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Evaluation of the Constancy of the Performance of Firefighters Suits

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Abstract
In the designing of advanced personal protection equipment, the problem related to the continuous loss of properties associated with functionality and safety over the course of its use, storage and cleaning cycles is rarely noticed. Products and their technical characteristics are applied for the conformity assessment process, which does not take into account the risk of the reduction of safety parameters. As part of the research conducted, we established the influence of factors arising from use and cleaning cycles on the reduction of physico-mechanical parameters describing critical requirements associated with the safety and functionality of special clothing for firefighters. The scope of the research covered evaluation of the influence of atmospheric factors over the course of a period including three seasons (spring, summer and autumn) and of cleaning cycles (20 cycles of washing in water at 60 °C, according to PN-EN ISO 6330:2012, distributed proportionally over three seasons of the year, with the use of commercial, commonly used washing powder) on the change in the level of parameters characterising special clothing for firefighters.

Key words: *protective clothing, validation, performance, firefighter suit.*

Introduction

Special clothing must be resistant to the action of external factors originating from the environment and should ensure sufficient protection against hazards present in predicted conditions of application, so that its potential user can freely perform all professional activities while benefiting from appropriate protection at the highest possible level, but at the same time the clothing preserves its protective properties during use, storage and cleaning processes.

A significant majority of research currently being conducted is focused on evaluation of the comfort of use of special clothing worn by firefighters, mainly with the goal of evaluating the influence of the clothing's design on thermal comfort [1-4], and risk assessment of the hazards arising from the use of PPE but without taking into account aspects associated with the loss of properties responsible for safety during use and storage [5-7].

Protective clothing used by firefighters during firefighting operations consists of three parts: jacket, trousers and a light jacket. The following colours of the outer fabric are permitted for the protective clothing: yellow, black or navy blue.

According to the guidelines given in [8], the design of the special clothing and technical parameters of the structural materials should meet the requirements given in Standard PN-EN 469:2008, and the design and technical parameters of the structural materials of the light jacket, as part of the special clothing, should meet the requirements defined in Standard PN-EN 15614:2009. The light jacket and jacket of the special clothing should have the same length. Markings on all elements of the special clothing should meet the requirements defined in the standards relevant to individual elements. The design of all elements of the special clothing should be ergonomic in order to ensure ease of movement, adequate protection against thermal and mechanical factors, as well as proper ventilation for the user.

The clothing design should be characterised by the following technical and qualitative features:
- limited flame spread;
- residual tensile strength after exposure to radiant heat;
- heat resistance – small shrinkage;
- tensile strength;
- tearing strength;
- dimensional stability in the cleaning process;
- penetration by liquid chemicals;
- penetration of water (does not apply to: structural materials of the light jacket) [17].

Materials intended for the manufacturing of protective clothing for firefighters should be characterised by preservation of the level of protective effectiveness during use or storage. Aging may be caused by the joint action of a series of factors, such as:
- cleaning, maintenance or disinfecting processes;
- exposure to visible and/or ultra-violet radiation;
- exposure to high or low temperatures or to temperature changes;
- exposure to chemicals, including humidity;
- exposure to biological agents, such as bacteria, fungi, insects or other pests;
- exposure to mechanical action, such as abrasion, flexing, pressure and strain;
- exposure to contaminants, such as dirt, oil, splashes of molten metal, etc.;
- exposure to wear and tear [16, 17].

The testing scope resulting from the European standards dedicated for firefighters suits should be enhanced by the application of usable studies (ageing in natural conditions by endangering of natural factors, cleaning cycles, etc.), which is not a part of the above-mentioned standards.

The review of literature performed indicated that the studies realised considered only verification of usable properties for new (unused) PPE or focused on validation of the comfort aspect in real conditions without analysing of the influence of the aging process on safety and performance. Implementation of the aging process generated new knowledge focused on the change in usable properties as well as the influence of aging factors on safety and performance.

The main goal of the research was to determine the influence of factors arising from use and cleaning processes on the reduction of physico-mechanical parameters describing critical requirements associated with the safety and functionality of protective clothing for firefighters differing in the composition of the outer fabric and design.

