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Testing Selected Personal Protection Items of Firefighters in Combined Conditions of Mechanical Loads and Temperatures Occurring during Gas LNG Leaks

Paweł Ogrodnik [1,*], Aleksandra Powęzka [2], Robert Piec [3], Tomasz Zwegliński [3], Marcin Smolarkiewicz [3], Paweł Gromek [3], Rafał Wróbel [2], Tomasz Węsierski [1], Małgorzata Majder-Łopatka [1] and Wiktor Wąsik [2]

1 Institute of Safety Engineering, The Main School of Fire Service, 52/54 Słowackiego Street, 01-629 Warsaw, Poland; twesierski@sgsp.edu.pl (T.W.); mmajder@sgsp.edu.pl (M.M.-Ł.)
2 Faculty of Safety Engineering and Civil Protection, The Main School of Fire Service, 52/54 Słowackiego Street, 01-629 Warsaw, Poland; apowezka@sgsp.edu.pl (A.P.); rwrobel@sgsp.edu.pl (R.W.); wwąsik@sgsp.edu.pl (W.W.)
3 Institute of Internal Security, The Main School of Fire Service, 52/54 Słowackiego Street, 01-629 Warsaw, Poland; rpiec@sgsp.edu.pl (R.P.); tzweglinski@sgsp.edu.pl (T.Z.); msmolarkiewicz@sgsp.edu.pl (M.S.); pgromek@sgsp.edu.pl (P.G.)
* Correspondence: pogrodnik@sgsp.edu.pl

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Abstract: The article examined selected individual protection used during rescue and fire-extinguishing activities. Fire helmet and special shoes were examined under conditions resembling the operational conditions of LNG gases. The assessment of the equipment consumption was based on strength tests. The main threats come from thermal and mechanical factors. Therefore, firefighters must properly protect their head and legs. At −80 °C, the energy of the impact force of the beater in the headache was, 12.4 J and 15.1 J for points P1 and P2, respectively. The studies showed that cooling the chamber to −80 °C adversely affected the structure of the fire helmet exposed to impact Dynamic. Research work was carried out as part of the Research and Development project No. DOB-BIO9/15/02/2018.

Keywords: firefighting personal protection; fire hazards; mechanical loads; thermal loads; LNG

1. Problem Description

Firefighters carrying out rescue and extinguishing activities are exposed to the extreme influence of environmental factors. The key research problem is to determine the level of personal protection of the first response of those exposed to the growing, permanent risk of chemical threats that accompany the leakage of LNG gas. The development of modern protective materials requires conducting an assessment and research on the effectiveness of protection in the possibilities of hazardous. In order to protect the firefighter's body against a threat associated with the leakage of cryogenic gases, personal protective equipment is used.

This publication contains the results of research carried out for helmets and fire boots. These results can contribute to creating new structural directions for personal protective equipment. First response firefighters require maximum protection from the broad scope of unpredictable threats and environmental factors encountered during rescue and fire-extinguishing activities.

Until now, no tests have been carried out at temperatures similar to those at the release of cryogenic liquids. In connection with the increase in LNG car transport, an attempt was made to examine the protection of personal firefighters in reference to the determinants of real phenomena and processes, in particular feet and head protection. A rescue workshop is rarely correlated with a research workshop. Therefore, deep analyses based on research in the context of world literature can be the highest valued material that will allow us to determine the effect of real terms of use of selected elements of special clothing. In addition, this will allow the aforementioned to improve the protection structure and their certification criteria.

2. Use of Personal Protection by Firefighters

Personal protection equipment (PPE) is a common way of assuring safety to workers; however, it is often perceived as the least favourite method in the hierarchy of hazards control [1]. Nevertheless, the use of PPE proves to be irreplaceable while working under harsh, uncertain and hardly controllable conditions. Such environments are typical during the rescue operations carried out by fire protection units [2]. Examples include the use of gloves protecting against blood-borne pathogens or wearing protective clothing to decrease the risk of being burnt while exposed to heat radiation. These are just some examples of a number of active measures related to personal protection equipment requiring the action of a firefighter for direct protection [3,4]. Hence, using PPE effectively is a complex safety issue, demanding broader elaboration. The use of PPE by individuals constitutes an active countermeasure, requiring an individual approach each time. Research conducted by [5–7] shows that although most firefighters declare the significance of PPE, they do not effectively apply it. This arises from a number of factors, which have been outlined in [8,9]. The situation is further complicated by the fact that suppressing fires and eliminating local threats is a unique type of activity, because the task of firefighters is not to avoid the threat, but to directly face it and suppress it. The problem of safety and of using the personal protection equipment of firefighters during rescue operations has been described in studies [10,11]. The authors point out that personal protective means should ensure safety during rescue operations in different conditions, while allowing the full mobility of rescuers. The mobility of firefighters during rescue operations has also been highlighted in studies [12,13]. There are several international standards in place for the evaluation of personal protection equipment for firefighters, but these standards are only assigned to the properties of protection against heat, flame and water (CEN TC 162:2002, EN 469:2005, ISO 11613:1999). In addition, several testing methods have been developed in order to assess how wearing certain PPE impacts a firefighter's mobility (BS 8469:2007, CEN TC 162:2002). Thus, a standard mobility method is important to make a comparison of different types of protection means feasible. The presented review clearly shows that research concerning firefighters' personal protection equipment is being conducted in various locations around the world. Thus far, however, they are not conducted in the context of their use in cryogenic liquid releases. This type of research consequently determines the necessity of a much more comprehensive development of personal protective means, in particular, taking into account, at all stages of design, a wide range of requirements for effective protection against almost all factors, including the risks associated with the release of cryogenic liquids.

