

APPLICATION OF NANOTECHNOLOGY IN THE DEVELOPMENT OF PERSONAL PROTECTIVE EQUIPMENT FOR FIREFIGHTERS AND RESCUERS

Lazar Miladinović¹ Radovan Radovanović² Nevena Puač³

Abstract: Nanotechnology is increasingly being applied in almost all branches of industry, including fire protection. Nanostructures can be incorporated into products and equipment designed for the direct protection of individuals involved in fire protection activities, such as personal protective equipment (clothing, footwear, protective helmets, and respiratory protection devices). This paper provides an overview of the practical applications of nanotechnology in the production and use of personal protective equipment for firefighters and rescuers. Additionally, the paper reviews existing studies with research results that highlight improvements in firefighter safety levels through the use of protective equipment incorporating nanotechnology. The aim of this paper is to establish a foundation for the development of nanotechnology in the fire protection sector, which necessitates continuous research in this field in the future.

Key words: nanotechnology, fire protection, personal and collective protective equipment.

1. INTRODUCTION

Nanotechnology refers to the understanding and manipulation of matter at the nanoscale, at dimensions approximately between 1 and 100 nanometers, where unique phenomena enable new applications. Matter can exhibit unusual physical, chemical, and biological properties at the nano level, which differ from the characteristics of bulk materials, individual atoms, and molecules. Some nanostructured materials are stronger or have different magnetic properties compared to other forms or sizes of the same material; others conduct heat or electricity better, may become chemically more active, reflect light more effectively, or change color when their size or structure is altered [1].

The application of innovative nanotechnologies can significantly transform many industrial sectors and completely change or modernize business methods and practices. Research results on the widespread use of nanotechnology in almost all industries and areas of life indicate that its application greatly improves the quality and properties of a wide range of products, from those used daily in individual life and work to those involved in the most complex technical and technological processes or those used in cases of accidents and emergencies that could jeopardize the safety and health of people, material assets, and the environment.

Nanotechnology and nanomaterials play an increasingly significant role in enhancing fire protection systems, as their application offers new possibilities for developing more efficient materials and technologies that can improve fire resistance during fires, thereby ensuring greater safety not only for individuals endangered by fire but also for all those involved in firefighting and rescue operations during fires and other emergencies (firefighters and rescuers, police officers, military personnel, and emergency medical staff).

The application of nanotechnology and nanomaterials in the field of fire protection can be observed through the following aspects:

- Improvement of fire resistance of materials and their properties when directly exposed to flames, high temperatures, and combustion products that may occur during a fire. The use of nanomaterials can significantly enhance the thermal characteristics of the material, primarily by making it more resistant to high temperatures. Additionally, the addition of nanoparticles can prevent or slow down the spread of flames on the material affected by the fire, thereby increasing reaction time, which allows for more efficient evacuation of endangered individuals as well as timely and adequate response and firefighting efforts. These properties of nanomaterials are particularly beneficial for the development of personal and collective protective equipment used by firefighting and rescue services and other emergency services.
- Enhancement of the mechanical characteristics of materials used for the production of personal and collective protective equipment. Furthermore, the use of nanotechnology and nanomaterials can improve resistance to moisture and water used during firefighting operations, as well as resistance to the effects

¹Lazar Miladinović, specialist criminalist, „Securitas Se“ Ltd. Belgrade, email: miladinovic.laza@gmail.com

²PhD Radovan Radovanović, University of Criminal Investigation and Police Studies, email: radovan.radovanovic@kpu.edu.rs

³PhD Nevena Puač, Institute of Physics Belgrade, email: nevena@ipb.ac.rs

of aggressive and hazardous substances that may arise during technical and technological accidents and disasters.

