Introduction

Protective clothing for firefighters must comply with a number of requirements contained in standards, varying from country to country (ASTM, European Standards etc.). Before protective clothing, gloves, helmets and other personal protective equipment for firefighters are approved for use, they must pass demanding tests and obtain a certificate. Tests are used to determine the material properties and check whether the product fulfils the minimum safety requirements. Thanks to research into protective clothing and the high requirements of the standards, injuries to firefighters during action, in particular burns (which are especially dangerous), can be better prevented. In 2006 - 2008, 14% of the injuries of firefighters were caused by burns [1], thus representing third place in terms of the incidence of injuries by nature (after overexertion/strains and wounds).

Regarding the safety of firefighters, a number of studies have been carried out to determine the real properties of protective turnout. Many test methods have been standardised all over the world. Performance standards are developed by a number of government and non-profit organizations to establish guidelines for protective equipment and procedures for working in hazardous areas.

In Europe, standards in the area of protective clothing are presented in the EN standards, published by the European Committee for Standardization, which specifies research techniques in a wide spectrum of possibilities. Standards developed in the United States of America are the ASTM standards, introduced by the organization “American Society for Testing and Materials”. Thanks to the cooperation of the ASTM with different companies involved in the implementation of new products on the market, with volunteers from testing organizations, and users, these standards take into consideration a number of important safety parameters. The other standards applicable in the USA are those introduced by the NFPA (National Fire Protection Association). Participants who serve on the NFPA are volunteers representing manufacturers, users, testing and special experts. The Russian standard for clothing for fire-fighters was developed by The Ministry of the Russian Federation for Civil Defence, Emergencies and Elimination of Consequences of Natural Disasters.

The subject of this work are requirements and test methods for firefighters' clothing in a range of protection against factors such as thermal radiation, flame, chemicals, leaking etc. In this review, test methods and requirements for firefighters' personal protective clothing in Europe (especially Poland), USA and Russia are compared.

Protection and firefighters’ clothing

The major hazards during fire-fighting are from radiant or convective heat, explosions, falling objects, debris, fine airborne particles, limited oxygen supply, hot liquid, molten substances, noise, toxic chemicals, smoke and hot gases [2]. The main role of firefighters’ clothing and equipment is to protect the firefighter from injuries from as many hazards as possible. A helmet protects against falling objects, an oxygen mask against limited oxygen supply, and protective clothing against radiant or convective heat, flame, hot liquids, toxic chemicals and water.

Table 1 presents a summary of requirements from thermal, mechanical and chemical factors in the standards chosen: NFPA 1971 „Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting”, EN 469 „Protective clothing for firefighters - Performance requirements for protective clothing”, НПБ 162-02 „Special Protective Clothing For Fire-Fighters Isolation Type. General Technical Requirements. Test Methods” [1]. An additional require-
Table 1. Summary of requirements from thermal, mechanical and chemical factors in the standards chosen: NFPA 1971[3], EN 469[4], НПБ 162-02[5], Ordinance of the Ministry of the Interior of Poland[6].

