PROSPECTS FOR ESTABLISHING REQUIREMENTS FOR FIXED COMPRESSED FOAM FIRE-FIGHTING SYSTEMS BY EUROPEAN STANDARDS

[a]VOLODYMYR BOROVYKOV, [b]VADYM NIZHNYK, [c]OKSANA SLUTSKA, [d]TARAS SKOROBAHATKO, [e]VIKTOR MYKHAILOV, [f]DMYTRO VOYTOVYCH, [g]ROMAN SUKACH, [h]YAREMA VELYKYI, [i]VOLODYMYR-PETRO PARKHOMENKO, [j]NAZAR SHTANGRET

[a-e]Institute of Public Administration and Scientific Research in Civil Protection, 21, Vyshhorodska Str., 04074, Kyiv, Ukraine
[f-j]Lviv State Univesity of Life Safety, 35, Kleparivska Str., 79000, Lviv, Ukraine
email: [a]foam2000@gmail.com, [b]nignyk@ukr.net, [c]sl_oksi@ukr.net, [d]tarasskorobagatko@gmail.com, [e]mvn2006@ukr.net, [f]voytovych.dmt@gmail.com, [g]sukach.r@gmail.com, [h]yaremavelikiy@gmail.com, [i]pvpo2016@gmail.com, [j]shtangretnazar1993@gmail.com

Abstract: The purpose of the work was substantiation of the requirements for foam concentrates, compressed foam fire-fighting systems and their components which could currently be included in the European standards for foam fire-fighting systems, as well as spheres for further research. For this, appropriate information available in literary sources and regulations was analyzed. It was established that the currently existing portable compressed foam fire-fighting systems were intended primarily for fighting fires at manned facilities. Statistical materials on the abundance of fixed compressed foam fire-fighting systems in the world, despite their proven suitability for fighting fires at many types of facilities, in particular, in the presence of combustible liquids, have not been found. At the same time, a tentative list of facilities that could be protected by compressed foam fire-fighting systems was outlined and approximate restrictions on the use of such systems were indicated. It was established that there were no direct correlation between expansion ratio, stability and fire-extinguishing efficiency of compressed foam. The possibility of amending appropriate European norms with the information on the applicability and conditions of use for the protection of facilities with compressed air foam sprinkler and deluge fire-fighting systems was substantiated. In particular, the types of foam concentrates allowed for this were named, as well as the proposed values of the application rate and duration of application of their foam solutions. Opinions were expressed regarding promising spheres for further research aimed at improving European standards for foam fire-fighting systems.

Keywords: burning; combustible liquid; compressed foam; expansion ratio; fire; fire hazard; fire-fighting system; foam concentrate; foam stability

1 Introduction

As it is known, the most common fire extinguishing agent is water. Most often, it is delivered with the help of branch pipes in the form of compact, less often sprayed jets from mobile fire-fighting equipment, primarily fire engines. For the formation and application of compact jets of water with the purpose of fighting fires, fire hose reels are also used which are provided in buildings and structures in accordance with building codes. Fixed water fire-fighting systems (mostly sprinkler systems) which protect manned facilities have also become widely used; these include residential, office, commercial, and industrial buildings.

The advantages of water as a fire extinguishing agent are its cheapness and availability, safety for people and the environment, and its suitability for extinguishing most solid combustible materials. In addition, the high specific heat capacity and specific heat of vaporization of water contribute to intensive cooling of the fire place and cessation of combustion. At the same time, it is characterized by such disadvantages as low viscosity, due to which there is an intensive emergence of water from the surfaces of burning materials, and high surface tension, due to which wetting of hydrophobic solids and materials with a developed surface (wool, paper in bundles, peat, etc.) with water is complicated. Moreover, water is unsuitable for extinguishing the absolute majority of combustible and flammable liquids, and it is also characterized by high electrical conductivity which complicates or makes it impossible to extinguish fires involving live electrical equipment with it. Its use is also unacceptable or ineffective for extinguishing combustible metals as well as substances that enter into a chemical interaction with water or release oxygen or other oxidants during their destruction. One way or another, the rate of water use during fire-fighting usually does not exceed 3-5 %, while the rest of it is wasted, often causing additional damage.