- Utilization of intelligent technical protection systems for the detection and monitoring of fire causes and other emergencies. This primarily refers to the use of nanodetectors—sensors utilized in fire detection and alarm systems. These sensors work by monitoring changes in predefined parameters within the working and living environment and respond to any deviations, thereby indicating the early signs of a fire. The use of nanotechnology in such sensors allows for better monitoring of environmental parameters, such as temperature, the presence of light, combustion products (primarily smoke), as well as various gases and vapors depending on the type and characteristics of the burning material. This enables precise detection of early fire indicators, which reduces the number of false alarms on the one hand and facilitates early fire detection, localization, and extinguishment on the other.
- Application of nanocoatings and paints, where nanomaterials are used to develop specific coatings and protective paints that shield materials from exposure to fire by creating a barrier that prevents fire penetration into the material's structure, thereby inhibiting its further spread.
- Increasing the efficiency of equipment, devices, and tools used for firefighting. The application of nanotechnology can enhance the efficiency of firefighting equipment, devices, and tools, while the development of lightweight yet durable nanomaterials contributes to the creation of innovative equipment that is easier and safer for firefighters to handle. Research into nanostructured materials enhances understanding of their thermal, electrical, and chemical properties, enabling better design of equipment, devices, and tools used in fire protection.

All of the above indicates that the application of nanotechnology and nanomaterials in practice can extend the time during which structural integrity and material properties remain unchanged when directly exposed to fire and the effects of a fire. This minimizes or eliminates the consequences of fire to the greatest extent possible, which, in addition to improving safety, can also have significant material and economic benefits.

In this context, the development and integration of nanotechnology and nanomaterials in the field of fire protection and emergency management is a priority. Research in this area should be directed toward enhancing human safety as well as improving the efficiency of fire protection systems.

2. APPLICATION OF NANOMATERIALS IN THE MANUFACTURE OF PERSONAL PROTECTIVE EQUIPMENT AND GEAR

The complexity and severity of various interventions by firefighting and rescue units highlight that their readiness and equipment for rapid and adequate response are primary prerequisites for success in protecting and rescuing people and material assets, especially in cases of large-scale fires and mitigating their consequences [2].

Fire prevention and extinguishment is a complex activity that, in addition to a good understanding of the properties of materials and technological processes, requires a thorough knowledge of firefighting techniques. Adequate and effective use of technical equipment in fire prevention and extinguishment always yields positive results. However, it is essential to emphasize that a poor assessment of the situation before initiating firefighting efforts, leading to inadequate use of technical equipment and personal protective gear, can have fatal consequences, including material losses and loss of human lives.

To successfully carry out firefighting and rescue operations, firefighting and rescue units utilize protective equipment, which can be categorized as follows:

- Personal protective equipment: Issued to each firefighter-rescuer individually, it serves to ensure their personal safety and protect the entire body or specific body parts during operations. This includes work clothing and footwear, firefighter protective helmets, work (climbing) belts, protective masks, climbing ropes, and flashlights.
- Collective protective equipment: Used by firefighting and rescue units, it ensures not only personal safety but also collective safety during operations under specific working conditions. This category includes protective gear against flame and heat, respiratory protection equipment, protection against acids, bases, and aggressive substances, as well as protection from radioactive sources of radiation.

Personal protective equipment used by firefighters during firefighting and emergency response operations plays a significant role, primarily in ensuring their safety and protection, which directly influences the success of task execution under hazardous working conditions during firefighting efforts. This equipment is highly engineered and designed to provide balanced protection for the firefighters while also meeting ergonomic and safety requirements.

In the legislation of the Republic of Serbia, this field is regulated by the adoption of the Rulebook on Personal Protective Equipment ("Official Gazette of RS," no. 23/2020) [3].

According to the American NFPA standard, this personal protective equipment encompasses a wide range of items, including:

- Protective helmets, which are among the most critical components of personal protective gear, protecting the firefighter's head from mechanical hazards, heat, and chemical exposure encountered during firefighting operations.
- Face protection equipment, such as protective masks, goggles, and visors that shield the face and eyes from smoke, gases, particles, and mechanical hazards.
- Protective clothing, designed using materials that ensure protection against mechanical, thermal, and chemical hazards.
- Protective gloves, which safeguard firefighters' hands from mechanical, chemical, and other hazards.
- Protective footwear—boots made from materials that provide protection against mechanical and thermal hazards, as well as chemical exposure encountered during firefighting operations [4].