Materials

Two models of different fabric raw material composition of the outer fabric were applied in tests, consisting of special clothing (heavy trousers and heavy jacket in variants I and II compliant with Standard PN-EN 469:2008) along with a light jacket compliant with Standard PN-EN 15614:2009 and made in one variant.

The special clothing consists of three parts: a heavy jacket and trousers compliant with Standard PN-EN 469:2008 and a light jacket for wildland compliant with Standard PN-EN 15614:2009.

Variant I special clothing (jacket and trousers), has a layered structure consisting of:
- outer fabric: fabric in a yellow sandy colour, composition: 98% meta-aramide & 2% anti-static, with a mass per unit area of 210 g/m^2;
- reinforcements on the elbows and knees made from Kevlar® fabric coated with silicone, as well as additional reinforcements on the ends of legs and cuffs. Moreover, elements exposed to damage were provided with additional reinforcements made of Kevlar® fabric coated with silicone. The clothing was marked with perforated tapes 50 and 75 mm in width;
- moisture barrier: membrane consisting of: 50% meta-aramide, 25% para-aramide & 25% PTFE laminate;
- thermal insulation insert: lining: 50% aramide, 50% FR viscose, fleece: 85% meta-aramide & 15% para-aramide.

Variant II special clothing (jacket and trousers) was made based on PBI fabric. The clothing has a layered structure consisting of:
- outer fabric: fabric in yellow sandy colour, with raw material composition: 58% para-aramide, 40% PBI & 2% anti-static;
- reinforcements on the elbows and knees made from Kevlar® fabric coated with silicone as well as on the ends of legs and cuffs. Moreover, elements exposed to damage were provided with additional reinforcements made of Kevlar® fabric coated with silicone. The clothing was marked with perforated tapes 50 and 75 mm in width;
- a moisture barrier: membrane with the following composition: 50% PTFE laminate, 25% meta-aramide & 25% para-aramide;
- thermal insulation insert: fleece: 100% aramide lining with the following composition: 93% meta-aramide, 5% para-aramide and 2% anti-static.

Figure 1. *Test stand for evaluation of the influence of atmospheric factors on protective clothing.*

The light jacket had a single-layer structure consisting of aramide fabric in a sandy colour, with the following composition: 98% meta-aramide and 2% anti-static, with a mass per unit area of 220 g/m^2. It was marked with perforated tapes 50 and 75 mm in width.

Methods

A test program was prepared based on the requirements of standards relating to the functional and safety features of firefighters' clothing used by functionaries of the State Fire Service. In addition, risk analysis according to the guidelines set forth in Standard PN-ISO 31000:2018-08 was applied to support the definition of the scope of the program of exposure cycles and cleaning processes.

Properties responsible for safety and functionality

Properties relating to safety and functionality aspects were verified according to the following test program:
- tensile strength according to PN-EN ISO 13934-1:2013-07;
- tearing strength according to PN-EN ISO 13937-2:2002;
- pilling resistance according to PN-EN ISO 12945-2:2002;
- water vapour resistance according to PN-EN ISO 11092:2014-11;
- flame spread according to PN-EN ISO 15025:2017-02 procedure A;
- heat resistance according to ISO 17493:2016 and (PBM-04/ITB:2008 ed. IV-01.2008);
- surface wetting (spray test) according to PN-EN ISO 4920:2013-02;
- resistance to water penetration according to PN-EN ISO 811:2018-07 (this parameter was not determined for the light jacket due to the absence of a barrier protecting against moisture in the product tested);
- abrasion resistance according to PN-EN ISO 12947-2:2017-02;
- colour differences according to PN-EN ISO 105-J01:2002 and PN-EN ISO 105-J03:2009;
- colour fastness to artificial light according to PN-EN ISO 105-B02:2014-11.

