

Firefighting: Challenges of Smart PPE

Gilda Santos ^{1,*} , Rita Marques ¹, João Ribeiro ², Adriana Moreira ², Patricia Fernandes ², Margarida Silva ^{3,4}, André Fonseca ^{3,4}, João M. Miranda ^{3,4} , João B. L. M. Campos ^{3,4}  and Soraia F. Neves ^{3,4} 

¹ CITEVE—Technological Centre for the Textile and Clothing Industries of Portugal, 4760-034 Vila Nova de Famalicão, Portugal

² CeNTI—Centre for Nanotechnology and Smart Materials, 4760-034 Vila Nova de Famalicão, Portugal

³ CEFT—Transport Phenomena Research Center, Department of Chemical Engineering, Faculty of Engineering, University of Porto, s/n Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

⁴ ALiCE—Associate Laboratory in Chemical Engineering, Faculty of Engineering, University of Porto, s/n Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

* Correspondence: gsantos@citeve.pt

Abstract: The continuous research and development regarding firefighters' personal protective equipment (PPE) has led to significant improvements in recent decades. Despite the evolution of firefighters' PPE, every year an undesirable number of firefighters are seriously burned during firefighting operations, with some of them eventually losing their lives. The protection given by firefighters' PPE can be further increased with the incorporation of smart textiles in the personal protective equipment, namely, wearable electronics (i.e., integrated sensors to monitor diverse parameters: heart rate, oxygen saturation, carbon dioxide detector, and setting real-time communication with a command post) and advanced materials such as phase change materials (PCMs). The evolution of firefighters' PPE has been followed by an evolution and update in the international and national standards that specify performance requirements for firefighters' protective clothing for structural and wildland firefighting as well as technical rescue. This study will focus on the analysis of firefighters protective clothing evolution regarding the use and integration of advanced smart materials, namely, phase change materials, taking into consideration the evolution and requirements of international and European standards as well as national legislation for firefighters' protective clothing.

Keywords: fire protection; smart PPE; phase change materials; normative requirements; care and maintenance



Citation: Santos, G.; Marques, R.; Ribeiro, J.; Moreira, A.; Fernandes, P.; Silva, M.; Fonseca, A.; Miranda, J.M.; Campos, J.B.L.M.; Neves, S.F. Firefighting: Challenges of Smart PPE. *Forests* **2022**, *13*, 1319. <https://doi.org/10.3390/f13081319>

Academic Editor:
Cristina Vega-Garcia

Received: 29 June 2022
Accepted: 9 August 2022
Published: 18 August 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Firefighters are often exposed to high temperatures and heat fluxes due to the high radiation produced by fire during fire extinguishing operations. Therefore, personal protective equipment is of extreme importance for firefighters to ensure their protection during firefighting activities. Due to its importance, several studies regarding the research and development of firefighters' protective clothing have been conducted, leading to a continuous evolution in firefighters' personal protective equipment (PPE). Currently, the emergence of smart textiles has opened a wide range of opportunities for increasing the level of protection of firefighters' protective clothing.

1.1. Evolution of Firefighters' PPE

The scientific developments that led to the introduction of high-performance fibers have been the first major contribution for the increase in the level of protection of firefighters' personal protective equipment; however, the biggest revolution regarding firefighters' protection was the use of flame-retardant polymer fibers, namely, aromatic polyamides (aramids) and polybenzimidazole (PBI). Currently, meta-aramids and para-aramids are widely used in firefighters' PPE due to the fact of their good thermal tolerance and long-term stability at high temperatures [1]. Alongside the research and development of innovative

fibers for firefighters' PPE, the major finding that contributed to increasing the level of protection of firefighters' PPE, resulting from studies regarding the clothing's structure, was the introduction of a multilayer system, used currently for structural firefighting. Three layers compose this multilayer system: an outer shell (flame-retardant fabric), a vapor barrier, and a thermal barrier. The design of the multilayer system allows for the wearer to be firstly protected from the heat and flames but also against moisture.

1.2. Smart Firefighters' PPE

The research and development carried out in the field of firefighters' PPE increasingly encompasses advanced materials and/or electronic components. From the combination of these smart materials with conventional PPE, there appeared a new typology of PPE for firefighters. Regarding the development of garments with wearable electronic technologies, many include the integration of sensors for the vital function and location monitoring in textiles, communication interface, and energy supply with the purpose of increased functionality and the protection of firefighters' clothing [2]. On the other hand, the evolution in the field of advanced materials led to the emergence of new materials that can improve the functionality of firefighters' clothing. Currently, the development of new materials with adaptive function, such as phase change materials (PCMs), has been a subject of interest for researchers.