In terms of regulatory frameworks and legislation in the European Union, fire protection guidelines are primarily outlined in Regulation (EU) 2016/425 on personal protective equipment, which repealed Council Directive 89/686/EEC and Directive 89/656/EEC. This regulation establishes minimum health and safety requirements for the use of personal protective equipment. Personal protective equipment is divided into three categories:

- Protection against minimal risks (Category I),
- Protection against specific factors that do not endanger life or health and cannot cause permanent health damage to employees (Category II),
- Specialist protective equipment, designed to protect against factors that can cause the most severe consequences for employees, such as death, serious, and permanent health damage (Category III) [5].

All the aforementioned regulations indicate that personal protective equipment must include gear, devices, and tools that are designed and engineered to ensure the safety of firefighters by providing adequate protection for the entire body or specific parts from one or more hazards they may be exposed to during firefighting and emergency response operations. To ensure that personal protective equipment meets prescribed safety and protection requirements, it must comply with all applicable local legislation, international regulations, and standards in this field.

The most common requirements for personal protective equipment used by firefighters include, among others, resistance to high temperatures and flames, resistance to chemical and hazardous substances, mechanical resistance (e.g., to abrasion, tearing, and punctures), and suitability for use in both indoor and outdoor environments.

In addition to safety and protection requirements, personal protective equipment must also be ergonomically designed, comfortable, and functional for the activities it is intended for. Given the wide range of parameters that define safety, protection, and ergonomics for firefighters involved in firefighting operations, the manufacturing, selection, and use of personal protective equipment require a specialized approach. This is particularly true for the selection of materials used to manufacture individual components of personal protective equipment, as these materials are subject to continuous modifications, including the integration of nanotechnology [6].

The use of improper protective equipment, lack of knowledge about its characteristics, or the absence of even one piece of protective gear can result in injuries ranging from minor to severe, or lead to the failure of an individual's intervention. This, in turn, can compromise the success of the team and, ultimately, the entire

operation. Therefore, during firefighting and rescue interventions, the use of complete protective equipment is essential, including:

- Personal firefighter protective equipment, which is assigned to each firefighter-rescuer and includes:
 - Work protective clothing and footwear,
 - Intervention protective equipment.
- Collective firefighter protective equipment, managed by the firefighting unit and includes:
 - Protective equipment against flame and heat,
 - Respiratory protection equipment,
 - Protection against acids, bases, and aggressive substances,
 - Equipment for protection against radioactivity [7].



Figure 1. Personal protective equipment used by firefighters [8]

In addition to work protective clothing and footwear used during regular work activities in shifts, every firefighter is also equipped with intervention protective gear used during all interventions. This intervention protective gear includes: firefighter protective clothing (jacket and trousers), firefighter protective gloves, firefighter protective boots, firefighter protective helmet with scarf, balaclava, and lamp, firefighter rescue belt with an axe and a short rope. The firefighter protective clothing is two-piece and consists of a jacket and trousers with overlapping sections. It provides protection to the upper and lower torso of the firefighter, neck, arms, and legs, excluding the head, hands, and feet. Due to its essential use during interventions, it is also referred to in practice as the intervention protective uniform [2].

The aforementioned protective clothing must be made of materials that provide maximum protection against harmful influences that may occur during firefighting. This means that it must be made of flame-resistant material capable of withstanding fire and high temperatures for a certain period while allowing heat exchange and absorption of body moisture produced by firefighters during physical exertion, and it must be waterproof. Additionally, this clothing must be designed to enable quick dressing in preparation for an intervention and must have fluorescent reflective strips sewn onto it to ensure that the firefighter is easily visible in low-visibility conditions, at night, or in darkened spaces.

When it comes to protective footwear, it must provide protection for the firefighter's feet against heat radiation and mechanical injuries caused by sharp objects during interventions. This protection is achieved through the use of multilayer thermal insulation and steel reinforcements in the toe and heel sections of the footwear.

To ensure compliance with all specified safety, protective, and ergonomic requirements, inherently flame-resistant fabrics and fibers, or chemically modified and treated fabrics and fibers with

high resistance to fire and elevated temperatures, are used during the production of protective clothing and footwear.

It is important to note that the terms "inherent flame resistance" and "modified, treated flame resistance" are not synonymous, and there are significant differences. Inherent flame resistance refers to a material's property that enables it to resist fire because the fabric and fibers themselves have built-in properties that prevent or reduce the spread of fire. In this regard, protective clothing for firefighters that is inherently flame-resistant is made from fabrics and fibers that are, by their very nature, resistant to fire. This approach provides long-lasting and stable protection over time because inherent flame resistance does not deteriorate with time or frequent washing of the clothing.