These disadvantages of water as a fire extinguishing agent forced researchers to look for alternatives to it. One of the main trends of this became the use of functional additives to water (surfactants, mineral salts, water-soluble polymers or their combinations), and another was the development of fundamentally new types of fire extinguishing agents (powder, gas, aerosol ones). The “hybrid” trend became development of foam concentrates for extinguishing fires, which could also be considered as functional additives to water. At the same time, the use of foam solutions is principally different in that it is not branch pipes that are mostly used for the formation of solid or sprayed jets, but ejection foam generators or spray nozzles with or without air aspiration. Accordingly, not aqueous solution of chemical substance(s), but air-mechanical foam is used for fighting fires. Having lower density than water, foam can be kept on the surface of hydrocarbons and other flammable liquids, spread across it, form a foam “cushion” and provide extinguishing. Thanks to the use of soap-like (those that form colloidal micelles) surfactants as the basis of foam concentrates, their aqueous solutions have high wetting capacity. Namely for this reason, foam concentrates are sometimes used for the preparation of wetting solutions for extinguishing solid combustibles. In addition, the release of aqueous solutions containing such substances during the destruction of the foam also contributes to the wetting of hydrophobic combustible materials, accelerates their extinguishing and prevents re-ignition. Finally, the high content of the gas phase causes the electrical conductivity of the foam to be lower than that of water, and with an increase in its content, the electrical conductivity decreases. Accordingly, under certain conditions foam can be suitable for extinguishing live electrical equipment.

The first attempts to fight fires with foam in a number of countries took place 120 to 150 years ago; however, according to available data, about a century has passed since the first foam concentrates as such appeared. During this time, a large number of types, sorts, and brands of foam concentrates have been developed, which differ in the raw materials used for their manufacture, purpose, suitability for use with various fire-fighting equipment, sensitivity to the quality of water used to prepare their foam solutions, etc. Currently, there are four standards in force in Europe regarding foam concentrates for fire-fighting, combined into the EN 1568 series [7-10].

As can be seen from the names of these standards, foam concentrates are divided into categories based on two features – expansion ratio of foam generated from foam solutions and the primary purpose. However, this division is actually quite arbitrary, and the first reason is that the same foam concentrate can meet more than one standard. For example, it can provide the possibility of generating low, medium, or high expansion foam with proper fire-extinguishing efficiency. It should be noted that the expansion ratio of foam is the ratio of its volume to the volume of the aqueous solution from which this foam is obtained, but different types of equipment are used to generate foam of these three types, which differ fundamentally in their design. Low expansion foam is foam for which this ratio does not exceed 20, medium expansion foam is the one whose expansion ratio is in the range of 20 to 200, and high expansion foam is the one with expansion ratio of more than 200. Suitability of foam for extinguishing combustible (flammable) water-soluble liquids is mainly achieved by using water-soluble polymers with thixotropic properties, and namely their presence in the formulation distinguishes the vast majority of foam concentrates which meet the requirements of EN 1568-4:2018 Fire extinguishing media – Foam concentrates, in its Part 4: “Specification for low expansion foam concentrates for surface application to water-miscible liquids” [10].

The second reason for calling the above-mentioned division "quite conventional" is that the scope of application of air-mechanical foam (and, accordingly, foam concentrates) in fire-fighting is much wider than it can be imagined considering the names of the regulations. For example, many foam concentrates are suitable for extinguishing non-polar combustible liquids stored in tanks by delivering low expansion foam not only to the surface of the liquid, but also to the lower part of its layer ("subsurface" method) through technological pipelines. At the same time, neither European [9] nor relevant International [19] standards set requirements for them. They only recognize the possible suitability of foam concentrates that meet their requirements for "subsurface" fire-fighting, but the responsibility for providing such information rests with the manufacturer. At one time, the corresponding standard has been being developed, but the work was suspended back in 1986 at the ISO/DIS stage (draft international standard), and we unable to find even the mention of the document previously available on the Internet at the time of preparation of this paper.

Similarly, despite the widespread use of foam concentrates for extinguishing solid combustibles, special requirements for them are not established by European standards. At the same time, it is quite reasonable to assume that by making special formulations, it is possible to achieve a significant increase in the effectiveness of foam concentrates in the case of extinguishing solid combustibles. This is confirmed both by the availability of a wide range of "class A foam concentrates" on the market and by the regulations regarding their use for extinguishing wild land fires [24].

A fairly complete idea of the areas of application of fixed foam fire-fighting systems (and, accordingly, foam concentrates for fire-fighting) can be obtained by analyzing provisions of [11]. Table 1 contains information taken from the mentioned standard.

To generate low and medium expansion foam and its application for extinguishing, ejection foam generators are traditionally used, expansion ratio of foam obtained with their help depends on a number of factors and is difficult to adjust. In the case of fixed fire-fighting systems, foam generation depending on the features of the protected facility can be ensured by the use of both fixed foam generators and spray nozzles of special designs that can function both with air ejection (aspiration) and without it. Low and medium expansion foam is used for extinguishing fires by surface application, i.e., by applying foam to the burning surface (in some cases – also by subsurface application). High expansion foam is obtained by forced mixing of foam solutions with air or another gaseous substance and is used to extinguish fires by flooding, i.e., by filling the spaces protected by it.