3. General Characteristics of Risks Associated with the Use of LNG

Over the years, the LNG industry has shown that the liquefied natural gas is a relatively safe source of energy. This is largely the result of well-defined regulations and industrial practice that are firstly designed to avoid the occurrence of diverse incidents and to mitigate their consequences when they do occur. Despite this, unsafe situations sometimes occur related to transport (road accidents) or other incidents including those of a terrorist nature [14–16].

Liquefied Natural Gas (LNG) is typically stocked and shipped at almost ambient pressure in duly insulated tanks. The unavoidable conduction of heat makes the liquid vaporise, and the release of the vaporised gas facilitates keeping the LNG in a liquefied state through automatic cooling. If LNG is poured on the ground, it promptly boils until the ground cools down. Then, the process slows down. Consequently, LNG evaporates completely as long as there is no residue. If spilled above a water surface, LNG rises up and evaporates even quicker, since naturally, the temperature of water is much higher than LNG. When LNG is boiling, it creates a convection of heat in the reservoir. Thus, ice only forms in shallow reservoirs [17,18].

Naturally flammable liquids neither burn nor explode. Firstly, they have to vaporise and mix with air, or another oxidiser, to set on fire. Typically, the spread between the lower and upper flammable limit of an LNG vapour cloud is from 4% up to 15% of the gas concentration with air. Then, normally, it appears to be a white coloured cloud of vapour including ice crystals being condensed by the cold LNG vapour from the air. The vapour released initially has a temperature close to −161.7 °C. This was confirmed by field tests carried out under the project, which are presented in Figure 1 [19].

(**a**) (**b**)

Figure 1. LNG expansion during field tests. (**a**) outflow at a height of 1 meter directed to the ground at an angle of 60 degrees; (**b**) outflow at a height of 1 meter directed parallel to the ground.

In the event of a failure during transport or a road accident, the vapour cloud tends to adhere to the ground, and therefore, it is very likely that it would encounter an ignition source [20]. LNG vapour consists of boiling, light, flammable and odourless hydrocarbons (mainly methane). The vapours are non-toxic; however, they might cause a suffocating effect if oxygen is displaced from enclosed spaces. Coyote, in his research [21] carried out on a larger scale, describes the burning of LNG clouds. Natural gas has a self-ignition temperature of 540 °C, significantly higher than many different fuels (e.g., diesel, 280 °C; gasoline, 400 °C; and propane, 468 °C) [22,23]. Methane radiation is much more intense compared to diesel fuel; therefore, a personal protective equipment (PPE) assessment should be considered.

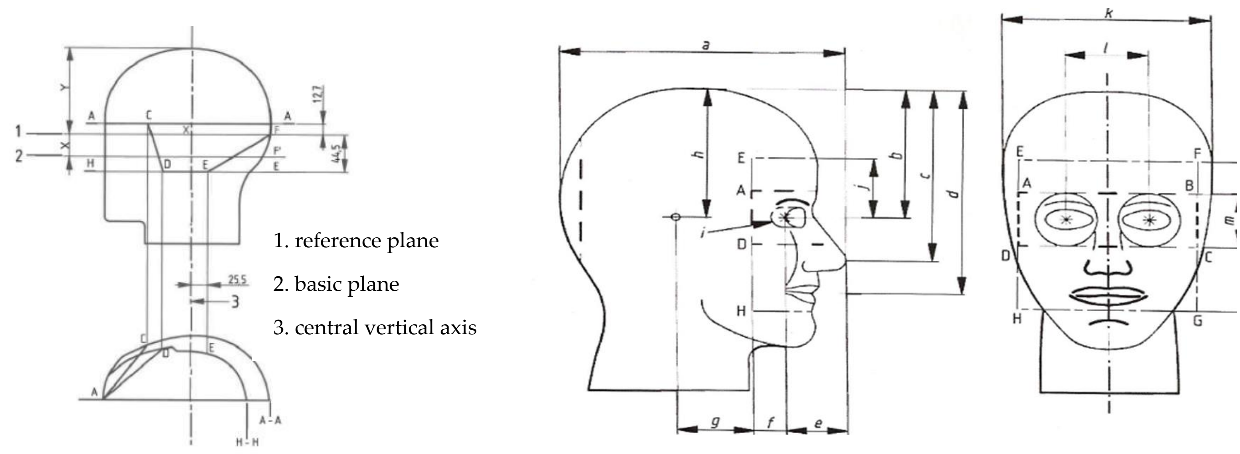
Research on and simulations of the flow of cryogenic liquids in tanks have been presented in the research [24,25]. These studies present the role of the tank shape factor, Rayleigh number and the ratio of the gaseous to liquid volume on the course of circulation and thermal stratification in tanks.

Since the establishment of the LNG trade in the late 1960s, eight maritime incidents involving LNG carrier ships that resulted in spills and some breakage of the hull as a consequence of cold cracking have been registered [26]. The majority of carbon steels characterise the range of embrittlement temperature from −73 up to −23 °C. Due to the high thermal conductivity of steel, structural steel achieves rapidly nominal failure criteria between one and five seconds, and this results in a potentially high risk associated with LNG transport. Meanwhile, storing large amounts of LNG in containers led to an event defined as “Rollover”. It might happen as LNG stratifies in a storage container onto two separate stratums of diverse density over a long period of time with insufficient mixing. The upper stratum evaporates light components and transforms into being a denser layer. This can cause pressure to build up in the tank and eventually lead to tank damage [27]. Today, all the modern LNG storages are furnished with duplicate walls. In principle, containment demands using only materials that are designed and approved for cryogenic substances. The storage is well prepared for their lifetime to remove vaporised vapour, prevent air ingress, prevent lifting by frost and endure a range of refilling cycles, cooling and heating operations [28,29]. As can be seen, the transport and storage of LNG can create a number of hazards. Therefore, it is so important to prepare the emergency services for LNG release operations.