Several European projects in the smart firefighters' PPE field have taken place recently, namely, ProFiTex and Prospie. The ProFiTex project consisted of the development of an innovative data transmission and tactical navigation system to mitigate the unreliable wireless communication problem in building structures, allowing for better communication between frontline firefighters and the command post. On the other hand, the Prospie project's main objective was the development of a comfortable PPE that was effective in high-temperature environments. This innovative PPE encompassed PCMs to absorb energy during temperature peaks and hygroscopic salts to avoid excess humidity on the skin of firefighters. In addition, the Prospie project studied a selection of sensors to monitor firefighters' activity including temperature, humidity, and heart rate sensors and one external CO₂ sensor [3].

Another study comprised the development of a self-powered fire alarm electronic textile based on advanced materials such as conductive aerogel fiber, comprising calcium alginate, Fe₃O₄ nanoparticles, and silver nanowire. This innovative advanced material was integrated into firefighters' PPE for wide temperature detection, transmitting an alarm signal to the firefighter before their PPE malfunctioned in extreme fire conditions [4].

Phase Change Materials

Phase change materials are substances that can absorb and release energy in the form of latent heat during a phase transition [5]. These materials are commonly used to improve thermal comfort; however, when applied in smart firefighters' PPE, they can be additionally used to improve heat protection due to the fact of its high thermal storage capacities. An extensive spectrum of PCMs for textile application is available with different heat storage capacities and melting points. Since PCMs become liquid when exposed to heat, when integrated into textiles they should be confined to a container. To avoid this problem, PCMs can be encapsulated in a polymeric structure [6]. Recent studies have shown that the addition of a PCM layer into a conventional firefighter suit can be used to mitigate severe burns [7].

1.3. Standardization and Certification

Due to the nature of their job, firefighters require the use of the most suitable PPE available in order to be protected from the risks inherent to their activities. Therefore, it is of the most importance to ensure a high quality of PPE that is assessed through compliance with standards. International and European standards specify the performance requirements for firefighters' protective clothing. Regarding wildland firefighting, the international standard

EN ISO 15384:2020: Protective clothing for firefighters—Laboratory test methods and performance requirements for wildland firefighting protective clothing prevails [8]. On the other hand, the requirements for structural firefighting protective clothing are defined in the European standard EN 469:2020: Protective clothing for firefighters—Performance requirements for protective clothing for firefighters’ activities [9]. As for technical rescue, the applicable European standard is EN 16689:2017: Protective clothing for firefighters—Performance requirements for protective clothing for technical rescue [10]. Although the PPE sector benefits from an abundance of standards, regarding smart PPE, there is still a gap in the standardization. Currently, an important study is being conducted concerning the requirements and testing procedures for innovative smart protective garments within CEN/TC 248/WG 31-Smart Textiles. In fact, the new European standard FprEN 17673 [11] is now in the final stage of approval. At the same time, there has been an evolution regarding the guidelines for selection, use, care, and maintenance (SUCAM) of garments protecting against heat and flame. In this field, a new technical report, CEN/TR17620:2021 [12], was developed that includes guidelines regarding smart personal protective clothing.

2. Materials and Methods

The purpose of this study involved the analysis of the major differences between structural and wildfire firefighting protective clothing as well as a comparison of the prevailing standards for both firefighting protective clothing and further examination of the alterations to the previous standards. This study is important for defining and understanding the prevailing performance requirements for each type of firefighting protective clothing, being the starting point for the development of innovative smart firefighters’ PPE.

In addition, this study concerned the possible ways to integrate phase change materials into a firefighters’ protective clothing to enhance heat protection and was approached through creating smart PPE.

In this study, different forms of PCMs were studied: in pure form, and microencapsulated in a silica matrix (the matrix acts like a barrier to prevent any PCM leakage during the solid–liquid transition resulting from heat exposure). The PCMs thermal performance was tested. As main outcomes, both the PCMs delayed the sample increase of temperature (increasing the wearers’ safety), and they showed lower probability of leakage. Thus, the study proceeded with the microencapsulated PCM. In addition, to increase user safety, this PCM was incorporated in a heat-resistant waterproof package, constructed using bonding technology, acting as a barrier to prevent PCM leakage.