At the same time, a technology of forced generation of low expansion foam used for fire-fighting was also developed at one time (one of its varieties is known as "One Seven", that is, it involves mixing 1 part of the foam solution with 7 parts of air), and in the recent years it has been becoming increasingly applicable. However, until now there are no unified requirements either for foam concentrates intended for use in such systems, for the corresponding fire-fighting systems, or for their components.

Table 1: Applicability of fixed fire-fighting systems for fire protection of facilities as per [11]

Fire hazards	**Low expansion foam systems**	**Medium expansion foam systems**	**Medium expansion foam systems (indoors)**
Flammable liquid storage tanks	Yes	No	No
Tank bunds/collecting areas	Yes	Yes	Yes (+ LNG/ LPG)
Process areas	Yes	Yes	Yes
Aircraft hangers	Yes	< 1 400 m^2 only	Yes
Fuel transfer areas	Yes	Yes	Yes
Plastic packaging and storage	Yes	No	Yes
Plastic recycling	Yes	No	No
Refuse handling and storage	Yes	No	No
Liquefied Natural Gas	No	No	Yes (and outdoors)
Tyre storage	Yes	No	Yes
Rolled paper	No	No	Yes
Marine jetties	Yes	Yes	No
Oil filled transformers and switchgear	Yes	No	Yes
Cable tunnels	No	No	Yes
LPG (Liquefied Petroleum Gas)	No	Yes	Yes (and outdoors)
Warehouses – Class A and B fuels	Yes	No	Yes

Note. These examples are not prescriptive and do not preclude other uses, providing there is a fire engineering basis.

The purpose of the work was substantiation of the requirements for foam concentrates, compressed foam fire-fighting systems and their components which can currently be included in the European standards for foam fire-fighting systems, as well as spheres for further research.

2 Method

In order to achieve the pre-set purpose, analysis of information available in open literary sources and regulations regarding foam concentrates for fire-fighting, fixed fire-fighting systems and their components, as well as their use in fire protection of facilities was conducted.

3 Results and Discussion

First of all, it should be noted that the suitability of foam concentrates of various chemical nature, which have different properties and different purposes, for foam generation is known from the literature. The type of generated foam (low, medium, or high expansion) depends on them as well as on the equipment used. Currently, the classification of foam concentrates depending on the chemical nature of the surface-active base and partly on the types of functional additives is established by the above-mentioned standards [7-10]. According to them, they distinguish:

- Protein foam concentrates (P): these are liquids derived from hydrolysed protein materials;
- Fluoroprotein foam concentrates (FP): these are protein concentrates with added fluorinated surface active agents;
- Synthetic foam concentrates (S): these are based upon mixtures of hydrocarbon surface-active agents and do not contain fluoroorganic compounds;
- Alcohol resistant foam concentrates (AR): these can be suitable for use on hydrocarbon fuels, and additionally are resistant to breakdown when applied to the surface of water-miscible liquid fuels. Some alcohol resistant foam concentrates can precipitate a polymeric membrane on the surface of alcohol;
- Aqueous film-forming foam concentrates (AFFF): these are generally based on mixtures of hydrocarbon surfactants and fluorinated surface active agents and have the ability to form an aqueous film on the surface of some hydrocarbon fuels;
- Film-forming fluoroprotein foam concentrates (FFFP): these are fluoroprotein foam concentrates which have the ability to form an aqueous film on the surface of some hydrocarbon fuels;

- Fluorine free foam concentrates (F3): these foam concentrates are dedicated to meet fire performance ratings and are targeting applications similar to AFFF and/or AR-foams without using fluoroorganic compounds. These foam concentrates are based upon mixtures of hydrocarbon surface-active agents and non-fluorine containing stabilizers.

Low expansion foam generated by forced mixing of foam solution and gas (air in most cases), is usually called compressed foam. The principle of its preparation consists in mixing these substances in special chambers with the aid of appropriate means. Unlike ejection foam, compressed foam can be supplied in a "ready" state by fire hoses (in the case of mobile fire-fighting equipment) or pipelines (in the case of stationary and portable fire-fighting systems).

Systematic mentions of this method of fire-fighting go back to the 90-ies of the last century (see, for instance, [4; 31]), although, according to the available data, it was first proposed about 60 years before that and even was implemented on some warships of the US Navy. Subsequently, a number of varieties of such systems of several brands appeared on the market, the possibilities and advantages of this technology were explained ([1], [5], [29], etc.); a rather detailed description of a number of them is given, in particular, in paper [21]. The compressed foam fire-fighting systems themselves can be both fixed and portable (those transported by fire engines and connected to the dry pipes of the building where the fire occurred).