This contrasts with modified, treated flame resistance, where fabrics and fibers are chemically treated to become fire-resistant—that is, their properties are altered through chemical treatments to gain fire-resistant characteristics that were not originally present in the fabrics and fibers.

However, it should be noted that these are marketing terms lacking a scientific basis. According to available marketing literature, it is often implied that one method is superior to the other, with the marketing angle being that treated fabrics lose their properties over time or with washing, while inherent fabrics do not. Nevertheless, as with everything in life, no method is perfect, and each has its advantages and disadvantages. Over time, perceptions have formed in the market that are simply not confirmed by testing or scientific evidence when it comes to flame-resistant fabrics and fibers [9].

Inherently flame-resistant fabrics and fibers used in the production of protective equipment for firefighters include compounds such as:

- Polyamides, such as poly(p-phenylene terephthalamide),
- Imide derivatives, such as polyaramid-imide, polyimide, and polyetherimide,
- Compounds containing azole groups, such as polybenzimidazole and polybenzoxazoles,
- Halogenated compounds, such as chlorinated and fluorinated,
- Melamine-formaldehyde,
- Polyetheretherketones,
- Phenolic compounds,
- Polyphenylene sulfide,
- Polyacrylates,
- Semi-carbon compounds,
- Glass and ceramics.

It is important to note that aramid fibers, which are aromatic polyamides, are known by the trade name „Kevlar™“, „Technora™“, „Twaron™“, poly(p-phenylene terephthalamide), „PPD-T“) or „Nomex™“, „Newstar™“, poly(m-phenylene terephthalamide), „PD-T“, „PPDT“ or „PPTA“) and „Conex™“, poly(m-phenylene isophthalamide), MPIA) [6].

Amides are chemical compounds that result from the reaction between a carboxylic acid and an amine. Specifically, amides are derivatives of carboxylic acids in which the –OH group is replaced by an –NH₂, –NHR, or –NR₂ group. These are referred to as unsubstituted, mono-, and dialkyl amides, or primary, secondary, and tertiary alkyl amides. The structure of an amide is inherently more complex due to the existence of a π -interaction between the C=O group and the lone electron pair on the nitrogen, i.e., the presence of the –R effect exhibited by the –C=O group and the +R effect of the –NH₂ group. As a result, the C–N bond acquires partial double-bond character, while free rotation around it is hindered [10].

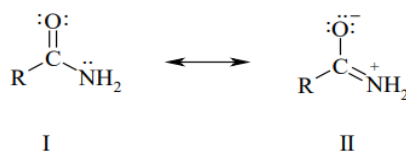


Figure 2. Resonance structure of the amide [10]

Amides play an important role in the production of synthetic polymers. For example, nylons are a type of amide used in the production of various types of textiles, equipment, and packaging. Additionally, amides are used in the pharmaceutical industry for the synthesis of drugs and play an important role in biochemistry as components of biological molecules such as proteins and nucleic acids. Therefore, these characteristics of amides suggest their potential application in various areas of chemistry and industry.

Aramids represent a group of exceptionally strong polymers that contain amide bonds in their molecules. These polymers possess outstanding mechanical and thermal properties, making them extremely useful in various applications. They are characterized by an increased number of conjugated double bonds in aromatic rings within their molecular structure, and the presence of these conjugated double bonds contributes to their exceptional physical properties. Polyaramids have a wide range of applications in the production of protective elements and personal protective equipment used to protect against heat as well as mechanical injuries caused by sharp objects. Specifically, aramid polymers are widely used in the production of technical textiles that are characterized by exceptional durability and thermal stability. Aramids are also applied in the creation of light and strong materials used in aerospace and aircraft construction, as well as in the automotive industry. In certain cases, aramids can also be used in the production of medical implant equipment.

Aramid fibers consist of synthetic linear macromolecules formed from aromatic groups connected by amide or imide bonds, with at least 85% of these bonds directly linked to two aromatic rings. In the case of imide bonds, their number does not exceed the number of amide bonds.