4. Basic Requirements for Selected Firefighter's Personal Protective Equipment

4.1. Helmets

The helmets used during rescue actions in buildings and in other objects are designed to provide protection to a firefighter, protecting the head from potential dangers that can appear during the firefighting action in buildings and in other objects. According to normative requirements [30], the area protected by the helmet is divided into zones, which are presented in Figure 2.



(**a**) (**b**)

Figure 2. Protection zones: (**a**) 1a—the part above plane AA, 1b—the area between the planes AA and CDEF and 3a—the neck protection zone; (**b**) 2—comprises at least the eye protection zone defined by EFGH and 3b—comprises at least the CDHG zone.

Currently, type "B" helmets are used in fire protection in Poland, as defined in [31]. They protect at least zones 1a and 1b, have low temperature class −20 °C and are furnished with eye, face and neck protection. According to general assumptions, the helmets should be made so that they do not injure body parts (head) and assure the necessary comfort to a firefighter. Those surfaces of those helmets that touch or may touch the head during wearing may not have any roughness, sharp edges or protruding elements that could pose a hazard to safety during use. The materials of the helmet, which are likely to come into contact with the wearer's skin, may not cause irritation or be hazardous to health. Furthermore, all the helmet components must be intact after cleaning or disinfection. The face protection supplied with the head protection should meet requirements specified in the standards [32]. Where neck and zone 3b protection is recommended or provided by the manufacturer, these shields shall ensure that the requirements for these shields are met. The neck protection shall be made of leather, woven or metallised fabric.

4.2. Special Footwear

Firefighters' boots are designed to protect the legs from mechanical injuries, harmful factors, high and low temperatures, moisture, electric current and slipping. In terms of requirements applicable for special footwear, the currently binding Polish standards are [33,34]. Depending on the nature of the hazard, to which the protective footwear is adapted, the following three categories of footwear can be distinguished:

- Safety shoes (S),
- Protective shoes (P),
- Occupational shoes (O).

The footwear most commonly used by firemen are special leather boots. The structure of special leather boots is reinforced with a metal reinforcement of the sole and the nose of the boot. The material of which they are made is characterised by high resistance to atmospheric conditions in a temperature range from −20 to +40 °C. The upper material is specially impregnated cowhide. This technology increases the surface tension of water molecules, which stops them from seeping through. A climate membrane ensures that perspiration and excessive heat are freely disposed of, while at the same time ensuring waterproofness.

The specific advantages of leather lace-up shoes are as follows:

- good thermal insulation with the possibility of vapour transmission to the outside;
- protection against heat radiation;
- protection against mechanical damage by metal reinforcements of the heel, sole, toe, Achilles' tendon and ankle joint;
- dielectric properties of the boot;
- energy-absorbing sole;
- anti-slip properties of the boot sole;
- use of zippers and laces allowing to adjust and fit the shoe profile to almost every leg;
- high resistance of the sole to contact with hot ground.

As far as the requirements for the cold insulation of footwear are concerned, the standard applicable for testing is [30]. However, it does not take into account all the existing forms of heat loss, or the influence of factors that result from the use of footwear, such as the intensity of movement while walking, on the magnitude of these losses.

5. Studies of Selected Personal Protection Equipment of Firefighters at Reduced Temperatures

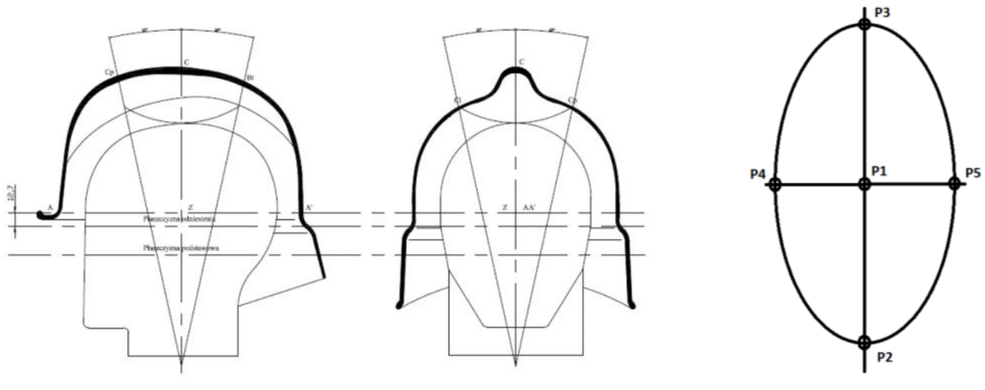
5.1. Helmets

The objective of the study was comparing the magnitude of the mechanical force that is transmitted by selected models of firefighter helmets in normal conditions of 20 °C and in reduced temperatures. The tests were performed on helmet type Calisia Vulcan CV 102 MO (Kaliskie Zakłady Przemysłu Terenowego S.A., Kalisz, Poland), which was manufactured in 2015, in stock (new). The helmets (Figure 3) have a shell made by an injection moulding of polyamide PA66 (Ultramid). The material itself can be used in temperatures up to a maximum of 310 °C.

(a) (b)

Figure 3. Tested helmets: (**a**) The front view; (**b**) The aft view.

The test rig was based on a DP Fest 1000 (Labor Tech, Opava, Czech Republic) universal column hammer with dynamic loads in the range of impact energy from 0.5 to 1000 J with velocities from 0.80 to 4.60 m/s. The test was conducted in a combined force−temperature environment of −80 °C. This was made possible by lowering the temperature in the machine's working chamber. During the test, the headform was rotated so that the impact point lay in the vertical axis of the tup insert with the force transducer. The drop of the tup insert was performed at each of the five points shown in Figure 4.