The study of the integration methods was based on the technical report CEN/TR17620:2021 (i.e., the section dedicated to smart garments with PCMs). In addition to the best practices mentioned by SUCAM, the integration study also took into consideration circular economy and sustainable principles using techniques such as ecodesign.

3. Results

The purpose of the phase change materials’ integration is to improve heat protection. Thus, this study focused on protective clothing for structural and wildland firefighting and did not analyze protective clothing for technical rescue, which is only applied for protection against limited heat and flame.

According to Portuguese firefighters’ legislation (dispatch 7316/2016) and accomplishing the respective standards, Figure 1 presents the current personal protective clothing for structural and wildland firefighting.

The protective clothing suit for structural firefighting consists of a multilayer system composed of three layers with different functions, as described in Section 1, to be worn over the undergarment. In contrast, the wildland firefighting protective clothing suit has only one layer, an outer shell, to provide protection against the heat and flames and must be worn over a long-sleeved shirt.

The standards for structural and wildland firefighters’ protective clothing (EN 469 and EN ISO 15384) define the performance requirements that must be accomplished. The focus

of this study was the thermal, mechanical and comfort performance requirements. Table 1 comprises a comparison regarding the minimum compliance values for test methods used both in structural and wildland firefighting protective clothing standards.

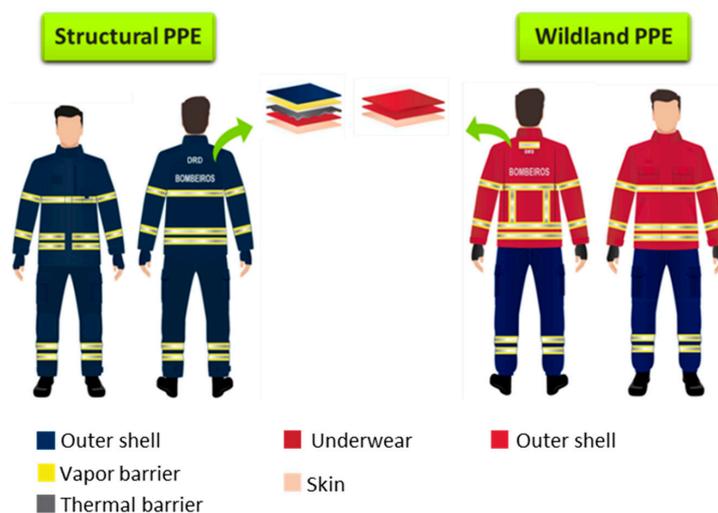


Figure 1. Structural and wildland PPE according to dispatch 7316/2016.

Table 1. Comparison between the minimum compliance values for wildland and structural firefighting protective clothing, which used the same test methods.

Protective Clothing Standard	Standard	Description	Minimum Compliance Values	
EN 469:2020	EN ISO 15025	Flame spread test	A1 or A2	
EN ISO 15384:2020			A1 and A2	
EN 469:2020	ISO 6942	Heat transfer (radiation)	Level 1: RHTI ₂₄ ≥ 10.0 s	Level 2: RHTI ₂₄ ≥ 18.0 s
EN ISO 15384:2020			RHTI ₂₄ -RHTI ₁₂ ≥ 3.0 s	RHTI ₂₄ -RHTI ₁₂ ≥ 4.0 s
			RHTI ₂₄ ≥ 11.0 s RHTI ₂₄ -RHTI ₁₂ ≥ 4.0 s	
EN 469:2020	ISO 17493	Heat resistance	180 °C	
EN ISO 15384:2020			260 °C	
EN 469:2020	ISO 13935-2	Main seam strength	≥300 N	
EN ISO 15384:2020				
EN 469:2020	ISO 13937-2	Tear strength	≥30 N	
EN ISO 15384:2020			≥25 N	
EN 469:2020	ISO 13934-1	Residual tensile strength	≥450 N	
EN ISO 15384:2020			≥600 N	
EN 469:2020	ISO 5077	Dimensional change	≤3% woven fabrics	
EN ISO 15384:2020			≤5% nonwoven and knitted fabrics	
EN 469:2020	EN 31092	Water vapor resistance (Ret)/thermal resistance (Rct)	Level 1: Ret > 30 m ² Pa/W	Level 2: Ret ≤ 30 m ² Pa/W
EN ISO 15384:2020			Ret ≤ 10 m ² Pa/W Rct ≤ 0.055 m ² K/W	