Meta-aramids represent a subgroup of aramids with amide bonds arranged in the meta position relative to the carboxyl group in their molecules. Chemically, these polymers are characterized by atomic configuration in their molecules. One example of a meta-aramid is poly(meta-phenylene isophthalamide) (MPDI), which contains amide bonds arranged in the meta position and has various applications, primarily in the production of fire protection equipment [11].

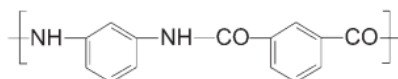


Figure 3. Structure of poly(meta-phenylene isophthalamide) [12]

Para-aramids are polymers that contain amide bonds in the para position relative to the carbonyl (C=O) group in their molecules. These polymers are known for their exceptional mechanical strength and thermal stability, making them suitable for numerous applications. One example of a para-aramid is poly(para-phenylene terephthalamide), commonly known as Kevlar™. Kevlar™ is widely used in protective clothing, fire protection equipment, the automotive industry, and other areas where exceptional durability and heat resistance are required [13].

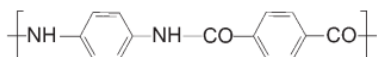


Figure 4. Structure of poly(para-phenylene terephthalamide)[12]

To achieve better characteristics and fabric properties, a mixture of different materials is often used in practice, where meta-aramids and para-aramids are regularly combined. This results in a fabric where the meta-aramid contributes good fabric properties related to comfort, dyeing ability, etc., while the para-aramid ensures the fabric has high mechanical strength and thermal resistance. For similar reasons, polybenzimidazole is mixed with para-aramids, resulting in a fabric with improved properties such as better moisture removal, a softer feel on the skin when wearing the clothing, and increased softness and fineness of the fabric. An additional advantage of such fabrics is also their reduced cost [14].

These fibers typically do not contribute to the overall flammability of the polymer matrix composite (PMC) because they tend to char or form ash when exposed to fire. Furthermore, aramid fibers burn faster than carbon fibers. Cellulose fibers, used to reinforce PMCs, are generally employed in composites with lower performance and bio-renewable PMC composites. Although these fibers may

burn with the polymer and negatively impact flammability, in the presence of flame retardants, cellulose fibers can serve as additional sources of carbonization for fire protection in formulations that expand. Such behavior is often not observed with glass or carbon fibers [15].

The goal of modification is to achieve a limited oxygen index, which represents the minimum percentage of oxygen required for combustion. The techniques applied for the production of chemically modified fire-resistant fibers depend on the type of base fiber in the process, whether synthetic – nylon, polyester, acrylics, etc., or natural – cotton, wool, viscose, etc. During modification, various substances are used to retard fire development, with halogens, nitrogen, silicon, and phosphorus being the most commonly used. These substances can be incorporated into the polymerization process or added during fiber preparation from solution, and the fibers, when exposed to high temperatures and fire, form a gaseous-phase (non-volatile ester compound) or a condensed solid-phase (carbonized carbon compound). All of this reduces the flammability of the fabric, and such modified materials play a significant role in maintaining the integrity of personal protective clothing when exposed to fire [16].

A large number of scientists have researched the properties of fire-resistant fabrics and fibers, and the results indicate that the application of nanotechnology in the production of fabrics and fibers used for personal protective equipment for firefighters is beneficial. Scientists Mandal, Annaheim, Greve, Camenzind, and Rossi [17] conducted research and comparative studies on single-layer and multi-layer fabrics developed using conventional or nanotechnology, specifically nano nonwoven fabric. The study involved 6 single-layer and 13 multi-layer fabrics used for the production of personal protective equipment worn by firefighters. Characteristics such as weight, thickness, air permeability, evaporation resistance, and water spreading speed were tested using standard testing methods developed by the International Organization for Standardization (ISO) or the American Association of Textile Chemists and Colorists (AATCC).

The study measured the efficiency of thermal protection under conditions of flame exposure and radiant heat of varying intensity, finding that the protective performance of the fabrics exposed to different heat intensities (10 kV/m² radiant heat, 40 kV/m² radiant heat, and 80 kV/m² flame) were linearly correlated. This indicates that heat absorption and energy degradation generated by the fabrics are aligned under all heat conditions and intensities. The study showed that thermal resistance and evaporation resistance are key fabric properties that directly affect protective performance. Specifically, fabric weight and evaporation resistance were found to inversely affect comfort performance. On the other hand, the moisture spreading rate in the fabric in contact with the firefighter's skin was identified as a key property that directly influences comfort performance [17].