(**a**) (**b**)

Figure 4. Points at which impact was applied: (**a**) Headform; (**b**) Measurement points.

The results obtained for the selected points are presented in Figures 5–8.

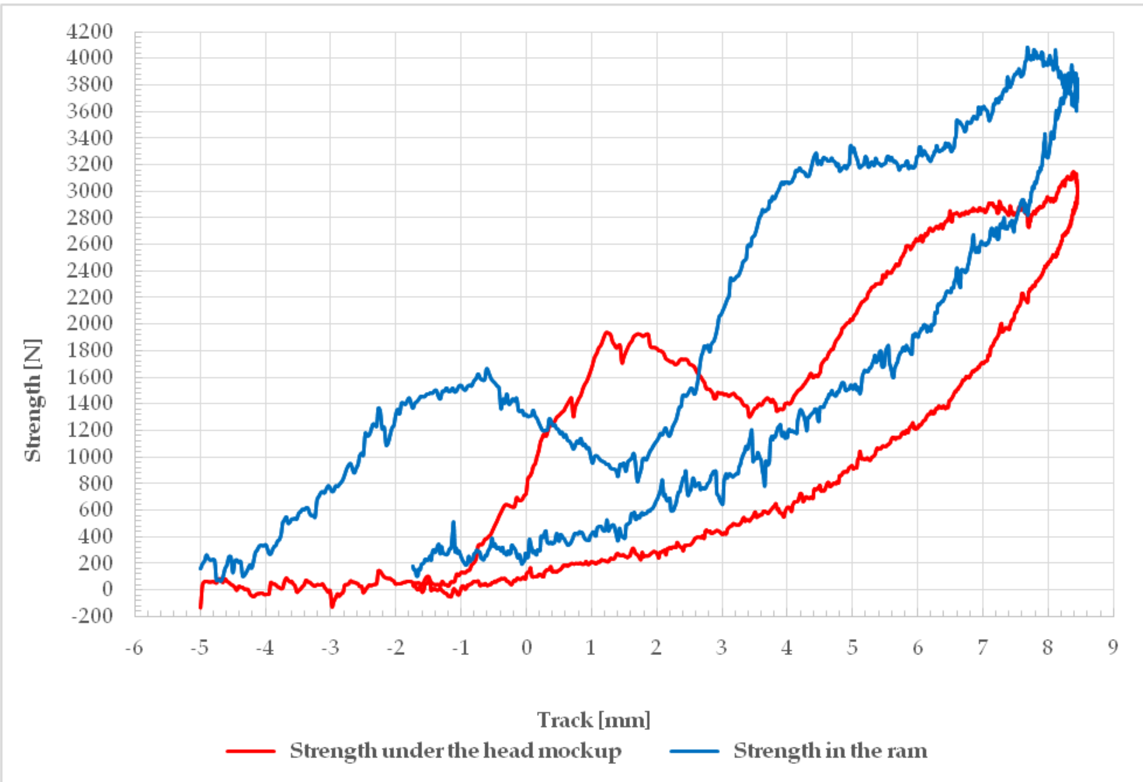


Figure 5. Diagram 1 Strength after striking at point P1−temperature of 20 °C.

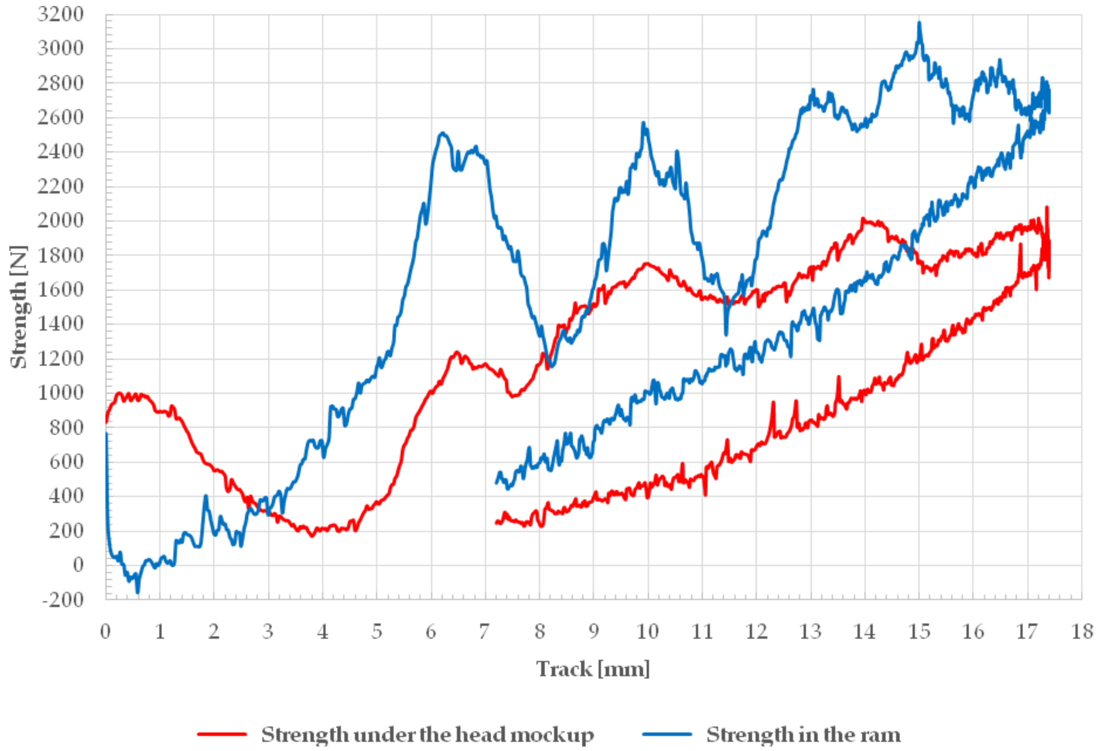


Figure 6. Strength after striking at point P2−temperature of 20 °C.

