

Experimental Assessment of the Flame Resistance Properties of Firefighter Protective Ensembles, including the SPF1 Helmet

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Abstract

Firefighters rely on their protective gear for thermal insulation during fires. This study evaluated the flame resistance of firefighter PPE, including helmets, turnout gear, and gloves, under extreme conditions. Results showed excellent performance of the F1 helmet but identified areas for improvement in gloves and turnout gear. The study provides insights into the heat transfer properties of different PPE components and offers recommendations for enhancing firefighter safety.

Keywords

Firefighter PPE, Flame Resistance, Thermal Protection, Heat Transfer

1. Introduction

Firefighters operate in environments with extreme heat, exposing them to significant risks. Their personal protective equipment (PPE), including turnout gear and helmets, is essential for their safety. International standards such as ISO 11999-3:2015, EN 469:2014, and NFPA 1971:2013 set minimum requirements for the thermal performance of PPE. However, the real-world application of these standards under extreme conditions remains insufficiently studied [1] [2].

Recent research has explored the degradation mechanisms of PPE materials under prolonged heat exposure, improper maintenance, and aging processes, which can compromise protective capabilities [3] [4]. These studies underscore the urgency of revisiting design approaches and maintenance protocols to enhance the resilience and efficiency of PPE in high-stress scenarios. Moreover, advancements

in material science and thermal treatment techniques present opportunities to optimize PPE performance, yet their practical integration requires further investigation [6]-[8].

This study aims to address these gaps by critically evaluating the limitations of current PPE designs under extreme thermal conditions. By leveraging experimental data and recent findings, the research seeks to propose innovative improvements in material selection, design architecture, and maintenance strategies. Such contributions are vital to advancing firefighter safety and ensuring PPE effectiveness in the most challenging operational contexts.

2. Experimental

2.1. Materials

The materials used for the test include firefighter protective equipment sourced from Ouagadougou. These consist of:

2.1.1. The Firefighting Jacket and Trousers

The firefighting suit is composed of 93% Nomex (meta-aramid), 5% Kevlar (para-aramid), and 2% antistatic carbon fibers. This combination ensures fire resistance and antistatic properties [2]. It is designed with three layers of different materials separated by air gaps. The tested firefighting suits (**Figure 1**) were utilized for varying durations, as detailed in **Table 1**. **Table 2** provides a comprehensive summary of their performance characteristics.

Table 1. Usage details for the selected firefighting suit [3].

Designation	Date of Manufacture	Service Start Date	Usage Duration	Fire Exposure Time
Firefighting Suit	2019	2020	12 Months	8 Hours

Table 2. Detailed performance of the firefighting suit [4] [5].

Layers	Layer Code	Component and Description	Fabric Structure	Thickness (mm)	Density (kg/m ³)	Thermal Conductivity (W/m/K)	Volumetric Heat Capacity (kJ/m ³ /K)	Global Heat Transfer Coefficient (W/m ² /K)
Outer Layer	C1	93% meta-aramid (black), remainder Kevlar and other fibers	Plain weave (tear-resistant)	0.42	605	0.038	708.1	8.02
Moisture Barrier	C2	5% Kevlar, remainder Nomex and other fibers	Plain weave (tear-resistant)	0.75	212	0.041	210.5	6.96
Total Thermal Barrier	C3	2% carbon fibers, remainder Nomex and Kevlar	Plain weave (tear-resistant)	1.55	112	0.081	115.1	7.4
Full Jacket	-	-	-	-	-	0.038	161.9	6.17



Figure 1. Photographs of the intervention jacket and trousers.

2.1.2. The SPF1 Helmet

The helmet shell is made of polyamide PA 6.6 (nylon) reinforced with fiberglass, featuring a nickel coating and photoluminescence properties. It weighs 950 grams. Usage duration is documented in **Table 3**.

Table 3. Information on the usage duration of the SPF1 helmet [3].

Designation	Date of Manufacture	Service Start Date	Usage Duration	Fire Exposure Time
SPF1 helmet	2008	2018	18 Months	12 Hours

Table 4 presents the detailed performance specifications of the SPF1 firefighter helmet.

Table 4. Detailed performance specifications of the SPF1 firefighter helmet [3].

