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Péter Pántya,[1] Lilla Horváth[2]

Analysis of the Material Characteristics of Firefighter Personal Protective Clothing

Abstract

The firefighter's personal protective apparel is the most significant aspect of the firefighter's profession since it protects practically the entire body of the firefighter. Protective clothing must not only provide protection during firefighting, but also against other environmental effects. The purpose of the article is for the authors to propose possible directions for development along with a description of the material and ergonomic characteristics of the personal protective clothing worn by firefighters. After processing the related Hungarian and international literature, the authors present all the material properties that serve as the basis for the protective ability of protective clothing. Based on these, the reader can deepen their knowledge within this topic. At the end of the article, the authors offer solutions and suggestions, in order to increase the resistance of the firefighting protective clothing and, in addition, to improve the ergonomic characteristics.

Keywords: firefighter, PPE, ergonomics, underwear, protective ability

Introduction

The human body detects and reacts to changes in the environment (e.g. temperature, humidity, etc.) with the help of the nervous system and the senses. These external stimuli affect the person's health, including their mood. The body strives for energy balance, so the goal is to maintain a constant level even in case of the internal temperature, i.e. the processes of heat gain and heat release should be in balance. Maintaining this internal balance is mostly influenced by the external environment.[3]

[1] Associate Professor, University of Public Service, e-mail: pantya.peter@uni-nke.hu
[2] University of Public Service, Doctoral School of Military Engineering, e-mail: lilla.horvath@katved.gov.hu
[3] Restás 2019: 320–350.

If this balance is disturbed, we are talking about thermal damage, of which the following types are known:

- thermal collapse: in this case, the fluid volume of the body and the blood supply to the brain decrease
- heat exhaustion: it usually results in a disturbance of the salt–water balance
- heat cramps: muscle cramps occur due to hyponatremia caused by sweating
- heat stroke: the body temperature rises to an abnormal range, the typical symptoms of which are: nausea, vomiting, tachycardia, dizziness, confusion, convulsions, body temperature higher than 40°C, coma[4]

Firefighters have to endure unusual conditions during their work, be it extreme weather conditions (ice, snow, extreme high or low temperatures, etc.), fire, or sudden mechanical and chemical impact on the human body during the technical rescue. The response to different events may vary from general to individual, but one factor remains the same for each person, and that is personal protective equipment. The protective clothing (firefighting protective jacket and protective pants, protective gloves, boots, hood, firefighting protective helmet) must be made of special materials due to the high level of stress. These properties include a certain degree of waterproofness, heat and flame resistance, as well as a higher degree of abrasion resistance.

Before describing the protective clothing, it is important to cover all the tasks and situations in which firefighters participate in their work, as this allows you to fully understand why it is necessary to talk about the material of the protective clothing and its development.

Regarding the activities of the firefighters who intervened, firefighting and technical rescue stand out the most. The figure below shows how the number of interventions in Hungary has developed in recent years (Figure 1).

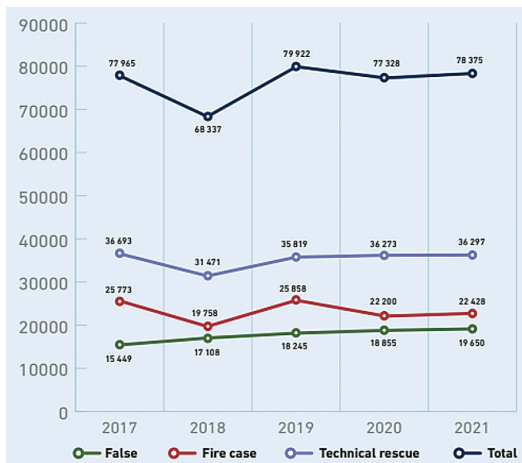

Figure 1: Annual fire dispatch data

Source: National Directorate General for Disaster Management, Ministry of the Interior 2021

[4] Radics 2016: 39–43.