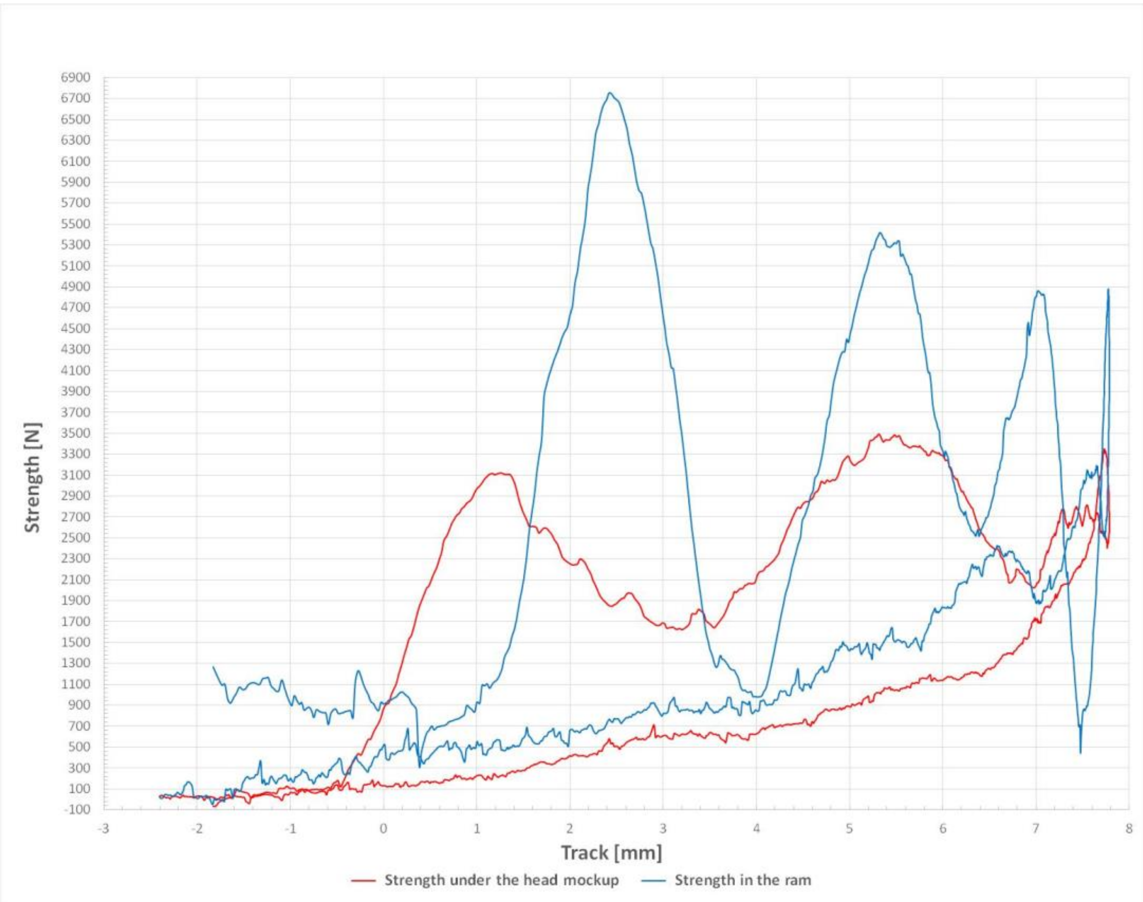


Figure 7. Force after impact on point P1−temperature of −80 °C.