Helmet Components	Values/Materials
Outer material	Fiberglass reinforced with PA 6.6
Inner material	EPS foam (expanded polystyrene)
Thickness (mm)	4
Helmet density (g/cm ³)	1.5
Thermal conductivity (W/m ² ·K)	0.5
Mass (kg)	1.5
Visor	Tempered glass

2.2. International Standards for Selected Firefighter PPE

The primary standards reviewed for firefighter suits include ISO 11999-3:2015, NFPA 1971:2013, and EN 469:2014. Among these, ISO 11999-3:2015 encompasses most aspects of NFPA 1971 and EN 469 [1]. Consequently, the thermal protection

performance (P-TP) of the firefighter clothing was evaluated in accordance with ISO 11999-3:2015 [1]. The helmet was assessed following EN 443 standards.

2.3. Thermal Protection Testing

2.3.1. Flame Protection Performance Test for Helmet

The flame protection performance of the SPF1 helmet was tested per EN 443. The test involved exposing the helmet to a heat source at 426°C for 15 seconds and verifying the criteria outlined in **Table 5**.

Table 5. Thermal protection performance requirements for SPF1 helmet (EN 443) [5].

Standard	Test Method	Criteria/Requirement
EN 443	EN 443	- The helmet shell must not drip. - No flames or incandescence should be visible 5 seconds after the flame is removed.

In addition to the requirements in **Table 5**, the internal temperature evolution of the helmet was recorded for the tested components.

2.3.2. Flame Protection Performance Test for Firefighting Suit

The firefighting suit was tested following ISO 11999-3:2015, using the test methods summarized in **Table 6**. The ISO 9151 method was conducted with a forced-air burner delivering a heat flux of 80 kW/m².

Table 6. Thermal protection performance requirements for firefighting suit (ISO 11999-3:2015) [1] [8] [9].

Standard	Test Method	Index	Level A1	Level A2
ISO 11999-3:2015	ISO 9151	HTI24(s)	+13	+17
	ISO 9151	HTI24-HTI12(s)	+4	+6
	ISO 17492	TTI (J/m ²)	1050	1400

- **HTI12:** Time required to achieve a 12°C temperature increase inside the garment at a specified incident heat flux density. This time is an approximate measure of the duration before pain is felt.
- **HTI24:** Time required to achieve a 24°C temperature increase inside the garment at a specified incident heat flux density, roughly equivalent to the time needed to sustain a second-degree burn.
- **HTI24-HTI12:** Escape time between the sensation of pain and the occurrence of a second-degree burn.

According to the ISO 17492 method, the thermal threshold index (TTI) in units of J/m² was determined at a heat flux density of 80 kW/m² [10]. The TTI value is calculated using the following equation [1]:

$$TTI = F \cdot t_{2burn} \quad (1)$$

In this equation:

- F is the heat flux used for the test;
- t_{2burn} is the time required to sustain a second-degree burn.

2.4. Test Bench for Experiments

The test bench consists of an oven with dimensions $1\text{ m} \times 0.7\text{ m} \times 0.7\text{ m}$, insulated with 2 cm thick layers of clay on all sides. It includes a 6 kg butane gas cylinder supplied by the SODIGAZ company, an air blower with a rotation speed of 13,000 rpm and an airflow rate of $2.3\text{ m}^3/\text{min}$, and a forced-air burner made from a steel tube measuring 40 cm in length and 25 mm in external diameter.

The system is equipped with an electrical extension for power supply, an air flow regulation valve, and a K-type thermocouple. The thermocouple probes are strategically placed inside the chamber and within the equipment being tested. Flexible tubes are used to transport the gas and air. The test bench is adjustable and can be calibrated to deliver the desired heat flux based on testing requirements (Figure 2).

Figure 3 shows the thermocouples, probes, and heat flux for the turnout gear and helmet.

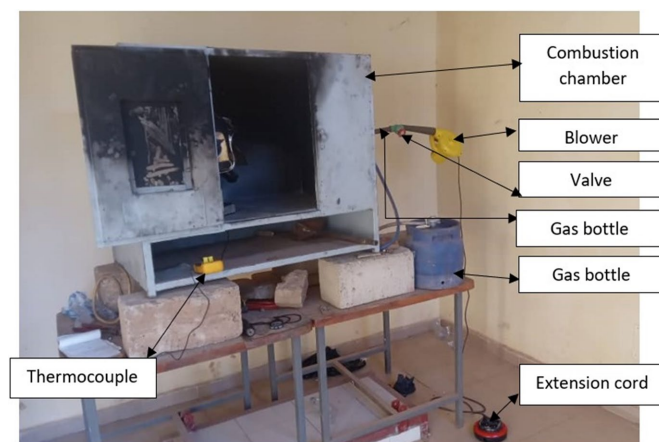


Figure 2. Complete equipment and setup for the FPP test.