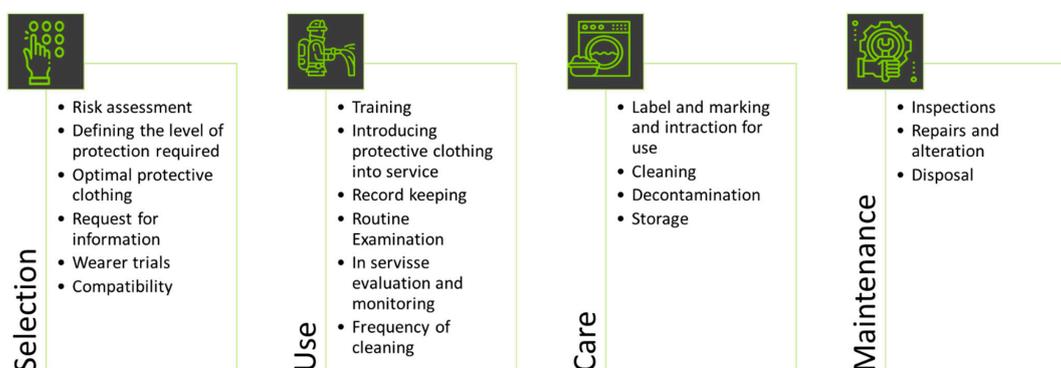
The comparison presented in Table 1 allows to conclude that despite the fact that both standards used the same test methods, the minimum compliance values changed for several tests. In addition to the test methods described in Table 1, structural protective clothing has several specific required tests as presented in Table 2.

Table 2. Specific required tests and minimum compliance values for structural firefighting protective clothing.

Standard	Description	Minimum Compliance Values	
ISO 9151	Heat transfer (flame)	Level 1: HTI ₂₄ ≥ 9.0 s HTI ₂₄ -HTI ₁₂ ≥ 3.0 s	Level 2: HTI ₂₄ ≥ 13.0 s HTI ₂₄ -HTI ₁₂ ≥ 4.0 s
EN ISO 12127-1	Contact heat test	Level 1: -	Level 2: 250 °C (10 s)
EN 20811	Water penetration	Level 1: <20 kPa	Level 2: ≥20 kPa
EN 6530	Resistance to chemical penetration	No penetration of the innermost surface; index of repellence ≥ 80%	

Regarding the test methods to evaluate the performance requirements, the recent update of the standard for structural firefighting protective clothing, in 2020, consists in the introduction of the contact heat test and the reduction of the number of chemicals that are used in the chemical penetration test. In addition, flame testing of hardware, such as labels ($\geq 10 \text{ cm}^2$), badges, and retroreflective materials as well as the moisture barrier are to be tested as part of the assembly. For wildland firefighting, EN 15614 was superseded by EN ISO 15384, which now demands slightly higher values for the mechanical parameters and a higher temperature (260 °C) for the heat resistance of the materials.

PCMs' integration into firefighters' protective clothing have considered the guidelines present in CEN/TR17620:2021. This technical report defines guidelines regarding the selection, use of care, and maintenance of smart garments protecting against heat and flames. Figure 2 shows the main topics within each step of the PPE life cycle.

**Figure 2.** Main topics approached in the SUCAM guideline.

In addition to the generic guidelines concerning protective clothing on use, care, and maintenance up to and including the disposal of the protective gear, this document provides examples of the scenarios and SUCAM procedures, with garments with PCM packages as one of the given examples.

PCM packages must be selected considering a melting temperature more suitable for the exposure needs that vary with different parameters: activity level (heat produced by the body), climatic conditions, exposure length, and logistical opportunities or limitations, for instance, the possibility of replacing the PCM packages during a mission.

Regarding cleaning and decontamination of garments with PCMs, the PCM packages must be withdrawn from the garment, and cleaned according to the manufacturer's instructions and wiped with a soap solution. Garments with PCM packages must be stored horizontally during the solidification process to avoid material accumulation at the lower end of the package and, consequently, an uneven cooling effect, reduced protection, and potential tactile discomfort during next use. If noticing any problems during the care and

maintenance procedures, such as the PCM substance leaking or if any package has not melted even if being above the melting temperature, the situation must be reported.

Concerning the inspection of PCM packages on a regular basis, the user must inspect the packages according to the outline in Figure 3 and at least once a year verify whether the PCM will melt at their melting point. The disposal of broken packages must be conducted according to the manufacturer's instructions.



Figure 3. Inspection and disposable procedures for PCM packages.