| Category           | Standard for requirements | Parameter                                      | Requirements                                                                 | Standard for test method |
|--------------------|---------------------------|------------------------------------------------|------------------------------------------------------------------------------|--------------------------|
| Radiant Heat       | NFPA 1971                 | TPP (Thermal protection performance)           | TPP ≥ 35.0 at: heat flux during test 84 kW/m²                                 | ISO 17492                |
|                    |                           | RPP (Radiant heat performance)                 | Intersect time ≥ 25s                                                          | ASTM F 2702              |
|                    |                           | Transmitted and stored energy                  | Time before 2nd degree burns ≥ 130s                                          | ASTM F 2731              |
|                    | EN 469                    | Total Heat Loss                                 | THL ≥ 205 W/m²                                                                | ASTM F1868               |
|                    |                           | RHTI₂₄ (heat transfer - radiation)             | RHTI₂₄ ≥ 18.0 for level 2 at: heat flux during test 40 kW/m²                  | EN ISO 6942              |
|                    |                           | RHTI₂₄ - RHTI₁₂ (heat transfer - radiation)    | RHTI₂₄ ≥ 10.0 for level 1 at: heat flux during test 40 kW/m²                  |                          |
|                    | НПБ 162-02                | Heat flux on inner surface not more than 2.5 kW/m² at: heat flux during test 40 kW/m² | НПБ 161                      |
| Flame              | NFPA 1971                 | Flame Resistance                               | After flame no more than 2 s no melting or dripping                         | ASTM D 6413              |
|                    | EN 469                    | Heat resistance                                | H₅T₂₄ ≥ 13.0 for level 2 HT₁₂₄ ≥ 9.0 for level 1                             | EN ISO 9151              |
|                    |                           | HTI₂₄ - HTI₂₄ (heat transfer - flame)           | HTI₂₄ ≥ 4.0 for level 2 HTI₁₂ ≥ 3.0 for level 1                               |                          |
|                    | ЕN 469                    | Flame spread                                   | Index 3 of p/EN ISO 14116                                                     | EN ISO 15025              |
|                    | НПБ 162-02                | Flame Resistance                               | After flame no more than 2 s shrinkage ≤ 10%                                  | ISO 6941                 |
| Hot atmosphere     | NFPA 1971                 | Heat resistance                                | Shrinkage ≤ 5% at: temperature 180 ± 5 ºC exposure time: 5 min               | ISO 17493                |
|                    | EN 469                    | Heat resistance                                | Shrinkage ≤ 5% at: temperature 180 ± 5 ºC exposure time: 5 min               | ISO 17493                |
|                    | НПБ 162-02                | Heat resistance                                | Shrinkage ≤ 5% at: temperature 150 ºC                                       | НПБ 161                 |
| Contact heat       | NFPA 1971                 | Conductive and Compressive Heat Resistance     | Time before 2nd degree burns ≥ 25 s                                          | ASTM F1060               |
|                    | EN 469                    | Conductive and Compressive Heat Resistance     | -                                                                           |                          |
|                    | НПБ 162-02                | Conductive and Compressive Heat Resistance     | Shrinkage ≤ 5% at: 400 ± 5 ºC exposure time: 5 s                             | НПБ 161                 |
| Water              | NFPA 1971                 | Resistance to water                            | Water penetration resistance minimum 172 kPa                                 | Method 5512 of Federal Test Method Standard 191A |
|                    | EN 469                    | Resistance to water                            | Water penetration resistance minimum 20 kPa                                  | EN 20811                 |
|                    | Ordinance of the Ministry of the Interior (Poland) | Resistance to rain                             | Inner layer cannot be wet after one hour of artificial rain on complete garment | Ordinance of the Ministry of the Interior (Poland) |
| Other liquids      | NFPA 1971                 | Table 2 (see page 134)                         | No liquid penetration to the innermost surface                               | ASTM F 903 procedure C   |
|                    | EN 469                    | Table 3 (see page 134)                         | No liquid penetration to the innermost surface                               | EN ISO 6530              |
|                    | НПБ 162-02                | Table 4 (see page 134)                         | No liquid penetration to the innermost surface                               | НПБ 162-02              |
| Mechanical         | NFPA 1971                 | Tear resistance - outer material               | ≥ 100 N                                                                      | ASTM D 5587              |
|                    |                           | Tear resistance - moisture and thermal barrier | ≥ 22 N                                                                       |                          |
|                    | EN 469                    | Tear strength - outer material                 | ≥ 25 N                                                                       | EN ISO 4674-1            |
|                    |                           | Tear strength - moisture and thermal barrier   | Not required                                                                  |                          |
|                    | НПБ 162-02                | Tear resistance weft/warp                      | ≥ 35/30 N                                                                    | ГОСТ 17074               |
|                    |                           | Tear strength weft/warp                        | ≥ 600/700 N                                                                  | ГОСТ 17316               |

The table presents a summary of requirements from thermal, mechanical, and chemical factors in the standards chosen for personal protective clothing for firefighters. The table includes parameters such as radiant heat, flame resistance, heat resistance, tear resistance, resistance to water, resistance to rain, resistance to other liquids, and mechanical properties. Each parameter is associated with specific standards and test methods, ensuring compliance with safety and health regulations in the context of firefighting operations. The table highlights the importance of these regulatory standards in ensuring the safety and effectiveness of protective clothing for firefighters.
To predict the injuries, the sample is put on a test stand consisting of two radiant panels and trolley assembly. The value of the index TPP required replaces an earlier requirement for a minimum thickness of material for protective clothing. During the test of heat flow through a sample, the ability of the material tested to protect against radiant heat is measured. For protective clothing it is required to achieve a TPP of at least 35, which corresponds to 17.5 seconds of protection against second-degree skin burns during exposure to an external constant heat flux of 84 kW/m² (2 cal/cm²-sec) [8]. The TPP method uses a combination of heat sources, which gives a better reflection of the fire conditions.