In Hungary, based on the aggregated data, there has been no significant change in the number of different types of interventions in recent years, although a slight upward trend can be observed. The presentation of these data is important, because it shows how many times the firefighters have to intervene in hazardous environments in a year.

When most people think about firefighting, the first thing that comes to mind is intervention. During this, firefighters can be exposed to enormous heat stress, and in addition to their professional training, personal protective clothing provides (limited) protection against this. The proper wearing of this clothing must be learned as part of training since if the given person does not wear it properly, the clothing cannot provide the protection level that would ensure injury-free work. In addition, before the application, it is necessary to check whether the protective equipment has any damage or defects. If so, the protective equipment must be replaced immediately.[5]

The other – most common – intervention is the technical rescue, when they liquidate damage caused by major storms (e.g. cutting branches, lifting fallen tree branches from the road, etc.) or rush to rescue people trapped in vehicles and de-energise cars in the event of a car accident. In the process, they can suffer mainly mechanical and electric shock accidents. During these activities, not only a fallen tree or a vehicle battery can pose a danger to them, but also the dangerous machines they use. Appropriate prior theoretical and practical training is required for their use, and regular maintenance of the machines is also essential in order to avoid accidents.

In addition, they can also be affected by chemical effects, since firefighters are called to the scene during the transport of dangerous goods or in the event of an accident in a chemical plant. Even with adequate prior information, protective clothing may contain chemicals that can cause irritation, burns or other adverse effects in contact with the skin. Protective clothing must therefore be limited but resistant in this area as well.[6]

It can therefore be seen that danger can come from many directions and ways for firefighters, but some of them can be prepared by using certain professional knowledge and appropriate personal protective equipment (PPE), thus reducing the chance or extent of injury.

Protection and ergonomics

The manufacturers strive to develop and release on the market protective clothing that meets the minimum conditions of the standard requirements and also meets additional, higher-level expectations. For a fabric-based suit to be more resistant to mechanical effects and thermal stress, it may seem logical that its thickness should be increased, as long as the material properties remain constant. In this case, not only the thickness but also the mass increases, which makes movement more difficult. Based on the feedback from firefighters, movement is already limited in the current protective clothing, and the demand is moving towards lighter and more comfortable

[5] Pántya 2013: 47–58.
[6] Urbán 2019: 5–20.

clothing.[7] The task for manufacturers is therefore to produce lighter clothes, but at the same time more resistant. Is this even possible? Before answering this, it is worth taking a brief look at the world of material composition, since everything starts here.

Firefighter protective clothing consists of several layers to ensure flame resistance, waterproofness and vapour permeability at the same time.

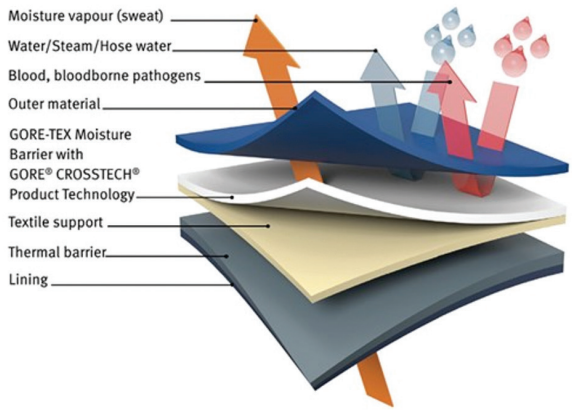

Figure 2: Roles of different layers within the firefighter's turnout gears
Source: Gore 2021.

The outer material of most firefighter protective clothing is Nomex®, patented by the Dupont company. Fibres have inherent flame retardant properties due to polymer chemistry. Nomex® meta-aramid, poly (meta-phenyleneisophthalamide) is produced by the reaction of meta-phenylenediamine and isophthaloyl chloride amide in a solvent (Figure 2).[8]

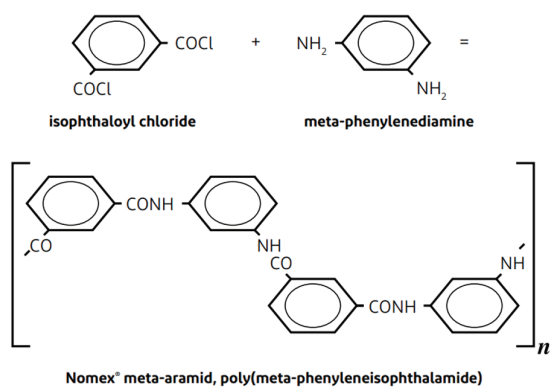

Figure 3: Synthesis
Source: Dupont s. a.