Considering that recent studies determined that the optimum position of the PCM layer was closest to the external heat, PCM packages are being integrated into a vest to be worn over a conventional firefighters' PPE, creating a smart protective clothing system. The design of the vest was studied to protect mainly the torso of the firefighter, preserving ergonomics. However, after some feedback from firefighters, a second version was developed to enhance the protection of the upper limbs (Figure 4).



Figure 4. Study of a PCM vest design: ergonomic (left) and enhanced protection (right).

The distribution of PCM packages in the vest took into consideration different variables, namely, the amount of PCM in each package, and the size and number of PCM packages needed to achieve a compromise between heat management and breathability.

Considering the SUCAM guidelines for garments with PCM packages and the different parameters concerning PCM package distribution in the vest, the integration of PCM packages is described schematically in Figure 5.



Figure 5. Study of the integration of PCM packages in the vest.

As evidenced in Figure 5, PCM packages were integrated in a matrix composed of two layers: an insulation material and a flame-retardant fabric. The introduction of the PCM packages through laser cut openings makes routine inspections and cleaning procedures described in the SUCAM easy and allows for the replacement of broken packages. Afterwards, this matrix was inserted into the vest's main structure, creating a PCM vest. In addition to making SUCAM procedure's easier, the design of the vest also considered circular economy principles, since this removable system allows for the separation of all the components of the vest, making it possible to recycle them.

4. Discussion

The starting point for the development of firefighters' protective clothing is the analysis of the prevailing relevant standards (i.e., structural and wildland firefighting) and the respective performance requirements. The analysis of the prevailing standards resulted in a comparison between the performance requirements and minimum compliance values for structural and wildland firefighting, useful for achieving a modular solution for use in both structural and wildland firefighting. Despite the evolution of firefighters' protective clothing standards, given the growing trend towards the incorporation of smart materials in firefighters' PPE, it is important to study and develop new standards to certify these innovative protective clothing for firefighters, regardless of the efforts being conducted within CEN/TC 248/WG 31-Smart Textiles.

Considering the satisfactory results obtained in several studies conducted regarding the incorporation of PCM in firefighters thermal protective clothing and taking into account the analysis of the requirements described in firefighters' protective clothing standards, this study will proceed with the incorporation of microencapsulated PCM to enhance firefighters' heat protection without introducing additional risk.

The integration of phase change materials into firefighters' PPE took into consideration different factors such as sustainable principles, wearers' safety, and cost minimization. To enhance the wearers' safety, microencapsulated PCMs were used, confined in heat-resistant and waterproof packages to prevent any PCM leakage. This PCM packages are incorporated in a matrix inserted in a vest to be worn over the conventional firefighting suit.

To preserve the protection of firefighters protective clothing there are some actions that must be taken during the protective garments' life cycle. Therefore, recently, a technical report was developed, CEN/TR17620:2021, which describes the guidelines for the selection use, care, and maintenance of smart garments protecting against heat and flames.

The selected PCM integration method allows for the inspection of PCM packages foreseen on the SUCAM report, and the inherent substitution of the damage to PCM packages. In addition, this modular system, designed using ecodesign techniques, allows for the recyclability of every individual component, which follows sustainability principles.

Firefighters' PPEs entail high costs due to the use of high-performance materials to ensure users' safety and protection against several hazards inherent to the nature of their job. The integration of smart advanced materials in firefighters' protective clothing, results in an increase in the costs associated with firefighters' PPE. The increase in costs can be divided into three parcels: the cost associated with the PCMs themselves; the cost related to the integration of the PCMs (i.e., vest manufacturing, package construction, and materials); the cost corresponding to the maintenance and conservation of the equipment (SUCAM). Therefore, the integration method studied, a modular system, was thought to reduce the costs associated with the introduction of PCMs in a PPE. Regarding, PCM packages, the fact of being individual and removable allows the substitution of only the damage packages. In addition, the developed matrix, which support the PCM packages can be used in different vests, increasing global system lifetime.

In the later stage of the study, a cost-benefit analysis will be performed to verify if the additional cost related to the integration of PCMs for improving firefighters' heat protection is worth considering the thermal performance of these advanced materials. If the new

solution presents safety advantages for the wearer, the benefits resulting from PCM use outweigh the increased cost.

5. Conclusions

The use of smart textiles, and in this specific case textiles with integrated PCMs, combined with conventional PPE, can play an important role towards the increase in firefighter's heat protection.