In the Radiant Protective Performance test in accordance with test method ASTM 1939, two standard sets of exposure conditions are specified: 21 kW/m² (0.5 cal/cm²s) and 84 kW/m² (2.0 cal/cm²s) [10], either of which can be used. In this test a series of quartz lamps are used as an energy source rather than a burner. This test method is used for determination of the radiant heat resistance value of a material, and skin burn injury is predicted based on Stoll burn criteria.

ASTM F2731 [11] for the Transmitted and Stored Energy test method is the result of reports from firefighters on cases of burns under clothing, where there were no signs of damage to the outer and inner layers of clothing. The transmission of low-level energy and the combination of transmission energy and releasing energy stored inside clothing layers may be sufficient to cause this type of injury. This method allows to determine stored and transmitted energy. The specimen is subjected to radiant heat of 21 kW/m² (0.5 cal/cm²) for 120 seconds and then compressed with a force of 2 MPa for 60 seconds.

For the safety of fire fighters during action, the heat accumulated in the inner layers of protective clothing should be considered as a threat to them that could lead to burns. The survey conducted in CNBOP-PIB among firefighters shows that 9% of respondents experienced burns while the surface of the clothing remained intact. European standards do not have requirements for testing Transmitted and Stored Energy and there is no equivalent test. US standard require

| Chemical                 | Concentration                      |
|--------------------------|------------------------------------|
| Aquaeus film-forming foam (AFFF) | 3% concentration                  |
| Battery acid             | 3% by weight sulfuric acid to water |
| Fire resistant hydraulic fluid | phosphate ester base              |
| Surrogate gaseous fuel C | 50/50 by volume of toluene and iso-octane |
| Swimming pool chlorinating chemical | at least 65% free chlorine, saturated solution |

**Table 2. Chemical penetration testing - requirements for testing in accordance with NFPA 1971.**

| Chemical*          | Concentration weight, % |
|--------------------|-------------------------|
| NaOH               | 40                      |
| HCl                | 36                      |
| H2SO4              | 30                      |
| C6H10 (o-xylene)   | 100                     |

**Table 3. Chemical penetration testing - requirements for testing in accordance with EN 469. * Temperature of all chemicals: 20 ± 2 °C.**

| Chemical          | Concentration weight, % | Time of protective action in contact with aggressive media, not less than, minutes, at temperature |
|-------------------|-------------------------|-----------------------------------------------------------------------------------|
| NaOH              | 50                      | 90, 30, 5                                                                          |
| H2SO4             | 30                      |                                                                                  |
| KNO3              | 100                     | 20, 10, -                                                                           |
| HCl               | 70                      |                                                                                  |
| 1,2- dichloroethane | 100                    |                                                                                  |
| Benzene           |                         |                                                                                  |
| CH3COOH           | 100                     |                                                                                  |
| Oil and petroleum products | 100      |                                                                                  |
| NH3               | 100                     |                                                                                  |
| Cl2               | 100                     |                                                                                  |

**Table 4. Chemical penetration testing - requirements for testing in accordance with НПБ 162-02.**

**Figure 1. Test stand for thermal protection performance [9].**
European standard EN 469 recommends two tests to be performed: in accordance with EN ISO 9151 and EN ISO 15025. In test method “heat transmission on exposure to flame” described in EN ISO 9151, the specimen is placed horizontally. The heat transfer index, which is an indication of the relative heat transmission, is checked. In test method “limited flame spread” described in EN ISO 15025, the specimen is placed vertically. There are two test methods: A and B. In method A the burner is positioned perpendicular to the surface of the test fabric, and surface ignition is tested. In method B the burner is below the test specimen and inclined upwards at a 30° angle. In both test methods, the exposure time is 10 s.

Only the NFPA 1971 standard and НПБ 162-02 have a requirement for protection against contact heat.

The method for testing appointed by NFPA is ASTM F1060 for Conductive and Compressive Heat Resistance. In the test Conductive and Compressive Heat Resistance (CCHR) layer, a composite of clothing originating from the area of the elbows and knees is used. The test is carried out in two ways: using a dry or wet sample. Depending on the area from which the test sample comes from, the pressure applied is:
- 140 g/cm² (± 1.4 g/cm²) for the arm,
- 562 g/cm² (± 56 g/cm²) for the knees.