The authors [21] mention such advantages of compressed foam as less time spent on extinguishing a fire, lower consumption of water and foam concentrate (by 2 to 5 times) and foam (by 5 to 15 times), the possibility of applying foam over a long distance, and possibility of extinguishing live electrical equipment. It is also stated that the compressed foam is much lighter (than water), which increases the maneuverability of the branch pipe operator and allows for a faster change of his position. Also, in the case of using this foam, due to the low content of the liquid phase, indirect material damage during fighting fires in residential buildings is reduced. In the same paper, a hypothesis was put forward about the possibility of using compressed foam for fighting fires in tanks by "sub-surface" application, and it was stated that this hypothesis requires mandatory experimental verification.

An attempt to implement the idea presented in paper [21] was made in the study [15]. For this purpose, some experiments were conducted with the injection of certain amount of foam under a layer of hydrocarbon combustible liquids (diesel fuel, petrol) poured into vessels with a capacity of 5 liters. This paper does not take into account the intensive absorption of oil products by foam generated from aqueous solutions of synthetic foam concentrates containing no fluorosurfactants due to which successful extinguishing of fires by the "subsurface" method in the case of their use is unlikely to be achieved. EN 13565-2 [11] standard does not provide for the use of the "subsurface" fire-fighting method for hydrocarbon liquids with a flash point lower than 25°C and a boiling point lower than 40°C.

The suitability of foam for fire-fighting by the "subsurface" method during the study conducted by the authors of [35] was evaluated using exclusively the time interval of the existence of a layer of foam on the surface of a cold liquid without applying any quantitative criteria. In their opinion, the obtained results "showed the possibility of using compressed foam for "subsurface" fire-fighting". At the same time, the authors admit that "in order to determine the effectiveness of fire-fighting with compressed foam in fire conditions, it is necessary to conduct a study on fighting fires in tanks with oil products by the "subsurface" method and to determine the main fire-extinguishing properties of the foam".

Development of compressed foam fire-fighting systems continues in a number of countries of the world, including Ukraine. For example, in paper [37] technical requirements for a portable compressed foam fire-fighting module for fire and rescue divisions are substantiated. Certain developments aimed at studying the properties of compressed foam and creating domestic prototypes of compressed foam fire-fighting systems are also described in papers [28; 32; 33]. Papers [32; 36] contain even declarations about the applicability of compressed foam for extinguishing class D fires (burning metals) without mentioning any source of such information.

The authors of all these publications simulated the processes of generating compressed foam and also investigated the dependence of its properties on the designs of the corresponding equipment, working pressure, the ratio between the amounts of the foam solutions and air used, the nature of the combustible liquid, and even on the concentration of the foam concentrate in its aqueous solution which is not usually subject to variation. During the study, mainly synthetic foam concentrates and prototypes were used, all of which were intended primarily for generating medium expansion foam with the help of ejection foam generators and limitedly suitable for extinguishing large quantities of combustible liquids [11].

This approach can be explained primarily by the outdated practice of using relatively cheap and in some cases ineffective synthetic ("general purpose") foam concentrates in fire-fighting, which has developed since Soviet times due to the lack of more effective fire extinguishing agents. The predominant field of application of such foam concentrates is fighting fires of a relatively small area, mostly with relatively small amounts of combustible liquids [6]. However, even their use has shown the possibility (at least, in principle) of use, and in some cases also the effectiveness of compressed foam fire-fighting systems in the case of their use for extinguishing both solid combustibles and combustible (flammable) liquids. They also confirmed the conclusions made earlier by foreign researchers that the adhesive properties of the foam played an important role.

At the same time, for extinguishing combustible (flammable) liquids, numerous formulations of foam concentrates have been developed, the molecules of the surface-active bases of which were characterized by a lower chemical affinity with hydrocarbon molecules, which was achieved by replacing part or all of the hydrogen atoms with fluorine ones. The foam generated from the foam solutions of such "fluorine-containing" foam concentrates is poorly "wetted" by hydrocarbons and is more slowly destroyed by non-polar combustible liquids. Moreover, the adsorption layers formed by molecules of fluorine-containing surfactants are more resistant to high temperatures and thermal radiation. These foam concentrates can be fluorosynthetic or fluoroprotein and shall be film-forming (belonging to the "AFFF" or "FFFP" type). The possibility of the formation of an aqueous film on the surface of the liquid means that extinguishing and resistance to re-ignition under the influence of heat sources can be achieved after the formation of a relatively thin layer of foam on the surface of the liquid (unlike the case of using synthetic foam concentrates). It is worth noting that namely the nature (type and chemical composition) of the foam concentrate is the primary factor affecting the properties of the foam formed from its foam solutions, but the features of the used equipment affect them to a lesser extent.