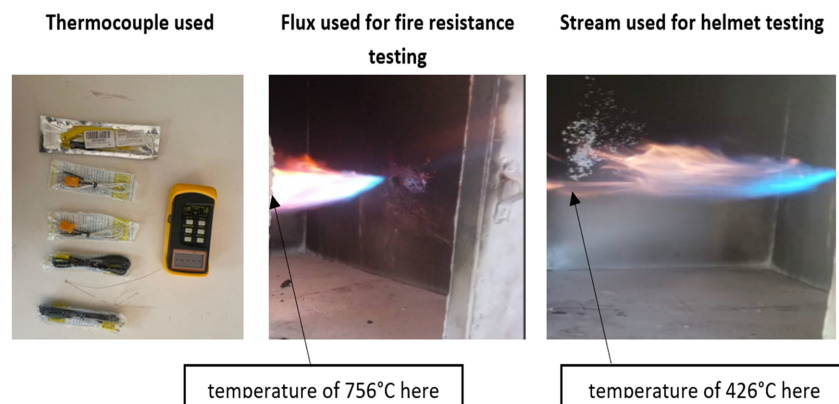


Figure 3. Thermocouples, probes, and heat flux for the turnout gear and helmet.

2.5. Methods for Determining Burn Degrees

2.5.1. Stoll Curve

One of the scientific methods used to determine burn degrees is the Stoll curve. Its principle can be summarized as follows:

- The curve of the variation (difference from the initial temperature) in the internal temperature of the sample is plotted as a function of exposure time.
- The HTI24 curve (a straight line with the equation $T = 24^\circ\text{C}$) is plotted.
- The curve of ΔT evolution is plotted, based on the reference table of values from the Stoll experiment [10].

In most cases, two intersection points are observed: an intersection between the HTI24 curve and the internal temperature evolution curve of the tested sample, corresponding to the time required for a second-degree burn. Another intersection between the internal temperature evolution curve of the sample and the Stoll curve corresponds to the HTI24.

In some situations, no intersection points are observed.

2.5.2. Henriques and Moritz Degradation Kinetics

The rise in temperature has a destructive effect on living cells, with tissue necrosis corresponding to burns. The first studies on the kinetics of this thermo-degradation were conducted at the end of World War II and published in 1947 by Henriques and Moritz.

The state of the cell, determined through histological analysis, can be characterized by a parameter, which is zero when the cell is intact and equal to 1 when it is completely necrotized.

The experiments conducted by these authors led to the proposal of a degradation kinetics law, based on the Arrhenius equation [11] [12]:

$$\frac{d}{dt} = K_0 \exp\left(-\frac{E}{RT}\right) \quad (2)$$

In this equation:

- Ω is the factor characterizing the state of cell degradation;
- t is time;
- $E = 67800 \text{ J}$ is the activation energy;
- $R = 8,32 \text{ J/mol}$. K is the universal gas constant;
- T is the absolute temperature in Kelvin;
- $K_0 = 3,1 \cdot 10^{98} \text{ s}^{-1}$ is a constant.

3. Results and Discussion

3.1. Helmet Test Results

Tested helmet components:

- Front part (visor) of the helmet;
- Left side of the helmet;
- Rear part of the helmet.

Results and observed temperatures for a temperature of 426°C are as follows.

3.1.1. Front Part (Visor)

Figure 4 shows the different phases of our tests: before, during, and after the helmet visor test.

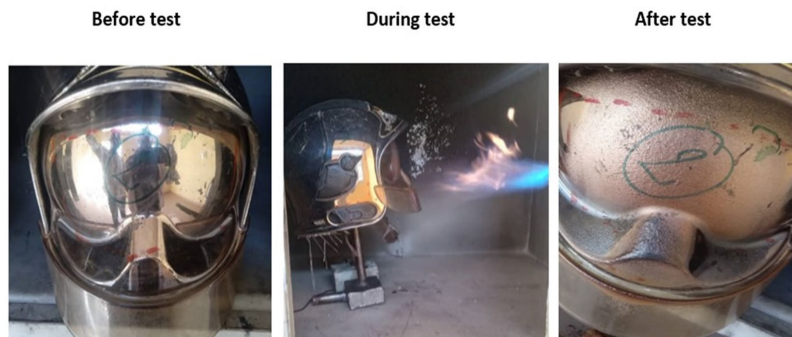


Figure 4. Images of the front visor at different stages of the test.

The initial temperature of the test chamber was 31.9°C and was then taken at a time interval of three seconds. **Figure 5** shows the evolution of the temperature inside the helmet during the first 15 seconds of the test.