All of this suggests that when choosing fabrics for personal protective equipment for firefighters, a balance must be considered between thermal protection performance and fabric comfort. This is where nanotechnology and nanomaterials play a crucial role, as they improve the thermal properties of the fabric without increasing its weight or thickness, thereby preserving the ergonomic characteristics of the fabric and not compromising comfort during wear, especially under challenging working conditions that firefighters face during intervention and emergency response.

Existing research has shown that the weight and thickness of fabrics containing nano nonwoven materials have classified them among the three thinnest and five lightest fabrics. Additionally, the investigation of thermal resistance parameters, air permeability, and moisture spreading speed (i.e., sweat) demonstrated that these fabrics belong to the group of five fabrics with the best parameters. This means that the properties of fabrics containing nano nonwoven materials indicate that these fabrics meet the requirements for both protection and comfort [6].

Other scientists have also studied this area, focusing on the protective performance of aerogel nonwoven materials used in the production of personal protective equipment for firefighters during fire suppression and emergency response. The research showed impressive results, indicating a drastic reduction in the risk of burns for firefighters when exposed to fire and high temperatures. Furthermore, the studies showed an increase in comfort without compromising protective performance.

The results of the research show that aerogel nonwoven fabric can provide up to five times greater heat resistance, while the heat resistance is eight times higher than that of commercial materials used

in the production of personal protective equipment for firefighters. These materials also demonstrated significant resistance to heat and pressure before burns occurred. The research showed that a firefighter would experience instant burns within a maximum of 30 seconds using commercial reinforcement materials, while using only aerogel nonwoven fabric, the firefighter would feel mild pain after 86 seconds, first-degree burns after 107 seconds, and more severe burns after 150 seconds. Thus, using aerogel nonwoven material in the production of personal protective equipment would give the firefighter more than 60 additional seconds to retreat from a dangerous area in the event of an emergency that could compromise firefighter safety. These studies also demonstrated significantly better properties of such materials in terms of air permeability and improved moisture evaporation cooling [18].

Scientists Lessan, Montazer, and Moghadam [19] conducted research on the development of new flame retardants that can be applied to cotton fabrics using sodium hypophosphite, maleic acid, triethanolamine, and nano TiO_2 through the conventional dry curing method. They tested charring length, char yield before and after five washing cycles, limited oxygen index, and whiteness index of treated cotton fabrics. The results indicated the significant role of sodium hypophosphite, where using 5% of it increased the limited oxygen index from 18.6 to 23, leading to a lower initial decomposition temperature and greater carbon formation. Additionally, nano TiO_2 proved effective in increasing carbon formation. Titanium dioxide (TiO_2) is a white, naturally occurring mineral that is often used as a whitener and opacifier in various products. Nano-sized TiO_2 is a well-known photocatalyst characterized by high chemical stability, good heat resistance, and non-toxic properties, with no negative health consequences for humans. It was also found that the presence of 6% triethanolamine significantly prevented cotton fabrics from yellowing during the drying process [19].

Due to the increasing market demand for materials that are resistant to heat and flame while maintaining safety, comfort, and functionality of personal protective equipment, as well as being cost-effective, more research is being conducted on methods for the simple casting of fire-resistant composite materials consisting of hydrogels and fabrics, based on acrylamide and SiO_2 . The results of this research suggest that the active diffusion of water-based SiO_2 gel into the textile structure led to the formation of strong interfacial adhesion between the hydrogel and textile, with the resulting bonds based on semi-permeable polymer networks and fibers at the interface. Silicon was used to limit the expansion of the hydrogel, also acting as a physical crosslinker and inorganic filler to improve the mechanical properties and interfacial bonding of the composite. The application of the hydrogel as a coating layer contributes to the improvement of the protective insulating properties of nonwoven fabrics. Thus, this simple yet cost-effective method opens up possibilities for the production of hybrid materials for use in firefighting and personal protective equipment manufacturing [20].