Having in mind a modular approach that could fit both wildland and structural firefighters, the analysis of the major differences between the respective protective clothing as well as a comparison of the prevailing standards and legislation was performed.

A first design of a PCM vest to be worn over the conventional protective clothing was designed based on an integration study conducted aimed at protecting mainly the torso to preserve ergonomics. Protective standards requirements, best practices mentioned by SUCAM, and circular economy and sustainable principles using techniques such as ecodesign were taken into account.

The study will proceed with testing and simulation measurements in straight collaboration with ENB (Portuguese National Firefighters' School) towards the solution's improvement.

Author Contributions: Conceptualization, G.S., R.M., J.R., J.M.M., J.B.L.M.C. and S.F.N.; investigation, G.S., R.M., J.R. and S.F.N.; writing—original draft preparation, G.S. and R.M.; writing—review and editing, all authors; project administration, G.S., J.B.L.M.C. and S.F.N.; funding acquisition, J.M.M., J.B.L.M.C. and S.F.N. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by LA/P/0045/2020 (ALiCE), UIDB/00532/2020 and UIDP/00532/2020 (CEFT), and by PCIF/SSO/0106/2018-Project for "Development of an Innovative Firefighter's Jacket", funded by national funds through FCT/MCTES (PIDDAC).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to confidentiality agreements.

Acknowledgments: The authors would like to express their gratitude to the Portuguese National Firefighters' School support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hertleer, C.; Odhiambo, S.; van Langenhove, L. Protective clothing for firefighters and rescue workers. In *Smart Textiles for Protection*; Woodhead Publishing Limited: Cambridge, UK, 2013; pp. 338–363. [[CrossRef](#)]
2. Mäkinen, H. Firefighters' protective clothing. In *Advances in Fire Retardant Materials*; Woodhead Publishing Limited: Cambridge, UK, 2008; pp. 467–491. [[CrossRef](#)]
3. Van Langenhove, L. Smart textiles for protection: An overview. In *Smart Textiles for Protection*; Woodhead Publishing Limited: Cambridge, UK, 2013; pp. 3–33. [[CrossRef](#)]
4. He, H.; Liu, J.; Wang, Y.; Zhao, Y.; Qin, Y.; Zhu, Z.; Yu, Z.; Wang, J. An Ultralight Self-Powered Fire Alarm e-Textile Based on Conductive Aerogel Fiber with Repeatable Temperature Monitoring Performance Used in Firefighting Clothing. *ACS Nano* **2022**, *16*, 2953–2967. [[CrossRef](#)] [[PubMed](#)]
5. Fonseca, A.; Mayor, T.S.; Campos, J.B.L.M. Guidelines for the specification of a PCM layer in firefighting protective clothing ensembles. *Appl. Therm. Eng.* **2018**, *133*, 81–96. [[CrossRef](#)]
6. Zhu, F.; Feng, Q.Q.; Liu, R.; Yu, B.; Zhou, Y. Enhancing the thermal protective performance of firefighters' protective fabrics by incorporating phase change materials. *Fibres Text. East. Eur.* **2015**, *23*, 68–73.
7. Zhang, H.; Liu, X.; Song, G.; Yang, H. Effects of microencapsulated phase change materials on the thermal behavior of multilayer thermal protective clothing. *J. Text. Inst.* **2021**, *112*, 1004–1013. [[CrossRef](#)]
8. *EN ISO 15384:2020*; Protective Clothing for Firefighters—Laboratory Test Methods and Performance Requirements for Wildland Firefighting Clothing. International Organization for Standardization: Geneva, Switzerland, 2020.

9. *EN 469:2020*; Protective Clothing for Firefighters—Performance Requirements for Protective Clothing for Firefighting Activities. International Organization for Standardization: Geneva, Switzerland, 2020.
10. *EN 16689:2017*; Protective Clothing for Firefighters—Performance Requirements for Protective Clothing for Technical Rescue. International Organization for Standardization: Geneva, Switzerland, 2020.
11. *FprEN 17673*; Protective Clothing—Protection against Heat and Flame—Requirements and Test Methods for Garments with Integrated Smart Textiles and Non-Textile Element. Comité Européen de Normalization: Bruxelles, Belgium, 2021.
12. *CEN/TR17620:2021*; Guidelines for Selection, Use, Care and Maintenance of Smart Garments Protecting against Heat and Flame. Comité Européen de Normalization: Bruxelles, Belgium, 2021.