It is for these reasons that in the case of extinguishing "large-scale" fires in Europe and the USA, preference is given to foam concentrates designed for extinguishing flammable liquids with low expansion foam, and to the greatest extent – to those belonging to the "AFFF" or "FFFP" types. According to [9], they are usually characterized by the highest fire-extinguishing efficiency and resistance to re-ignition. In the case of using just such foam concentrates, the normative application rate of foam solutions for extinguishing is the lowest other conditions being equal (see EN 13565-2 [11]).

Some recommendations or even requirements for the use of exclusively film-forming foam concentrates in some cases are contained not only in European [11], but also in American [25] standards for foam fire-fighting systems. If it is necessary to use foam concentrates as additives to water in the case of sprinkler fire-fighting systems (for example, for extinguishing plastics), European standard (EN 12845 [12]) provide for the use exclusively of the ones belonging to the "AFFF" type (fluorosynthetic film-forming foam concentrates). The same provides for American standard for low expansion foam sprinkler and deluge fire-fighting systems NFPA 16 [26], but standard for fire protection of extraction enterprises NFPA 36 [27] allows the use of film-forming foam concentrates of "AFFF" and "FFFP" types.

Considering these facts, it should not be surprising that the work aimed at researching the properties of compressed foam and development of appropriate equipment is carried out in the world mainly with the use of foam concentrates of "AFFF" and "FFFP" types, and a lot of attention is paid to the study of the processes of mixing their solutions with a gas phase during the generation of compressed foam. Thus, it was established in work [15] that the three factors determining the structure of the mixing chamber were the regime of mixing gas and liquid, their contact area during it and design of the turbulator. Three more factors that were determined by the operating parameters were the ratio of gas and liquid flow rate, the pressure at which they are mixed, and the velocity of the process. As a result of the research, some recommendations were developed for the optimization of the relevant devices.

Paper [16] considers the mechanism of mass loss by compressed foam obtained from the foam solutions of a foam concentrate of "AFFF" type due to the evaporation and release of the liquid from it as well as its cooling effect on the surface of the combustible liquid at different temperatures. The authors obtained a number of very interesting results. In particular, it was revealed that for the same mass of foam, the rate of liquid release from it increased with an increase in the initial temperature of the surface of the combustible liquid. In addition, in the case of foam with expansion ratio of 5.5, the temperature of the surface of the combustible liquid had a smaller effect on the rate of release and evaporation of the liquid than in the case of foam with expansion ratio of 10. At a liquid surface temperature of more than 60°C, foam with expansion ratio of 10 was intensively destroying in the initial stages, while foam with expansion of 5.5 was slowly destroying under the same conditions. The very process of changing the temperature of the liquid surface after foam application is divided into stages of rapid decrease, relative stabilization, and gradual increase. The last two stages can be caused by dehydration of the foam, and increasing expansion of the foam accelerates the onset of the third of them.

As a result of varying the impact of initial temperature of the surface on the liquid and expansion ratio of the foam, it was established that at values of the first indicator not higher than 60°C, the intensity of liquid release from the foam depended relatively little on its expansion ratio (5.5 or 10.0), while a further increase temperature led to the acceleration of foam dehydration with the lower expansion ratio value. On the other hand, the loss of liquid due to evaporation was greater for foam with expansion ratio of 10. The same was true for the rate of decrease of the height of the foam layer with time at liquid surface temperatures higher than 70°C. In general, it was established that foam with expansion ratio of 5.5 provided more effective cooling of the surface of the combustible liquid than foam with expansion ratio of 10.

The authors of paper [23], while conducting desk and experimental studies, compared the characteristics of dehydration of foam obtained from foam solutions of "AFFF" and "FFFP" type foam concentrates. It was found that they differed to a great extent despite the similarity of the physical and chemical properties of the foam solutions. This phenomenon was explained by differences in the rheological characteristics of the surface layers. It was also revealed that the conventionally used method of determining the stability of air-mechanical foam did not reflect the comparative characteristics of the stability of compressed foam, and a more adequate method was proposed. Although, according to the authors' experience, there is no direct correlation between the stability of the foam and its fire-extinguishing efficiency, an increase in the first of these indicators usually contributes to an increase in the fire-extinguishing efficiency of the foam. Accordingly, the application of the new methodology can be a step towards standardizing the requirements for foam concentrates intended for fighting fires with compressed foam.

The data described in the available sources regarding the use of compressed foam for extinguishing fires by types of facilities can be conventionally divided into four groups. The first one includes the already mentioned works [32; 33], in which the possibility of using compressed foam for fighting wild land fires is established. Given the lack of combustible liquids in them, it can be assumed that conventional synthetic foam concentrates are effective enough when used for this purpose. Determining and standardizing the procedure for their use with portable fire-fighting equipment requires further research, but they are not the subject of this work. As for fire-fighting systems, the first group of protection facilities includes those that are high-rise (in particular, residential and office) buildings, but the second one contains facilities protected with sprinkler or deluge systems, and the third one consists of storage tanks for combustible (flammable) liquids.