All the mentioned research shows that the use of nanotechnology and nanoparticles in the production of materials for personal protective equipment used by firefighters improves mechanical, thermal, insulating, and electrical properties, thereby reducing material flammability and providing greater protection for firefighters during fire suppression and emergency response. Moreover, the above research indicates that combining nanoparticles with other flame retardants can enhance certain properties of fire-resistant materials.

Traditional textile processing methods used in the production of personal protective equipment for firefighters are based on passive protection, while the application of nanotechnology and nanomaterials enables the creation of "smart clothing" that provides active protection by greatly slowing the rise in temperature of the external layer of the material. "Smart clothing" also provides other advantages, such as incorporating various types of sensors within its structure, allowing for tracking of location and the physiological condition of the wearer. Furthermore, wireless communication systems are embedded in such textiles, which, particularly in personal protective equipment for firefighters, can significantly increase safety during fire suppression operations and emergency response. In fact, intelligent textiles are simple computing systems that consist of five elements: sensors, actuators, a data processing unit, memory for data storage, and a communication system for data transmission [21].



Figure 5. Functions of intelligent textiles and their application in the production of firefighter protective gear [22].

„Smart clothing“ represents an innovative form of clothing production and use, which integrates microcomputers directly into the fabric, i.e., this type of clothing is created by combining computing, electronic, and digital components into textile materials, enabling it to respond to external stimuli and environmental conditions. Protective clothing for firefighters made using this technology is usually equipped with various sensors that measure bodily functions (pulse, blood pressure, temperature, and other human body parameters), detect toxic gases, and measure external temperatures. The data about the condition of the protective equipment is monitored and analyzed, allowing for the optimization of firefighter protection and improving their performance in the difficult conditions encountered during fire incidents. The use of nanotechnology and nanomaterials in the production of "smart textiles - clothing" is an inevitable process.

Finally, all research has shown that nanofabric made from conventional materials used in the production of personal protective equipment for firefighters differs in that it exhibits significantly better properties in five main areas:

- It has a low weight, which significantly reduces the overall weight of the personal protective equipment,
- Hydrophilicity or hydrophobicity,
- Flame resistance,
- Flexibility, and
- Filtration.

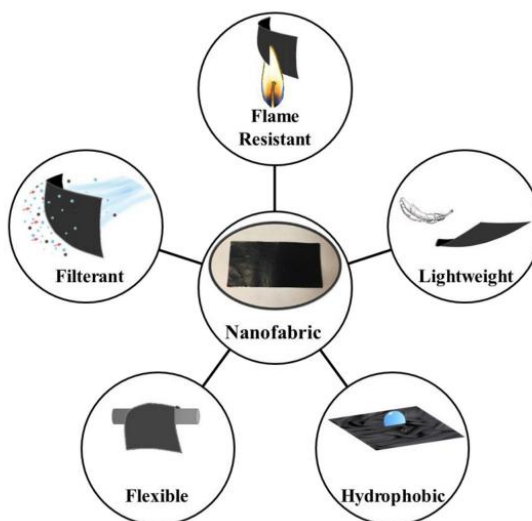


Figure 6. Basic properties of nanofabric [23]

3. CONCLUSION

The increasing use of nanotechnology in the production of materials for fire protection has elevated fire safety measures to a higher level, particularly in protecting firefighters involved in firefighting operations and responding to emergency situations, as well as in protecting buildings and industrial plants.

The use of nanomaterials, nanofibers, and nanoadditives allows for significant improvements in the properties of materials used in the production of personal protective equipment for firefighters. All research has shown that their use enhances the mechanical, thermal, insulation, and electrical properties of fabrics, thereby reducing the flammability of materials and providing greater protection to firefighters during firefighting interventions and responses to emergencies. In addition to improving the protective properties of materials, nanotechnology also preserves and greatly enhances the ergonomic characteristics of personal protective equipment, especially in terms of comfort and flexibility.

However, it should be noted that the development of new nanomaterials, despite all their positive characteristics, also has some negative aspects in terms of potential risks to human safety and health, as well as to the environment. In this regard, further research is needed to focus on the application of nanotechnology in fire protection and reducing the negative impact on the safety and health of firefighters and the environment.