[7] Son 2019: 209–219.
[8] Dupont s. a.

In case of long-chain polyamide, at least 85% of the amide linkages are directly connected to two aromatic rings. The phenylene in the meta position bends into the polymer chain, in contrast to Kevlar® para-aramid, thereby reducing the rigidity of the chain. By connecting the aromatic rings and the conjugated amide bonds, an extremely strong and chemically resistant bond is created.[9]

With the help of chemistry, a solution has become available that can offer the user a higher level of protection compared to previously used materials. Of course, the example presented above is only one of many variations, but the reader of this article may find it interesting how a small change at the molecular level makes a huge difference at the material level.

Another manufacturer, Tencate, has a patent called Millenia™, which, thanks to its three layers, provides flame resistance, waterproofness, protection against chemicals, ventilation and evaporation, similar to clothing produced by Nomex®. In terms of its composition, it consists of polybenzoxazole, (PBO) Para-aramid and antistatic fibres.[10] PBO is a heat-resistant fibre with a benzene-fused oxazole ring structure (Figure 3). This fibre is roughly twice as strong as aramid fibres (Nomex®, Kevlar®) and ten times stronger than steel, making it the strongest man-made organic fibre.[11]

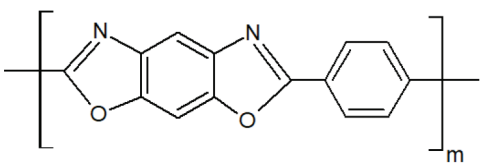

Figure 4: Polybenzoxazole
Source: Polymer Database s. a.

The multi-layered nature of firefighters' protective clothing ensures that it meets the ergonomic needs in addition to providing the adequate protection. So, in more rainy weather, it ensures waterproofness so that the clothes do not get soaked, and in a warm environment, in the event of perspiration, it can absorb the generated sweat and wick away the steam inside. This helps to prevent the firefighter from becoming ill from heat exhaustion during the intervention. A lot of research analyses the changing of the composition of materials and the number of layers to see how to create protective clothing that is more protective and at the same time more ergonomic. A study[12] found that the more the layers of a protective clothing, the higher the thermal protection, and it results in a significantly lower thermal comfort. They also described that the thickness and number of layers were of crucial importance in their measurements in terms of thermal protection and vapour permeability. In addition, it was determined that the material of the underwear has the greatest effect

[9] Dupont s. a.
[10] Tencate Protective Fabrics s. a.
[11] Polymer Database s. a.
[12] Eryuruk et al. 2022: 4480–4513.

on general comfort since the body is in direct contact with it and the resulting sweat must be drained away by this garment.[13]

Currently, in fire stations around the world, underwear is usually traditional outerwear and top and bottom sets, such as shirts, t-shirts, underpants, or shorts. The recommended material is cotton to avoid static build-up. The main purpose of these types of clothing is to absorb sweat, so currently they only fulfil an additional function. In the next section, the authors look for solutions by using the international literature, which can serve as help in the field of development.