Fire protection of high-rise buildings is associated with a number of problems. One of them is that water sprinkler fire-fighting systems commonly used for their protection require high water consumption, which in turn necessitates the installation of appropriate pipelines. Considerable weight of pipelines, especially after they are filled with water, means a high load on the load-bearing building structures, i.e., the need for their proper strengthening. Finally, as a result of a long-term fire, the load-bearing capacity and fire resistance of structures can decrease, and in the event of simultaneous interruptions in water supply (as happens despite the provision of precautionary measures) the consequences can be extremely severe.

It is the use of compressed foam fire-fighting systems is almost the best alternative to equipping high-rise buildings (and not only them) with water fire-fighting systems. The relatively small weight of dry pipes and the low density of foam compared to water mean a reduction in the requirements for the load-bearing capacity of building elements, and the proper design of the foam distribution system in combination with proper properties of the latter (stability, adhesion, spreading ability, fire-fighting efficiency) can be a guarantee of the effectiveness of fire fighting.

As already mentioned, compressed foam fire-fighting systems manufactured by various manufacturers and intended for the protection of buildings and structures are described in detail in the relevant documentation and systematized in separate papers (for example, [21]). Some scientific publications, including [38; 39], are devoted to the issue of their application. Moreover, a standard for such systems has been adopted in Europe (EN 16327 [13]). Since such systems are transportable and there is a European standard for them, they are not the object of standardization in the future regulations for compressed foam fixed systems. The requirements for dry pipes to which such systems are connected after the arrival of the fire and rescue division on a vehicle for the transportation of the compressed foam fire-fighting system are subject to building codes.

At the same time, the issue of fixed compressed foam fire-fighting systems for the protection of other facilities remains open. Taking into account the provisions of the existing European standards for fixed foam fire-fighting systems EN 13565-2 [11] and the fact that expansion ratio of compressed foam is usually lower than 20 (it is a low expansion foam), it can be stated that such fire-fighting systems can be suitable for the protection of the same facilities as conventional fixed low expansion foam fire-fighting systems, i.e. (see Table 1):

- Flammable liquid storage tanks;
- Tank bunds/collecting areas;
- Process areas;
- Aircraft hangers;

- Fuel transfer areas;
- Plastic packaging and storage;
- Plastic recycling;
- Refuse handling and storage;
- Liquefied Natural Gas;
- Tyre storage;
- Rolled paper;
- Marine jetties;
- Oil filled transformers and switchgear;
- Cable tunnels;
- LPG (Liquefied Petroleum Gas);
- Warehouses – Class A and B fuels.

As a rule, fighting fires at facilities with the presence of large quantities of combustible liquids is the most difficult; to a lesser extent it is complicated in the presence of solid combustible materials. Therefore, it can be assumed that the successful application of foam fire-fighting systems of conventional designs to protect facilities with the possibility of spills of combustible (flammable) liquids, tanks for their storage, etc. means the possible success of protecting these facilities with fixed compressed foam fire-fighting systems while applying the same requirements (the relevant issue is discussed in more detail below). Such requirements can turn out overstated, but such an overstatement will not be a critical problem. This is all the more true because the choice of different types of fire protection systems in accordance with European practice is usually entrusted to engineering workers in the sphere of fire protection and designers of such systems.

Accordingly, the primary task for the development of a separate European standard for fixed compressed foam fire-fighting systems or the inclusion of relevant requirements in the standard [11] is to substantiate the requirements for systems for the protection of spills of flammable liquids and for the protection of tanks for their storage.

In paper [3], a study of the influence of the conditions of compressed foam formation on its characteristics was carried out and the division of such foam into types was proposed depending on its stability, assessed by the rate of liquid release from the foam. For this purpose, various nozzles were used and different values of the working pressure and the ratio between the quantities of the foam solution and air being mixed with it were provided. The combination of parameters for which the foam has the highest stability was also established, and fire tests were conducted to extinguish petrol. The authors proposed a list of spheres and typical types of application of compressed foam for the protection of facilities (Table 2) and indicated the need for further research in order to determine the standardized parameters of foam application by such systems depending on the features of fire protection facilities.