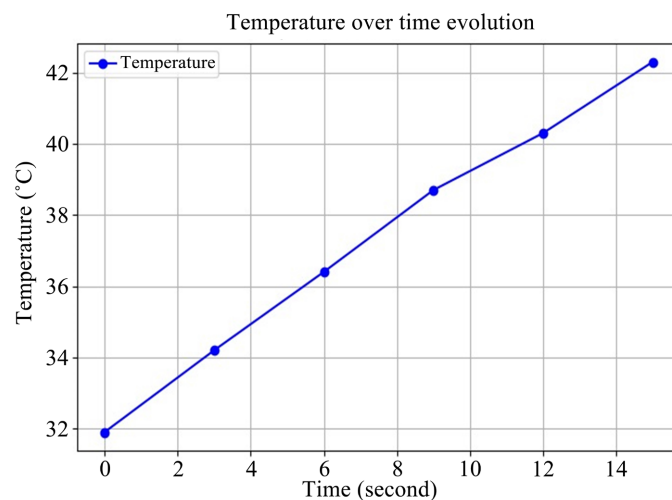


Figure 5. Evolution of the internal temperature of the visor.

The EN 443 standard was used to validate our visor test. **Table 7** shows the performance of the flame resistance test.

Table 7. Performance table of the flame resistance test conducted on the front section of the helmet.

Criteria	Standard Reference	Test	Validation
Criterion 1	The visor does not trip	During the test, the visor did not show any dripping	Yes
Criterion 2	No flame or glowing is observed 5 seconds after the flame is removed	After the burner flame was extinguished, no flame was observed	Yes

The deposit of stains (a form of carbonization) observed on the visor, which is not specified by the standard, should be given significant attention as it could hinder the firefighter wearing the helmet from having a clear view to escape or continue the mission. This carbonization is caused by incomplete combustion, releasing smoke that settles on the helmet visor. Implementing an anti-smoke deposit treatment on the helmet visor during its design could therefore enhance firefighter safety. This observation, which is not clearly addressed by the EN 443 standard, is considered a weakness of the latter. However, it is recommended that firefighters avoid exposing the helmet visor to a high heat source of approximately 426°C or more during interventions.

3.1.2. Lateral Side

Figure 6 shows photographs of the lateral side before, during, and after the flame test.

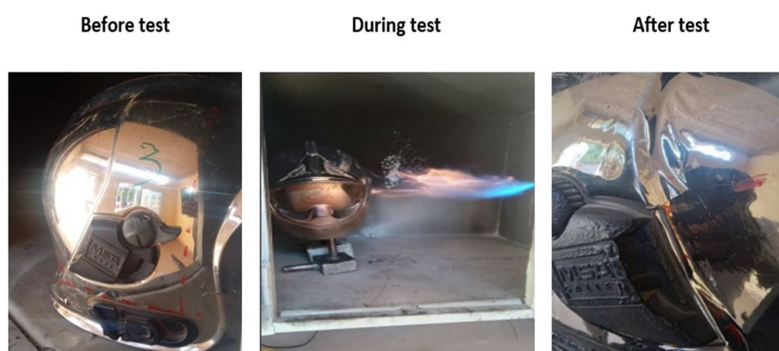


Figure 6. Lateral side of the helmet before, during, and after the test.

During the test, we recorded the temperature changes inside the helmet at three-second intervals, as shown in **Figure 7**.

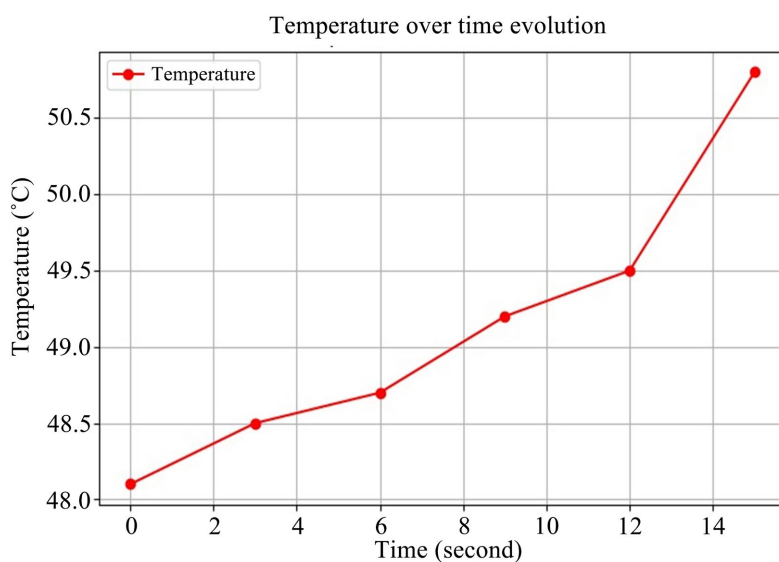


Figure 7. Temperature evolution curve of the lateral side.

