergent is specially designed for machine washing emergency clothing after intervention and maintaining other personal textile equipment of firefighters. In terms of chemical composition, it is primarily a combination of ethanolamine (cleansing effect and maintenance of optimal pH), methylchloroisothiazolinone (a chemical substance used as a preservative) and benzyl alcohol, which not only serves as a solvent but is also known for its bacteriostatic effects. Detergent F6 is used to wash firefighter emergency clothing with a disinfecting effect, while this is an additive used to disinfect emergency clothing at temperatures of 40°-60°C. This detergent has a broad spectrum of all the agents used. It has bactericidal, fungicidal and antituberculosis effects. The indicator of the effectiveness of the detergent F6 is the content of a 15-30% bleaching agent based on active oxygen and the solution of hydrogen peroxide and peroxyacetic acid, among the best-known decontamination agents.

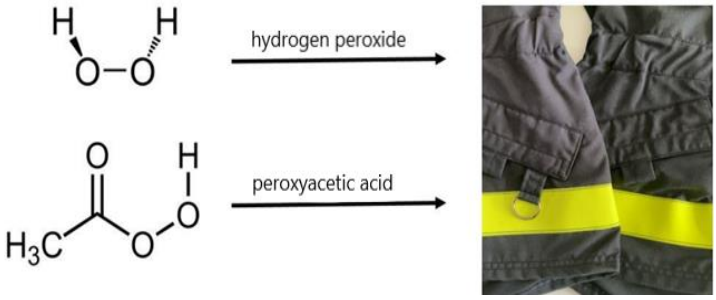

Fig. 4. Detailed visual comparison of emergency suits. Left LEC after several washing cycles, right LEC in original condition (source: elaborated by authors)

Results

Firefighters' emergency clothing is a classic personal protective equipment that is used to respond to all types of emergencies.

Colour fastness as an emergency clothing property for fire and rescue service units (F&RS units) is essential. In Figure 5, it is possible to see three pieces of PPE, while in the photo (a), they are arranged from left to right as follows:

- LEC that has been exposed to direct sunlight,
- LEC without any mechanical manipulation, protection against UV or VIS radiation,
- LEC is exposed to several cycles of washing and drying.

Visually, we can say that the changes were made to LEC no. 1, where the most significant loss of colour fastness occurred due to the action of UV/VIS radiation, as in the case of sample no. 3, where the original properties were affected due to mechanical handling and washing cycles. From the point of view of the stability of reflective elements in sample no. The three unevenness of the fluorescent material layer can be seen in (b) photo.

(a) (b)

Fig. 5. Comparison of LEC samples, loss of fluorescent material (source: elaborated by authors)

(a) (b)

Fig. 6. Loss of fluorescent element on PPE – incoherent exposed surface (source: elaborated by authors)

When testing the LEC, the minimum number of washing cycles was determined to be five according to the label on the emergency clothing, and the minimum concentration of the detergent intended for maintaining emergency clothing was also determined. Based on the material composition:

- 93% meta-aramids (MPIA) are known for thermal resistance with electrical insulation capabilities,
- 5% para-aramids (PPTA) are characterised by higher tensile strength and a higher elasticity modulus,
- 2% antistatic fibre.

The "mix" washing program was selected.

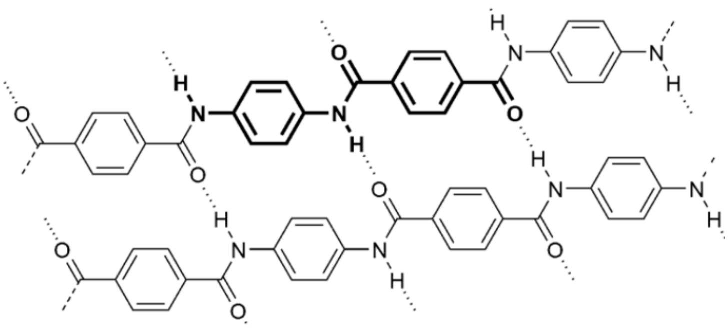

Fig. 7. The structural formula of synthetic aramid fibre [Deopura and Padaki, 2015]

Fig. 8. A label containing not only the composition and method of maintenance but also the relevant standards (in Slovak language) (source: elaborated by authors)

In the "mix" washing program, the conditions specified as standard were the same as those of the emergency clothing manufacturer - washing temperature 60°C.

Conclusion

The following conclusions can be drawn from the research:

- The individual characteristics and parameters listed on the label of the emergency clothing given by the manufacturer follow the applicable legal legislation that the manufacturer adhered to,

- If the number of repetitions exceeds individual washing cycles, destructive changes occur. Primarily in the retroreflective or fluorescent element and in the area of the seams. Changes can result in the risk of damage to health due to the influence of radiant heat, specifically the formation of burns, with long-term exposure to the radiant heat of heat in case of intervention during an emergency event with the occurrence of a fire. Also, with this damage to the emergency clothing, there is a risk of contaminants penetrating the skin of the intervening firefighters. Suppose they intervene in the event of a leak of a dangerous gas, liquid or biological substance. In that case, additional protection of the body surface with anti-chemical protective means is needed,
- In the case of interventions during fires, there is a risk of contamination of firefighters with polyaromatic hydrocarbons, carcinogenic substances and other substances that threaten the life and health of the intervening firefighters.

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