Exposure tests and tests simulating cleaning cycles under real-life conditions

Tests were conducted on acclimatised samples and ones following the action of atmospheric conditions during a period including three seasons of the year (spring, summer & autumn) and cleaning cycles (20 cycles of washing in water at 60 °C according to Standard PN-EN ISO

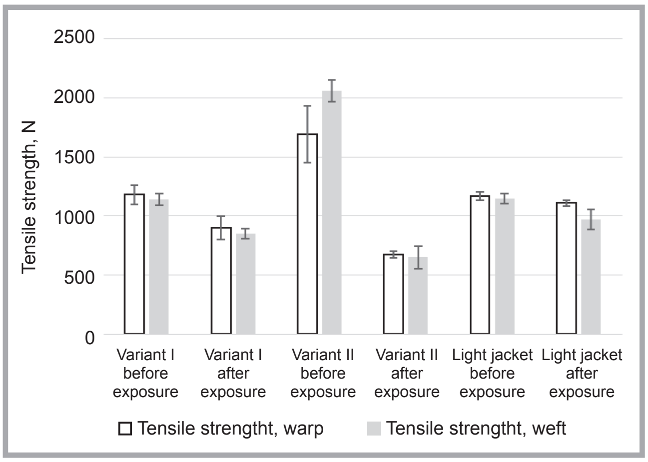

Figure 2. *Tensile strength of fabrics tested before and after exposure cycles.*

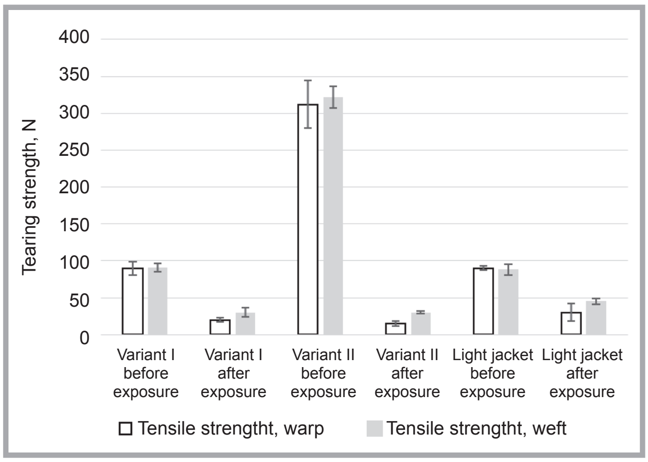

Figure 3. *Tearing strength of fabrics tested before and after exposure cycles.*

6330:2012 , in a WASCATOR FOM71 CLS washing machine (Electrolux, Sweden), the drying procedure in an Accudry dryer (James H. Heal, United Kingdom), distributed proportionally over three seasons of the year, using commercial, commonly used DOSIA washing powder for colours (Reckitt Benckiser). Exposure to atmospheric factors lasted 220 days, and the cleaning cycle was performed every 10 days. Washing was performed at 60 °C using commercial DOSIA washing powder in a front-loaded washing machine with a horizontal drum, and then tumble dried (acronym of method 6N, drying procedure F).

The cleaning cycle was performed alternatingly with exposure to atmospheric conditions. with 22 exposure cycles conducted in total.

In addition, after the completed exposure, water penetration tests were performed using a modified Bundesmann method rain-shower test, and water repellence tester from SDL ATLAS (United Kingdom).

The following parameters were adopted during test: time of rainfall – 1 h, a complete garment tested on clothes static mannequin with a metal leg exposed to artificial rain, water temperature – 20 °C, water pH – 7, water hardness – 14 °n. Two pieces of each variant of the product were tested. Wetting of the underside of the clothing was also evaluated.

Testing of exposure to atmospheric conditions was performed on an original test stand (***Figure 1***).

Variants of the special clothing along with light jackets were placed in the test stand (***Figure 1***) and exposed to the influence of atmospheric conditions.

Results and discussion

With respect to all of the properties evaluated, the reduction in the level of parameters was determined for the variants tested and for the light jacket, being part of the set in each variant; however, these changes were dependent on the type raw materials applied.