Table 2: Proposals for the application of fixed compressed air foam fire-fighting systems for fire protection of facilities [3]

Application fields	**Typical application place**
Information technology	Emergency generator and diesel storage areas
Pharmacy	Chemical processing, storage areas, laboratory
Communication and transportation	Gas stations, garage, hangar, heliport
Power generation and poser transmission	Transformers, turbines, nuclear facilities
Petroleum and gas production	Oil depot, oil pump room, oil refineries, offshore drilling platform
Construction	Wood processing machines, solvent storage and processing areas Residence, underground construction, tunnels, ancient architectural structures, high rise building, etc.
Agriculture and forestry	Garden, stacking storage and processing areas
Mining industry	Well, flammable liquid storage area

In work [2], full-scale fire experiments were carried out in order to evaluate the influence of the application rate of foam solution of an "AFFF" type foam concentrate, as well as expansion ratio of the foam, on the efficiency of extinguishing petrol spills with compressed foam sprinkler fire-fighting systems. It was established that the volume of the formed foam significantly affected both its fire-extinguishing efficiency and resistance to re-ignition. It was revealed that maximum fire-extinguishing efficiency and resistance to re-ignition as well as economic efficiency were achieved with foam with expansion ratio of 10. As the application rate of foam solution provided by the sprinkler system increased, the specified characteristics of the compressed foam improved, and the lowest consumption of extinguishing agent during the extinguishing of petrol spills was achieved at the application rate of foam solution of 3.48 l/(min m2). The specific consumption of the foam solution for localizing the burning on 90 % of the area was 0.99 l/m2, and that for complete extinguishing was equal to 2.38 l/m2.

The authors of [2] established the impossibility of localizing and extinguishing petrol spills at the application rate of foam solution of 1 l/(min m2), but already at its application rate of 1.32 l/(min m2) extinguishing was achieved for approx. 5 min. At the application rate of the foam solution of an "AFFF" type foam concentrate of 1.79 l/(min m2), the localization of the fire was achieved in about 1 minute, and its complete extinguishing lasted for about 2 minutes. At this, as well as higher values of application rate, rapid extinguishing of flare combustion cells occurred and the results completely satisfied the test success criteria established by the UL 162 test method standard [34]. It is also stated that the normative application rate of foam solutions by foam sprinkler fire-fighting systems of conventional designs was 6.5 l/(min m2), i.e., it was almost four times higher than the value of 1.79 l/(min m2).

The document to specify this normative application rate is not indicated (probably it is NFPA 11 [25]), but it is worth noting that the given value almost coincides with the application rate of foam solutions provided for extinguishing spills of flammable liquids with sprinklers and deluge foam fire-fighting systems according to EN 13565-2 [11]. According to this standard, in the case of use of foam concentrates with classes of fire-extinguishing efficiency and insulating capacity typical for the "AFFF" type, it is equal to 6.0 l/(min m2).

Despite obtaining a solid set of data, the authors of work [2] note the need to conduct further field experiments in order to verify the possibility of successful fire-fighting in the presence of different types of combustible materials and different combustible loads. However, taking into account the fact that such a highly dangerous flammable liquid as petrol was used for the tests, we believe that the so-called "optimal" [2] application rate of foam solutions of "AFFF" type foam concentrates of 1.79 l/(min m2) could be taken as a basic value for the drafting of relevant standard.

In paper [40], a number of aspects related to extinguishing combustible liquids in tanks with foam were considered. Based on the results of previously conducted research, the authors came to the conclusion not only about the suitability of compressed foam fire-fighting systems with for this purpose, but also the higher efficiency of such systems in comparison with systems of conventional designs. The obvious dependence of the extinguishing result on the fire extinguishing agent used and the need for experimental studies and modeling to solve the optimization problem are also indicated.

In paper [38] published relatively recently, a comparison of the fire-extinguishing efficiency of compressed foam obtained using air with that of compressed foam obtained using nitrogen when fighting fire in a n-heptane storage tank was carried out for the first time. The foam concentrate used belonged to the "AFFF" type. The authors found that the use of nitrogen instead of air accelerated the spread of foam across the surface of the combustible liquid and increased the thickness of the foam layer; they explained this primarily by increasing the stability of the foam and reducing the amount of water evaporating from it. The general conclusion drawn by the researchers was that foam obtained using nitrogen was slightly more effective in extinguishing tank fires.

The latest (dated 2021) published edition of the US standard for foam fire-fighting systems NFPA 11 [25] contains a separate section on compressed foam fire-fighting systems. According to the requirements of the standard, the components of such systems and the foam concentrate shall be allowed listed for this purpose, the quality of the water is to ensure the possibility of generating foam with the appropriate characteristics, and it is allowed to use air or nitrogen as a gas. Such a “generalized” approach is characteristic of NFPA standards; therefore, it is unlikely to be expected to be substantially specified in future editions of NFPA 11 [25].