The samples should be exposed to temperature 280°C (±3/0 °C). If the test is determined if the time to second-degree burns is equal to or exceeds 25 s.

The presence of moisture within clothing can affect heat transfer significantly. It can reduce the effective thermal insulation of the clothing and increase the effective water vapour resistance [13]. Moisture can come from both water from the environment (rain, extinguishing water) or can be a result of sweating. It is important to test personal protective clothing for water resistance. Testing a small specimen is important, but it does not reflect the actual conditions of use. The weakest element of clothing i.e. the most prone to leaking, are the seams. The test required in Poland by the Ordinance of the Ministry of the Interior and developed in CNBOP-PIB is the resistance to rain test. CNBOP-PIB has introduced an additional procedure to test the resistance to leaking of complete protective clothing, involving the exposure of a dressed manikin to artificial rain for 60 minutes. The test is positive if in a lined jacket and trousers no soaking is detect after the test [14].

**Development direction**

Along with the development of technology and electronics, protective clothing is more and more advanced. A number of studies investigated smart or intelligent protective clothing systems. Sensors can be used to record physiological data related to health and safety, such as the heart rate or location of fire fighters without changing the clothing characteristics of flexibility and comfort [15].

In project No. O ROB/0011/03/01/001, financed by the National Centre for Research and Development (NCBiR), and implemented by a consortium consisting of The Main School of the Fire Service, CNBOP-PIB, Warsaw University of Technology, Aspirants School of the State Fire Service in Krakow, and Thermodlab WZ, advanced test stands for innovative test methods for fire-fighters’ protective clothing were developed, combining the possibility to evaluate samples subjected to the influence of radiant heat, flame and contact heat in an innovative way compared to existing standards, with the possibility (after minor modifications) to test samples in accordance with existing standards. The end result of the project will also be physical and mathematical models of heat and moisture transport in parts of personal protection taking into account the different materials and possible configurations [16].

Henriques Burn Integral (HBI), used in the calculation in the project, allows to calculate the second degree burns of human skin as a result of heat flux. The study conducted within the project concluded that for a high level of heat flux the HBI criterion is stronger than the HTI criterion.

When heat flux has greater intensity, the HBI criterion becomes increasingly important. The exact level of superiority of one criterion over the other differs depending on the material composition and garment’s thermal insulation. This relationship is also visible for a flame as the heat source. For the heat flux level 43 kW/m² the HBI criterion is almost 3 times stronger.

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The use of the HBI criterion instead of the HTI criterion allows for more extensive analysis of the issues and more accurate results. This is a more stringent criterion, and it provides greater safety for firefighters. Therefore this technique, by calculating second-degree burn injuries using the HBI criterion, is a good development direction.

Conclusions

Standard NP1 162-02 has the highest requirements in terms of resistance to contact with aggressive media. It also specifies requirements depending on the temperature of the substance. On the other hand, the NFPA 1971 standard includes testing with aggressive media that are in common use.

Only the NFPA 1971 standard includes a test of contact heat in the context of safety (time before 2nd degree burns). In EN 469, a test of contact heat is not included at all, but in NP1 162-02 there is a test of the shrinkage of material caused by contact heat.

The difference between TPP and RPP is that the heat source in RPP is 100% radiant heat and TPP has both radiant heat and heat from burners. Test methods for clothing resistance to flame do not differ significantly in comparable standards - they vary the position of the specimen relative to the flame.

Only the Polish standard (Ordinance of the Ministry of the Interior) includes the requirement for resistance to rain and leaking.

The big disadvantage of current test methods for protective clothing is that they don't take into account actual fire conditions. The test is carried out in a static way on a small specimen and often does not take into account the seams, reflective trim, reinforcements, pockets etc.

Development directions in the area of protective clothing are new kinds of clothing (that use sensors) and new test methods.

Editorial note

1) Original title: NP1 162-02, "Specialychnaya ochishchennaya ozhjuh vokhiny izolirovkanego typa. Obshie tekhnikhnye deferentsiya. Metody ispytanii".
2) Internal research conducted in CNBOP-PIB on a group of 120 professional firefighters.
3) One of test stands developed in project No. O ROB/0011/03/01/001, photo CNBOP-PIB.

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