In the case of variant I, it initially meets the functional requirements for protective clothing intended for firefighting operations according to PN-EN 469:2008 in the range of tensile strength, tearing strength, water vapour resistance, flame spread, heat resistance, surface wetting, and water penetration, while in the case of variant II, it was determined that the requirements of the aforementioned standard are met in a broader scope, i.e.

Table 1. *Pilling resistance of fabrics tested before and after exposure cycles.*

Variant I before exposure, degree	Uncertainty	Variant I after exposure, degree	Uncertainty	Variant II before exposure, degree	Uncertainty	Variant II after exposure, degree	Uncertainty	Light jacket before exposure, degree	Uncertainty	Light jacket after exposure, degree	Uncertainty
3/4	±0.5	4/5	±0.5	4	±0.5	4/5	±0.5	3/4	±0.5	4/5	±0.5

Table 2. *Flame spread of tested fabrics before and after exposure cycles.*

Parameter	Variant I before exposure	Variant I after exposure	Variant II before exposure	Variant II after exposure	Light jacket before exposure	Light jacket after exposure
Mean after flame time, s	0	0	0	0	0	0
Mean glow time, s Mean afterglow time, s	0	0	0	0	0	0
Hole	none	none	none	none	none	none
Burning to upper and side edges Achieving by the flame the upper or vertical edge	none	none	none	none	none	none
Melting	none	none	none	none	none	none
Dripping	none	none	none	none	none	none
Ignition by flame	none	none	none	none	none	none

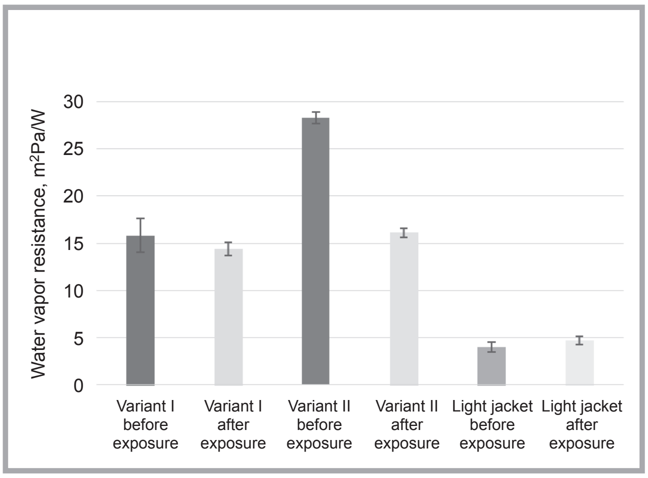

Figure 4. *Water vapor resistance of fabrics tested before and after the exposure cycle.*

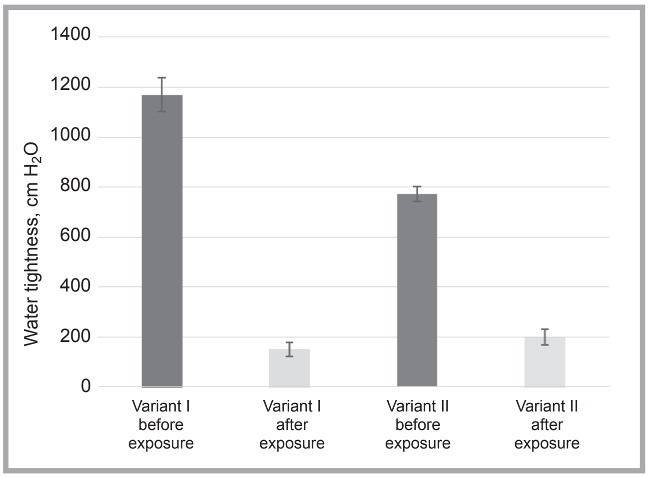

Figure 5. *Water penetration of fabrics tested before and after exposure cycles.*

tensile strength, tearing strength, water vapour resistance, flame spread, heat resistance, surface wetting, and water penetration (***Figures 2-5***; ***Tables 1-5***).

After exposure to atmospheric factors, variants I and II do not meet functional requirements for protective clothing intended for firefighting operations according to PN-EN 469:2008 in the range of the tearing strength (< 25 N) and surface wetting (***Table 4***).