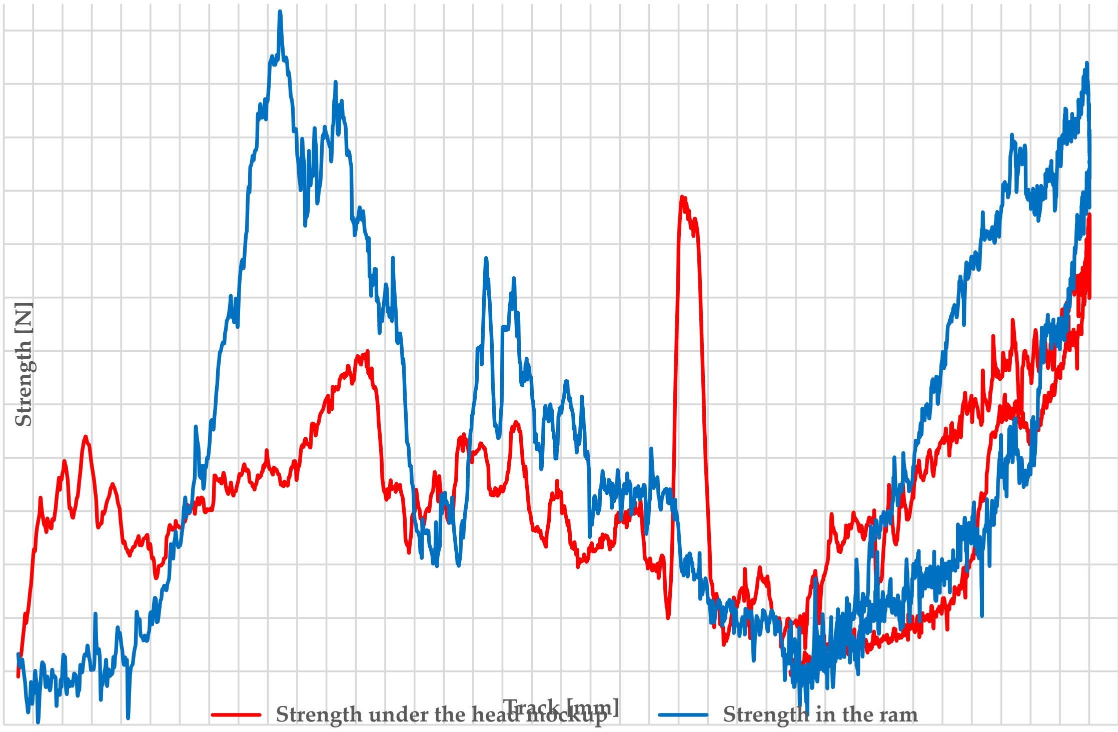


Figure 8. Force after impact on point P2—-temperature of −80 °C.

At −80 °C, the test was stopped after hitting the P2 point due to the complete destruction of the helmet. A view of the helmet after the test at −80 °C is shown in Figure 9. A summary of test results is presented in Table 1.

(**a**) (**b**)

Figure 9. Helmet after testing at a temperature of −80 °C: (**a**) after hitting point P1; (**b**) after hitting point P2.

Table 1. Summary of helmet test results at normal and reduced temperature.

Item	Maximum Force under Head Mock-Up (N)	Tit Deflection of Shock Absorbing System (mm)	Transfer Energy (J)	Dissipation Energy (J)	Time (s)
Point P1 (20 °C)	3144.84	8.46	17.0	12.9	0.025
Point P2 (20 °C)	2079.11	17.39	21.4	8.6	0.062
Point P3 (20 °C)	2875.78	18.65	21.3	8.7	0.034
Point P4 (20 °C)	2382.32	17.91	25.0	5.1	0.035
Point P5 (20 °C)	2665.28	16.34	26.2	3.7	0.034
Point P1 (−80 °C)	3489.99	7.78	12.4	17.7	0.028
Point P2 (−80 °C)	1778.42	36.02	15.1	14.8	0.062

5.2. Special Footwear

The purpose of this test was to determine the resistance of special footwear to puncture with a stylus. This consisted of pressing the blade into the sole of the shoe at a speed of 10 ± 3 mm/min until the shoe was completely punctured. The test itself was conducted at a normal temperature of 20 °C and at a reduced temperature of approximately −60 °C. The maximum shoe breakthrough force and temperature were measured during the test. Use was made of a universal testing machine, 6.100SP.1-2-2300, with an electromechanical drive capable of handling loads up to 100 kN.

As a result, five tests each were performed at both normal and reduced temperatures. An example of the puncture force diagram at 20 °C is shown in Figure 10.

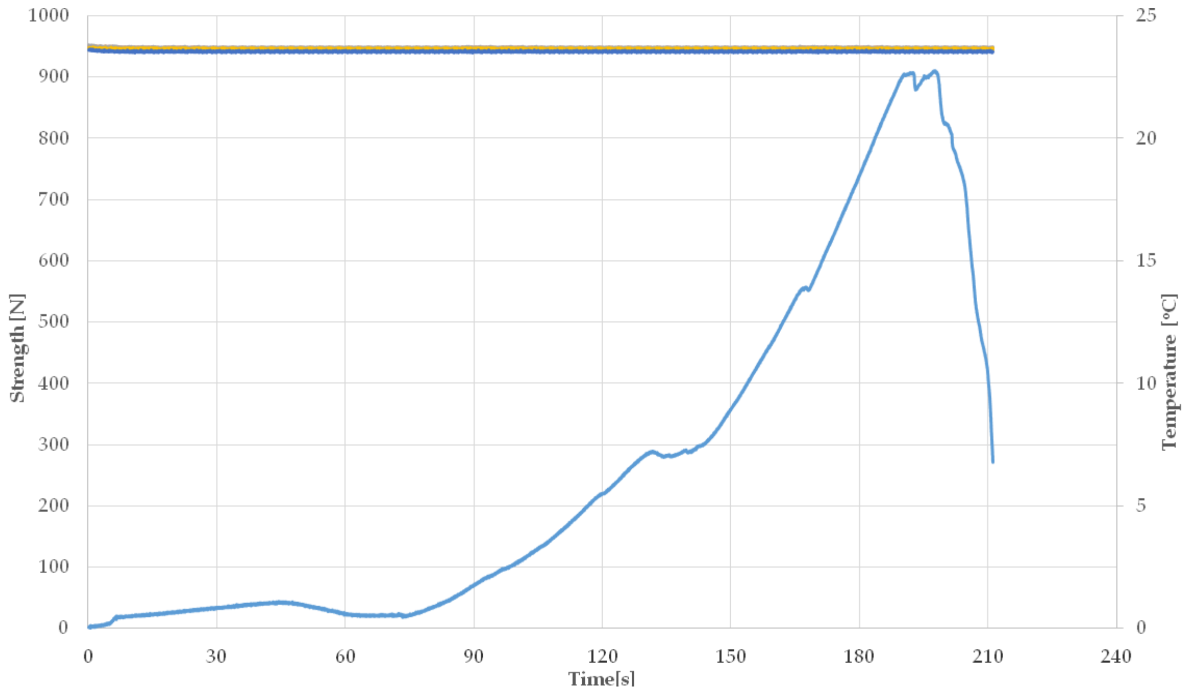


Figure 10. Breaking power of the shoe sole at 20 °C.