4. REFERENCES

- [1] National Nanotechnology Initiative. (s.d.). "What is Nanotechnology?", preuzeto 15. januara 2025. godine, sa <https://www.nano.gov/nanotech-101/what>.
- [2] Božović, M.: *Razvoj baze podataka za upravljanje rizicima na radu vatrogasno-spasilačkih jedinica u uslovima multirizika* (Doktorski rad). Fakultet zaštite na radu, Niš, 2021.
- [3] Pravilnika o ličnoj zaštitnoj opremi ("Sl. glasnik RS", br. 23/2020).
- [4] NFPA 1971 „*Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*”, 2013.
- [5] 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.
- [6] Rabajczyk, A.; Zielecka, M.; Popielarczyk, T.; Sowa, T.: *Nanotechnology in Fire Protection - Application and Requirements*. Materials 2021, 14, 7849, 2021.
- [7] Nikolić, S.: *Optimalni izbor vatrogasne zaštitne opreme pri intervencijama gašenja požara* (Magistarski rad). Fakultet zaštite na radu, Niš, 2018.
- [8] <https://sindikativvatrogasaca.org.rs/2018/03/>
- [9] Margolin, S.: *Flame Resistant Clothing: Get “The Facts,” not “The Story”*, Occupational Health & Safety, 2012.
- [10] Arsovski, V.: *Eksperimentalna i kvantno-hemijska proučavanja hinolonskih azo boja i njihovih prekursora* (Doktorska disertacija). Tehnološko-metalurški fakultet, Beograd, 2016.
- [11] Karsner, B.: *Meta-Aramid Fibers*. Journal of Engineered Fibers and Fabrics, Vol 5, I 4, 2010.
- [12] Magdalenic, B; & Bujanic, B.: Aramidna vlakna. *Polimeri: časopis za plastiku i gumu*, 32(3-4), 130-134, 2011.
- [13] Rošanžamir, A.; Šahnijarov, V.: *Poly(p-phenylene terephthalamide: A Review on Fiber and Composite*, J. Appl. Polym. Sci., 2012, 125, E421–E434, 2012.
- [14] Regent, A.: *Inherentna i tretirana vatrootpornost odjeće*, Vatrogastvo i upravljanje požarima, 2013.
- [15] Ru-Min, W.; Shui-Rong, Z.; Ya-Ping, Z.: *Polymer Matrix Composites and Technology*, Woodhead Publishing Limited, 2011.
- [16] Sheng, Z.; Xiong, Y.; Meiwu, S.: *The flame retardancy and pyrolysis mechanism of polyimide fibers investigated by cone calorimeter and pyrolysis–gas chromatography–mass spectrometry*, Journal of Industrial Textiles Volume 48, Issue 2, August 2018, 465-481, 2018.
- [17] Mandal, S.; Annaheim, S.; Greve, J.; Camenzind, M.; Rossi, M.: *Modeling for predicting the thermal protective and thermophysiological comfort performance of fabrics used in firefighters’ clothing*, 2836–2849, 2019.

- [18] Shaid, A.; Wang, L.; Padhye, R.; Bhuyian, R.: *Aerogel nonwoven as reinforcement and batting material for firefighter's protective clothing: A comparative study*, 95–104, 2018.
- [19] Lessan, F.; Montazer, M.; Moghadam, A.: *Novel durable flame-retardant cotton fabric using sodium hypophosphite, nano TiO₂ and maleic acid*. *Thermochim. Acta* 2011, 520, 48–54, 2011.
- [20] Nie, Y., Mugaanire, T.; Guo, Y.; Wang, R.; Hou, K.; Zhu, M.: *A hybrid hydrogel/textile composite as flame-resistant dress*. *Progress in Natural Science*. *Materials International* 31, 33–40, 2021.
- [21] Gavanski, D.; Petrović, V.: *Primena inteligentnog tekstila u vatrogasnoj zaštitnoj odeći*. 18. Konferencija sa međunarodnim učešćem zaštita od požara i eksplozije, 2023.
- [22] <https://www.moreinspiration.com/article/2046/turnout>
- [23] Hou, G.; Kim, J.; Beaucage, G.; Schulz, M.: *Carbon nanofabric: A multifunctional fire-resistant material* Vianessa Ng, *Carbon Trends*, 2022.