Initially and after the exposure cycles, the light jacket meets functional requirements for protective clothing intended for wildland firefighting operations according to PN-EN 15614:2009 with regard to tensile strength, tearing strength, water vapour resistance, flame spread, and heat resistance (***Figures 2-4***; ***Tables 2-5***).

The outer fabric of variant I is initially characterised by moderate resistance to pilling (evaluation: 3/4). However, after the exposure process, the evaluation of this parameter rose, being the effect of cleaning cycles, which removed all fine fibres from the surface. A similar phenomenon was observed for variant II (preliminary evaluation 4, after exposure 4/5) and for the light jacket (preliminary evaluation 3/4, after exposure 4/5). It should be noted that the highest initial evaluation was achieved by variant I; however, evaluation following the exposure cycles raised the level of this parameter to a value of 4/5 for all clothing variants evaluated, including the light jacket (***Table 1***).

Water vapour resistance evaluated for variants I and II decreased substantially after the exposure cycles, which is probably due to changes in the membrane's structure. After the exposure cycle, similar values of this parameter were obtained for variants I and II from a statistical perspective, and the highest reduction in the water vapour resistance value was observed for variant II. In the case of the light jacket, no statistically significant changes in water vapour resistance were determined after the exposure process (***Figure 4***).

All clothing variants and the light jacket tested maintain the flame spread properties required after the exposure process (***Table 2***).

Similarly, the heat resistance of the variants and light jacket tested did not change after the exposure cycles (***Table 3***).

Exposure to atmospheric factors and cleaning processes substantially deteriorated the surface wetting of the clothing variants and light jacket tested. The highest decrease was observed in the case of variant II (***Table 4***).

Water penetration of the clothing variants tested was subject to substantial deterioration after the exposure cycle applied. The greatest changes were observed in the case of variant I (***Figure 5***). The light jacket was not verified in terms of this parameter due to the absence of a membrane in the material configuration applied.

The initial outer fabric of variant I is characterised by very high resistance to abrasion (> 100.000 cycles), which de-

Table 3. *Heat resistance of fabrics tested before and after exposure cycles.*

Parameter	Variant I before exposure, degree	Uncertainty	Variant I after exposure, degree	Uncertainty	Variant II before exposure, degree	Uncertainty	Variant II after exposure, degree	Uncertainty	Light jacket before exposure, degree	Uncertainty	Light jacket after exposure, degree	Uncertainty
warp	0	0.1	0	0.1	0	0.1	0	0.1	0	0.1	0	0.1
weft	0	0.1	0	0.1	0	0.1	0	0.1	0	0.1	0	0.1
– ignition	none		none		none		none		none		none	
– melting	none		none		none		none		none		none	
– dripping	none		none		none		none		none		none	

Table 4. *Surface wetting of fabrics tested before and after exposure cycles.*

Variant I before exposure, degree	Variant I after exposure, degree	Variant II before exposure, degree	Variant II after exposure, degree	Light jacket before exposure, degree	Light jacket after exposure, degree
5; 5; 5	1÷2; 1÷2; 1÷2	5; 5; 5	1; 1; 1	5; 5; 5	1÷2; 1÷2; 1÷2

Table 5. *Abrasion resistance of fabrics tested before and after exposure cycles.*

Variant I before exposure, number of strokes	Variant I after exposure, number of strokes	Variant II before exposure, number of strokes	Variant II after exposure, number of strokes	Light jacket before exposure, number of strokes	Light jacket after exposure, number of strokes
>100,000	35,000	50,000	15,000	>100,000	25,000

Table 6. *CIELab colour space coordinates of fabrics tested before and after the exposure cycle.*

Parameter	Variant I before exposure	Variant I after exposure	Variant II before exposure	Variant II after exposure	Light jacket before exposure	Light jacket after exposure
L	55.46	52.23	61.04	60.65	55.17	52.45
a	3.28	5.73	3.38	4.26	3.18	5.08
b	28.64	22.72	31.24	26.54	27.4	23.85
ΔE	–	7.18	–	4.80	–	4.86

creases after the exposure cycle to a value of 35.000 cycles. A similar phenomenon was observed in the case of the light jacket (reduction to 25.000 cycles), while variant II is characterised by the lowest initial abrasion resistance (50.000 cycles) and the lowest abrasion resistance evaluated after the exposure cycle (15.000 cycles) – ***Table 5***.