During the low-temperature tests, the cryogenic fluid was injected directly into the testing chamber of the testing machine using a lance (Figure 11). At the same time, the temperature was measured at four different points during the test. An example of the temperature curves is shown in Figure 12. Figure 13 shows an example of shoe puncture with a stylus at the reduced temperature.

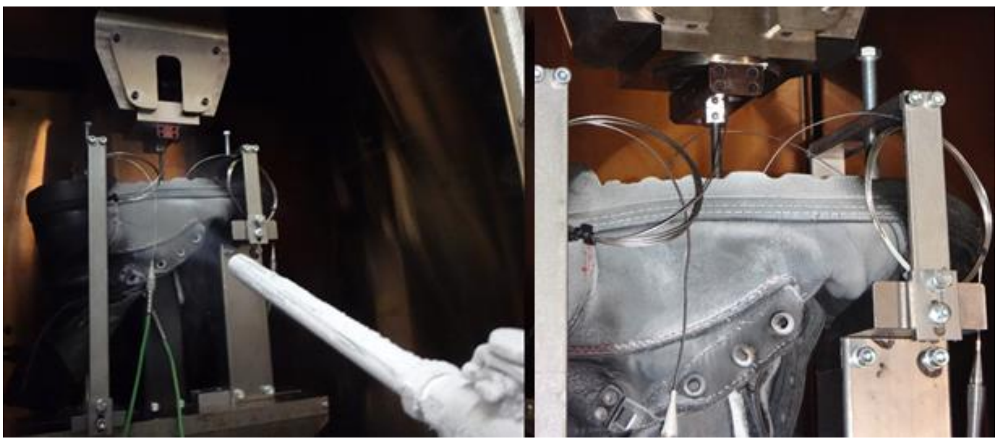


Figure 11. Reduction in sole temperatures of special shoes during the puncture test.

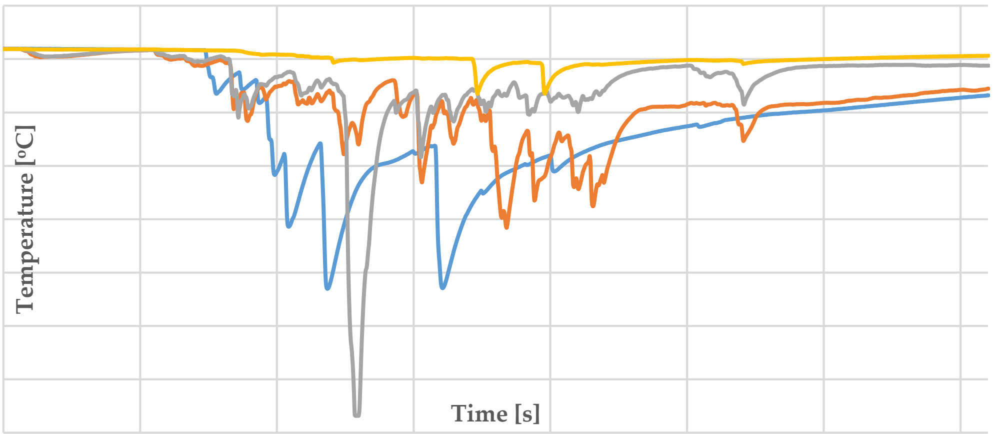


Figure 12. Temperature at different parts of the shoe during a stylus puncture test (yellow and orange—internal shoe temperature, blue—shoe sole temperature, grey—stylus temperature).

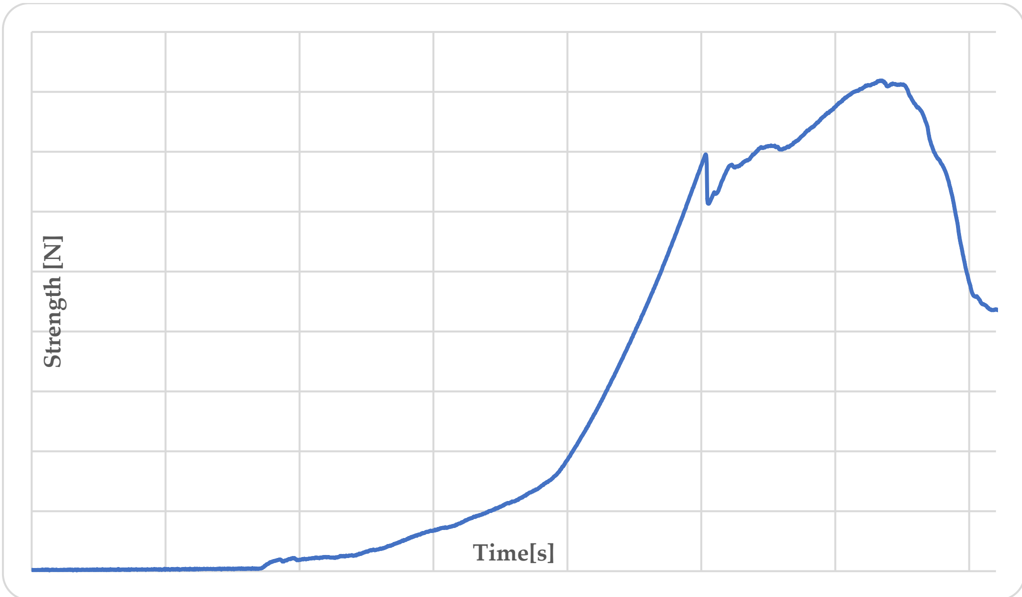


Figure 13. Breakthrough force of the shoe sole after cooling the sole to approximately −60 °C.

The results of shoe sole puncture tests under different thermal conditions have been presented in Table 2.