The EN 443 standard was used to validate our visor test. **Table 8** shows the performance of the flame resistance test.

Table 8. Performance table of the flame resistance test conducted on the side section of the helmet.

Criteria	Standard Reference	Test	Validation
Criterion 1	The visor must not drip	During the test, the visor did not show any dripping	Yes
Criterion 2	No flame or glowing is observed 5 seconds after the flame is removed	After the burner flame was extinguished, no flame was observed	Yes

3.1.3. Back Part

Starting from the initial temperature of 37.1°C, the temperature evolution inside the helmet after the flame test conducted on the rear of the helmet is shown in **Figure 8**. The final temperature recorded inside the helmet was 47.5°C, representing an increase of 10.4°C.

Figure 8 illustrates the back face of the helmet before, during, and after the test.

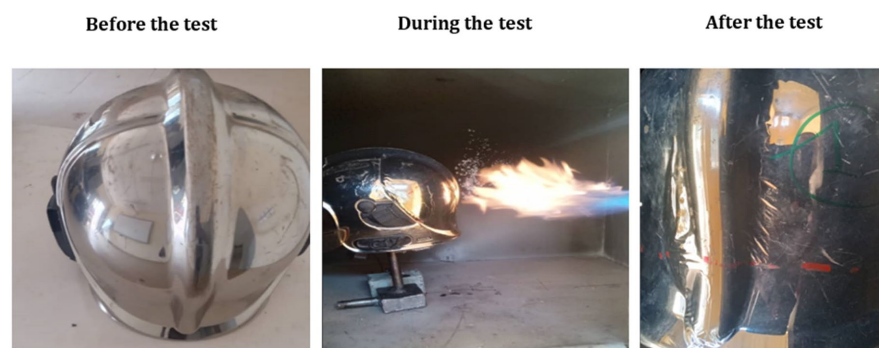


Figure 8. Back face of the helmet before, during, and after the test.

To validate the results, the EN 443 standard was applied. The performance of the flame resistance test is summarized in **Table 9**.

Table 9. Performance table of the flame resistance test conducted on the rear section of the helmet.

Criteria	Standard Reference	Test	Validation
Criterion 1	The visor must not drip	During the test, no drips were observed from the visor	Yes
Criterion 2	No flames or glowing embers should be observed 5 seconds after removing the flame	After the burner flame was extinguished, no flames were observed	Yes

In the test conducted on the lateral face, the final temperature of 47.5°C recorded and the maximum cellular degradation rate of 0.025 show that the helmet continues

to perform its protective function. Indeed, the 10.4 °C increase observed after 15 seconds, in compliance with the EN 443 standard, is explained by the excellent performance of the materials used in the design. The PA 6.6-reinforced fiberglass provides good heat resistance [13].

The evolution of the cellular degradation rate as a function of temperature is shown in **Figure 9** and **Figure 10**.

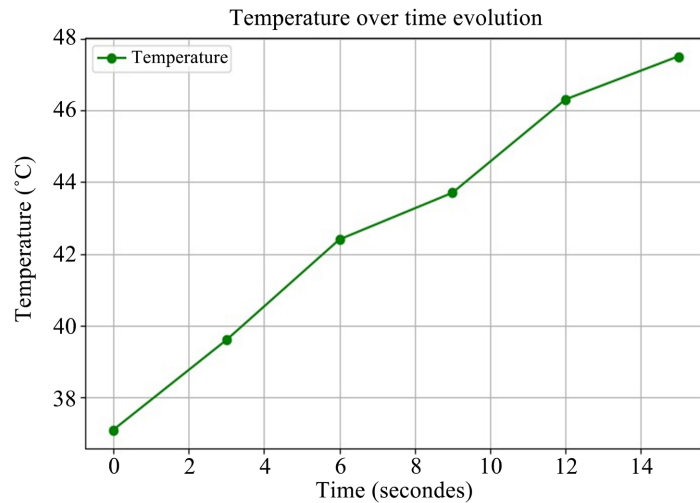


Figure 9. Temperature evolution curve of the rear face.