Exposure to atmospheric factors and cleaning processes resulted in a noticeable change in the preservation of colour fastness for variant I, with the calculated colour difference ΔE being equal to 7.18 in this case (***Table 6***). A lower yet significant ΔE difference was also observed for variant II (4.80) and for the light jacket (4.86).

Table 7 presents the influence of exposure cycles on the change in rain tightness of variants I and II before and after the exposure process for–outer fabrics and ready garments.

The outer fabric in variant I of the clothing is characterised by an approximately twice increase in absorbency after the exposure cycles.

The exterior fabric in variant II of the clothing is characterised by an over tenfold increase in absorbency after the exposure cycles.

After exposure to atmospheric factors, variant I of the clothing is characterised by low resistance to water penetration (absorbency: 97%, degree of resistance to rain: 1). Similar values were observed for variant II (absorbency: 79%, degree of resistance to rain: 1).

The water penetration resistance of the ready garment depends on the absorbency of the outer fabric; however, it is dependent to the greatest extent on the total mass of the clothing and of its individual components (variant I of the clothing is 300 g heavier than variant II). In variant I, we are dealing with a doubling of mass after the rain exposure process, which explains its high absorbency (97%), whereas variant II has lower absorbency (79%) due to the fact that the product has a lower initial mass.

Conclusions

Physico-mechanical properties, comfort of use, safety, and aesthetic properties of protective clothing for firefighters were evaluated in a laboratory by means of a carefully selected research program.

The closer the methodology of determining properties is to actual conditions of use, the closer the evaluation is to real-life conditions of use, allowing for more accurate indication of potential hazards arising from loss of properties directly associated with safety and functionality.

Tests under conditions similar to real-life conditions (laboratory conditions) make it possible to simulate exposure to atmospheric conditions, reflecting their influence on the preservation of aesthetic properties and safety of use.

Evaluation of the aesthetics, functionality and safety of using textile fabrics that shape the user's sensations is conducted by means of modern, valid and complicated measuring techniques applied in textile engineering. Moreover, these techniques are associated with regulations concerning safety assurance and work safety.

As part of tests based on existing normative documents, risk analysis was conducted, and evaluation criteria, functional requirements and their levels were determined with respect to the safety parameters of protective clothing intended for functionaries of the State Fire Service.

It was documented that exposure to atmospheric conditions and the method of cleaning processes have a significant impact on the preservation of functional parameters and safety. Protective clothing should be protected against loss of

Table 7. *Rain tightness (water repellency) of fabrics, textile system and garments tested before and after exposure cycles.*

Parameter	Variant I before exposure, outer fabric	Variant I after exposure, outer fabric	Variant I before exposure, system	Variant I after exposure, system	Variant I after exposure, final garment	Variant II before exposure, outer fabric	Variant II after exposure, outer fabric	Variant II before exposure, system	Variant II after exposure, system	Variant II after exposure, final garment
Absorbency, %	13.6 ± 1.5	28.0 ± 1.4	66.4 ± 1.6	116.0 ± 7.5	97 ± 2	6.3 ± 0.8	61.4 ± 1.7	44.2 ± 0.4	94.6 ± 3.8	79 ± 2
Degree of resistance to rain	2	1	1	1	1	3	1	1	1	1
Description of sample surface	Partially wetted sample	Sample wet over entire surface	Sample wet over entire surface	Sample wet over entire surface	Sample wet over entire surface	Droplets adhere to part of the sample	Sample wet over entire surface	Sample wet over entire surface	Sample wet over entire surface	Sample wet over entire surface

the above in the process of cleaning and storage, since sunlight has a destructive impact on it. Due to the large dimensions and weight of the clothing, cleaning processes should be carried out in industrial laundries with the application of tumble drying.

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