Results based on literature

Many studies deal with ensuring a pleasant balance – i.e. when heat protection and vaporisation and ventilation coexist – since the goal is to ensure the work of firefighters by increasing the level of protection and comfort. One of the subjects of the study is the simultaneous use of aerogel and phase change material. A gel is usually an extremely light nanoporous material that is obtained from a gel and the liquid component of which is replaced by gas. Among many different types of aerogels, silica aerogel seemed the most promising, as it is non-combustible and have a much lower thermal conductivity than air under similar conditions. The firefighter's protective clothing was modified in such a way that aerogel was placed next to the material providing heat protection. After that, Shaid et al. found that the heat protection ability of the clothing increased, but the vapour was less able to escape, so the thermal comfort decreased considerably. To solve this problem, the spotlight is increasingly on the phase change material, of which the organic type is the most suitable for this type of activity – in addition to the inorganic and eutectic ones.[14] The aim of the experiment was therefore to modify the material of the firefighter's protective clothing in such a way that, in addition to ensuring safety, it also satisfies ergonomic aspects.

Another study by Chuansong Wu highlights that personal protective equipment can even be adapted to the activity. So do Chinese firefighters, who have several different types of clothing, depending on the type of danger they are facing at a given location. It is said that changing the weave of the material also has an impact on thermal protection and resistance to other influences.[15] The most effective solution for the future firefighter's protective clothing would be this solution, i.e. the incorporation of fibre among the existing ones that would be able to increase the protective capacity without negatively affecting the vapour permeability property.

In addition to changing the material of the outfits, it may be possible to add additional functions. As Ismar et al. demonstrated, in case of firefighters who intervene, it is possible to integrate a measuring instrument into a vest or even a simple belt, which continuously monitors the electrical phenomena of the heart (ECG). In addition, these measuring devices may be able to measure other signs of the human

[13] Eryuruk et al. 2022: 4480–4513.
[14] Shaid et al. 2016: 611–625.
[15] Wu 2019.

body, such as pulse, breathing rate, or body temperature.[16] These accessories can be extremely useful during the interventions, since on the one hand the system notifies the individual if they measure values that are different from the normal values. On the other hand, the data used will allow to understand the interventions from a physiological point of view and to develop more specific protective clothing. The possibility of indicating the external temperature conditions is no longer a matter of the future since many developments have already been made thanks to some manufacturers. It can also be vital for the wearer, especially for firefighters, as the signal from the instrument arrives in time during prolonged firefighting. In this way, a more serious health problem can be avoided, e.g. heat shock.

Anett Urbán and Ágoston Restás examined some solutions for the cooling of the firefighter's body during fire interventions. Their proposal is based on an extra vest as a technical addition for the turnout gears.[17] According to the authors, this type of solution currently represents such a high financial burden, which is why it is not certain that this direction is the right way for development. All kinds of bigger accessories that are not part of the clothing add extra weight to the user, so they get tired earlier than usual, and – especially in case of firefighters – due to the stress caused by the alarm and the quick preparation, the tool may be forgotten or not picked up properly, which can lead to accidents. According to the authors' point of view, the development direction itself is excellent, but the material, the weight and design do not yet meet the expectations of the technical novelties expected in the future.

Further developments in this area are expected in the future, but the course of experimentation is an extremely slow process, as it is necessary to get from the laboratory to the production and testing of the finished clothing product, which can take years. In the meantime, it is worth thinking about additional protection options, such as underwear, as these will also play a crucial role in the intervention. It would also be important to hear the views of as many firefighters as possible on the protective equipment, as they are the ones who use this equipment in daily practice. During the compilation of questionnaires and interviews, the interviewer should try to ask relevant and collected questions that will actually help the research process.

Discussion

Due to general technological advancements as well as the fact that structures, tools, human behaviour and even the nature of work have changed and are changing, firefighting protective clothing is constantly evolving. This is especially true when a threat, such as a fire, presents itself. Nowadays, the market almost expects clothing to meet not only the minimum necessary requirements, but also ergonomic aspects. A secure grip in gloves and easier movement in jackets and trousers are all factors that are not directly responsible for safety, but indirectly contribute to safer work, as the user has an easier movement and tool use. In addition, clothing and equipment can

[16] Ismar et al. 2020.
[17] Urbán–Restás 2017: 47–51.

be equipped with several accessories that contribute to safe work and can also fulfil a preventive function for the human body, e.g. an integrated heart rate monitoring system. This area could include several directions for improvement that researchers should address to provide a higher level of protection for intervening firefighters.

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