Table 2. Shoe test results at normal and reduced temperature.

Puncture Force (−60 °C) (N)	Puncture Force (20 °C) (N)
1776.6	912.7
1820.7	896.7
1685.4	910.4
1764.2	900.7
1764.2	922.4

6. Discussion

LNG has a relatively low temperature and its boiling point at atmospheric pressure is about −160 °C. Under such conditions, the vaporised gas has a density greater than that of the ambient air. Similar to other gaseous hydrocarbons, LNG is flammable. In the atmospheric environment, it is flammable after mixing with air in a volume of 5–15%. After a leak occurs, LNG immediately reaches boiling point, absorbs heat from the environment and freely spreads on the ground [34]. This is confirmed by the research carried out at the training ground. The research on personal protection of firefighters conducted thus far has focused mainly on the conditions of elevated and high temperatures occurring during a fire. It is also compliant with the requirements of the standards for firefighting helmets for which the applicable standard [30] provides for tests of resistance to high temperatures and resistance to flame and heat flux (tests at a temperature of 1000 °C). At the same time, according to the requirements, fire helmets should provide protection at −30 °C. Thus far, no studies have been conducted in which helmets have been subjected to combined loads at temperatures that may occur during the release of LNG. The conducted research has confirmed that the materials used thus far for the production of helmet shells are not able to ensure the safety of users during this type of associated loads. During these tests, already during the second impact (Point P2), the shell was destroyed (Figure 10), which resulted in the discontinuation of the tests. The legs and arms are more vulnerable to cold than the rest of the body. The surface of the hands and feet is very large in relation to their volume. As a result, these parts of the body suffer from an extremely high rate of heat loss. This is confirmed by a number of studies conducted thus far [35,36]. The limbs have little local metabolic heat production due to the low muscle mass that decreases with tissue temperature. Previous studies show that the foot can generate up to 2 W, but at tissue temperatures below 10 °C, it decreases to about 0.2 W [37]. The temperature of the feet is related to many different factors, and it has been found that the most comfortable conditions occur when their temperature is around 33 °C and the relative humidity on the skin is around 60%. The general feeling of cold occurs in the toe temperature below 25 °C, while discomfort due to cold is observed at temperatures below 20–21 °C [38]. Figure 13 shows that during the tests during the impact of cryogenic fluid, the temperature inside the safety footwear dropped drastically and, depending on the measurement site, even reached −40 °C after about 180 s of the liquid exposure. This temperature is extreme because the first frostbite may occur at positive temperatures reaching 2–5 °C if it comes into contact with wet clothes. It should be noted that such extreme negative temperatures that may occur during the release of LNG cause an increase in hardness for most rubbers. This is confirmed by a number of studies conducted thus far [39–41]. This was also confirmed during our own conducted research. The increase in rubber hardness resulted in an increase in the puncture force at each of the points tested. The stylus puncture force at −60 °C was practically twice as high as that obtained at 20 °C.

7. Conclusions

Personal protective equipment is one of the basic elements used to ensure the safety of firefighters during rescue operations and also during training and practical exercises. The research conducted under the project DOB-BIO9/15/02/2018 proves that lowered temperatures that occur during the release of cryogenic gases such as LNG affect the mechanical properties (personal protection equipment). The conducted research allows us to make the following presumptions:

1. Impact tests of firefighter helmets have shown that as regards the temperature of 20 °C, the value of the maximum force under the mock-up head was uniformly dependent on selected points. The situation changed completely when the chamber was cooled to −80 °C. In general, when hitting the first point (according to the experimental plan), the value of the maximum force was similar to the force at 20 °C and was 3489.99. However, the impact itself significantly damaged the helmet shell. This made it necessary to discontinue further testing;
2. After lowering the temperature, the testing of the puncture force of firefighters' special footwear resulted in the hardness of the sole increasing and, consequently, in the puncture force increasing by approx. 50%;
3. The breakthrough time increased by approximately 100 s at a temperature of −60 °C.

The results of the conducted research justify the need for evaluating the safety procedures that determine the functioning of the National Rescue and Firefighting System. In this context, it is necessary to consider issues of the operational substitutability of rescue teams in situations when the personal protection equipment at their disposal have been exposed to the direct impact of LNG, as well as the substitutability of the personal protection equipment, such as in the described circumstances. It may turn out that mitigating the effects of LNG could lead to a reduced level of operational readiness due to the destruction or deterioration of personal protection equipment.

It should be borne in mind that the research was limited to two types of personal protection equipment—helmets and special boots. Although they are crucial from the perspective of safety of rescue actions, they are only a small part of the catalogue of personal protection equipment that firefighters use in their everyday service. Therefore, it is worth considering the option of conducting a similar scientific study for protective gloves, respiratory protective devices masks, protective goggles and special clothing. This would make it possible to holistically present the conditions of rescue operations in the case of LNG hazards and to formulate comprehensive operational guidelines in this field.

Moreover, the achieved results and formulated conclusions point to further areas of research concerning rescue operations conducted in connection with the release of LNG. It is worth mentioning at this point the indicators of the loss of properties of personal protection equipment due to LNG impact, the rationalisation of procedures for responding to incidents involving LNG, the structural optimisation of safety systems and entities (e.g., fire services) responding to incidents involving LNG, in-depth analyses of safety conditions of these actions (e.g., the extent of the danger zone) along with their impact on the continuity of fire service operations. This will make it possible to benefit from the achievements of technical sciences in the process of solving problems of both a technical nature (e.g., improvement of personal protection equipment for firefighters, development of new ways of technical protection in LNG facilities) and of a social nature (e.g., formulation of operational guidelines, ensuring the continuity of safety systems).

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