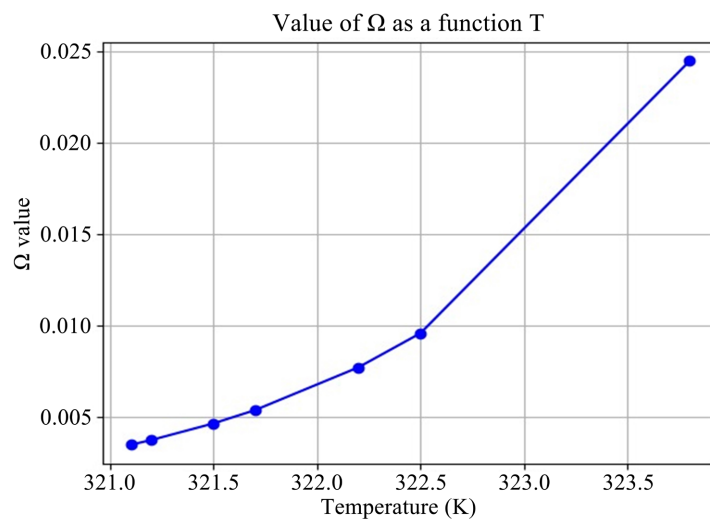


Figure 10. Curve of cellular degradation rate evolution as a function of temperature.

3.1.4. Evaluation of the Degree of Burn

For the determination of the degree of burn, we refer to the work of Moritz and Henriques, as cited above. The choice of the left lateral side is based on the fact that the maximum temperature, after testing all three parts, was recorded on this side. To calculate the burn degree, we used Simpson's method. In numerical analysis, Simpson's method, named after Thomas Simpson, is a technique for numerically calculating an integral [14].

Using relation (2), we obtained **Figure 10**, which shows the evolution of the degradation parameter Ω over time. **Figure 10** reveals a maximum degradation rate of 0.025, which is well below 1. Therefore, the temperatures observed during the test cannot cause total cellular degradation. However, minor burns may be felt, as Ω is not zero.

3.2. Results of Flame Resistance Tests on Firefighter Protective Clothing

To assess the thermal protection provided by the turnout gear in the most exposed areas (forearm, shoulder), we conducted flame resistance tests according to ISO 9151 and ISO 17492 standards (756°C).

3.2.1. On the Forearm

The results of the FPP test are shown in **Figure 11**, which provides a photograph of the forearm section of the protective suit before and after the test.

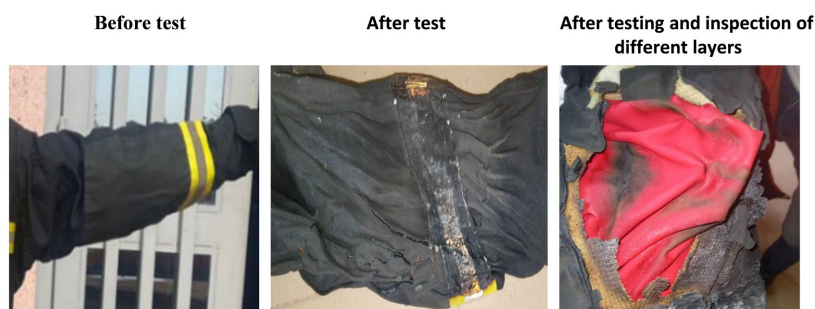


Figure 11. Photograph of the forearm of the protective suit before and after the test.

Figure 11 indicates that the first and second layers of the turnout gear failed the FPP test, whereas the last layer showed only minor degradation. The internal temperature evolution during the test is illustrated in **Figure 12**.

The test conducted on the forearm section of the turnout gear achieved a performance level of A2, meaning that the samples generally resisted the FPP test. However, the destruction of the first (C1) and second (C2) layers can be attributed to prolonged exposure to ambient conditions, improper washing practices (disregard of washing instructions), and the gear's age (as detailed in **Table 1**).

A discussion with a firefighter from the Ouagadougou brigade revealed that these turnout gears were washed by laundries unfamiliar with technical garments. Additionally, the washing temperature was unknown, a significant contributor to fabric degradation. According to the NFPA 1851 (1999) standard, the washing temperature must not exceed 40°C [15].

Among the tested samples, none maintained combustion after the flame was removed, demonstrating that the flame-retardant treatment remains effective despite the gear's age. Another observation, made after flame removal, showed a rapid increase in temperature within the tested area. This phenomenon results from heat accumulation within the internal layers, which accelerates thermal transfer after a

certain threshold. The determination of $t_{2\text{burn}}$ and HTI24 parameters, using the forearm section as the test sample, is presented in **Figure 13**.

It is therefore recommended to retire turnout gear exposed to significant heat for sufficient time to allow heat dissipation before reuse, particularly for long-duration interventions.

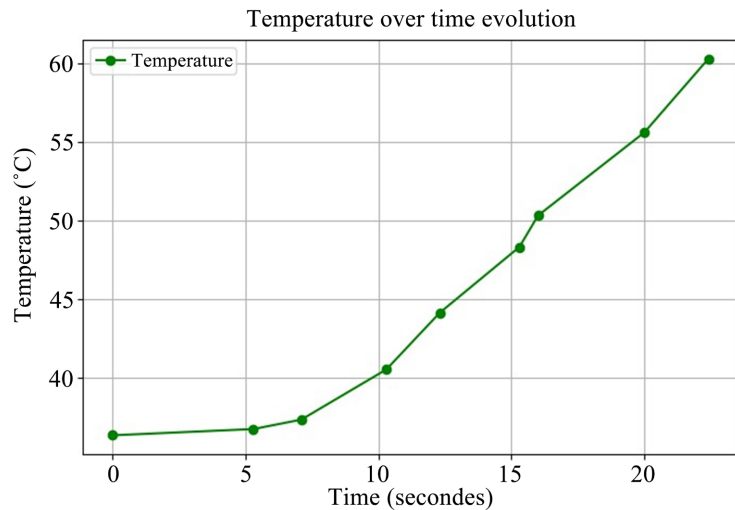


Figure 12. Evolution of the internal temperature of the fire suit, forearm section, after the FPP test.

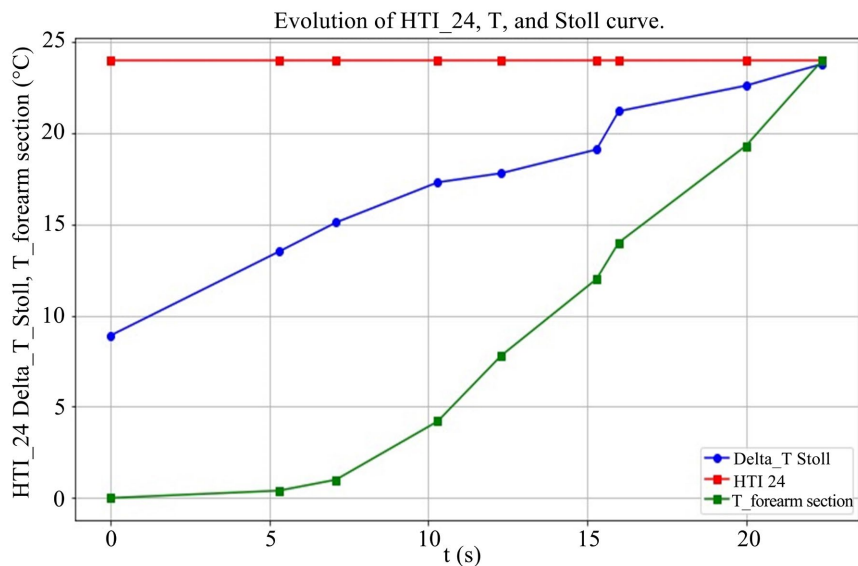


Figure 13. Determination of $t_{2\text{burn}}$ and HTI24 using the forearm section of the firefighter's intervention suit as the test sample for flame protection performance.

3.2.2. On the Shoulder

The results of the flame resistance performance test, conducted on the shoulder area of the turnout gear, are presented in **Figure 14**.

As shown in **Figure 14**, only the first layer of the turnout gear failed the FPP test, while the other layers exhibited minimal degradation. The evolution of the

internal temperature during the test is illustrated in **Figure 15**, and the parameters t_{2burn} and HTI24 for the shoulder area were determined and are presented in **Figure 16**.



Figure 14. Photograph of the intervention suit, shoulder part before and after FPP test.

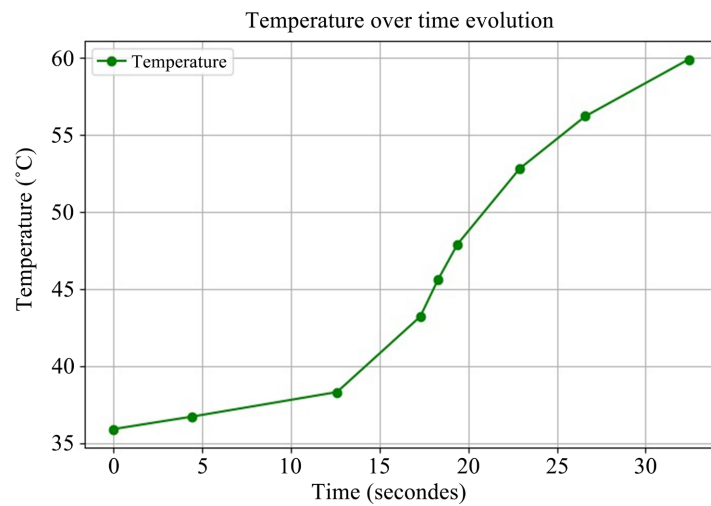


Figure 15. Evolution of the internal temperature of the fire suit, shoulder part, following the FPP test.

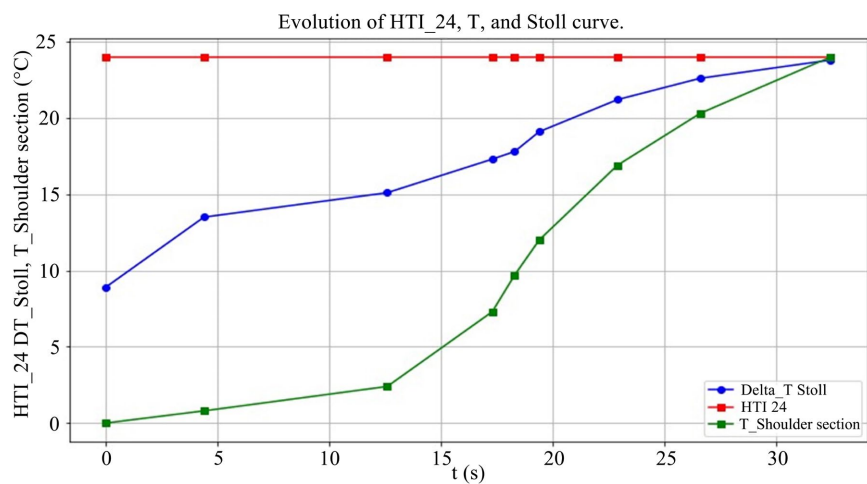


Figure 16. Determination of t_{2burn} and HTI24 with the shoulder part of the firefighter's intervention suit as the sample for the flame protection performance test.

Table 10 summarizes the results of the tests conducted on the samples in accordance with ISO 11999-3:2015. The shoulder test achieved a performance level of A2, indicating a high level of protection. The degradation of the first layer can be attributed to prolonged exposure to environmental conditions, improper washing practices, and the gear's age.

None of the tested samples continued to burn after the flame was removed, confirming the sustained effectiveness of the flame-retardant treatment. The rapid increase in temperature observed after flame removal (as shown in **Figure 15**) is due to heat accumulation within the layers, which accelerates thermal transfer once the materials reach a critical threshold.

The tissue injury index (TTI24) for the shoulder area exceeded 17 seconds, classifying its performance as A2. Additionally, the escape time (TTI24-TTI12) increased proportionally with TTI24, and no t2burn was observed before reaching TTI24. This result suggests that higher TTI24 values reduce the difference between t2burn and TTI24, a phenomenon explained by the convergence of the Stoll curve, which quantifies burn risk, towards the TTI24 threshold during prolonged exposures.

Table 10. Determination of t2burn and HTI24 with the shoulder part of the firefighter's intervention suit as the sample for the flame protection performance test.

Samples	t2burn (s)	HTI12 (s)	HTI24 (s)	HTI24-HTI12 (s)	Performance Level	TTI (kJ/m ²)
Forearm	22.41	15.30	22.41	7.11	A2	1792.8
Shoulder	32.44	19.40	32.44	13.04	A2	2595.2

To enhance safety, we propose retiring turnout gear that has been heavily exposed to heat and ensuring sufficient time for heat dissipation before reusing it, especially during prolonged interventions.

4. Conclusions

This study assessed the fire resistance of firefighters' helmets (SPF1) and turnout gear under extreme conditions. The results confirmed that while these protective equipment items retain their flame-resistant properties, prolonged use and improper maintenance significantly impact their performance, particularly in the outermost layers of the turnout gear. These findings underscore the critical need for strict maintenance protocols and regular replacement schedules to ensure continuous and optimal protection for firefighters.

Additionally, this study highlights opportunities for advancing the design of firefighter PPE by incorporating more durable and resistant materials. Future innovations should focus on fabrics with superior thermo-physiological properties to balance thermal protection and wearer comfort during prolonged exposure to extreme heat [16]. The integration of cutting-edge technologies, such as flame-retardant phase change materials (PCMs), holds promise for significantly enhancing

thermal resistance and ensuring firefighter safety in the most demanding operational environments [17].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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