At the same time, the mentioned standard provides for the possibility of using fixed compressed foam sprinkler and deluge fire-fighting systems as well as fire-fighting systems equipped with foam pourers of traditional designs. There are no specified requirements for the foam generation and application devices themselves (see the previous paragraph). At the same time, the minimum values of application rate of foam solutions are specified and the need to fulfill the requirements established for facilities of the corresponding type and the recommendations of the foam concentrate manufacturer are indicated. For non-polar combustible liquids (hydrocarbons), the standardized minimum value is 1.63 l/(min m2), but for polar combustible liquids it should be at least 2.3 l/(min m2). If the area of the fire is “three-dimensional”, then the location of spray nozzles for applying foam shall ensure its arrival on all burning surfaces. The minimum duration of foam application according to NFPA 11 [25] is set equal to 5 min for sprinkler and 10 min for deluge compressed foam systems.

As can be seen, the minimum application rate of foam solution during the extinguishing of non-polar combustible liquids regulated by NFPA 11 [25] standard is quite close to the value recommended by the authors of study [2]. At the same time, for extinguishing non-polar flammable liquids with foam sprinkler fire-fighting systems of conventional designs this standard recommends a minimum application rate of 6.5 l/(min m2), i.e., there is also a match with the conclusions of the authors [2] on the possibility of fourfold reducing the application rate of foam solution at such a “transition”. If these values are accepted during the future amendment of the European standard for foam fire-fighting systems [11], the future version of the standard for components of such systems [14] should be supplemented with appropriate requirements for components intended for use in compressed foam fire-fighting systems.

NFPA 11 [25] standard does not contain recommendations for fighting fires with compressed foam in tanks for storing flammable liquids, which can be explained both by the lack of a sufficient amount of reliable experimental data and by the possible lack of compressed foam generators of adequate capacity. Indirect confirmation of at least the first of these assumptions is the fact that the authors of this work did not find relevant information in the literature.

Taking this into account, in the case of a decision to protect tanks or other hazards where non-polar combustible liquids are stored or circulated using compressed foam generators and foam pourers of conventional designs, the design of such systems before the approval of reasonable standards should be carried out with the provision of the same values that for foam fire-fighting systems of conventional designs.

Such a statement can be made on the basis of the conclusions of the authors of papers [38; 40] on the principal suitability of compressed foam fire-fighting systems with such facilities and their higher efficiency, as well as the fact that compressed foam is the same low expansion foam the structure of which is characterized by greater uniformity. Compressed foam is obviously also suitable for extinguishing by the “subsurface” method, but in this case, instead of high-pressure foam generators one needs to use devices for generating compressed foam and special compressors for introducing it into the layer of combustible liquid. At the same time, for this purpose, it is necessary to use foam concentrates being suitable/intended for “subsurface” extinguishing, the mandatory requirement for which is the availability of film-forming properties.

As for the use of systems equipped with compressed foam generators and foam pourers of conventional designs at any facilities with the presence of polar combustible liquids, to date, in our opinion, there are no data that could be reasonably accepted for design. In particular, comprehensive studies of the fire-extinguishing efficiency of foam during the extinguishing of ethyl alcohol conducted in Sweden [30] showed that in case of provision of the parameters of applying foam solution of an “alcohol-resistant” foam concentrate for extinguishing a polar combustible liquid regulated by European standard for foam fire-fighting systems EN 13565-2 [11], the success of extinguishing is not guaranteed in any way. The researchers concluded that it was necessary to carry out field tests in order to make justified amendments to this standard.

There is certainly reason to believe that the efficiency of fighting fires involving polar liquids increases when moving from conventional low expansion air-mechanical foam to compressed foam. However, an attempt to use the existing requirements as a starting point for the design of compressed foam fire-fighting systems for the protection of tanks for the storage of polar flammable liquids may also not ensure the success of their application. Accordingly, attempting to apply compressed foam fire-fighting systems to the protection of such tanks prior to the development of reasonable requirements can discredit this undoubtedly progressive fire-fighting technology.

4 Conclusion

1. As a result of analyzing of appropriate literary sources, it was established that the currently existing portable compressed foam fire-fighting systems were primarily intended for fighting fires at manned facilities (residential, office, and public buildings), including buildings with increased number of floors and high-rise buildings. In the case of taking measures to quickly commence application of foam for extinguishing, the implementation of this fire-fighting technology can be an alternative to the provision of fixed water fire-fighting systems and contribute to reducing the requirements for the load-bearing capacity of building elements. Currently, the requirements for such systems are regulated by the European standard EN 16327:2014, and there is no urgent need to develop any new standards.
2. Studying of the materials of previously conducted research gives reason to assert that, to date, the suitability of compressed foam for fighting fires has been theoretically confirmed and experimentally verified not only in buildings for the stay of people, but also in wild lands as well as at facilities with the presence of combustible liquids, where the formation of their relatively shallow spills or where they are stored in tanks with a layer thickness of several meters is possible.
3. The data available in open literary sources regarding the dependence of the stability of compressed foam on the surface of flammable liquids from its expansion ratio have no any direct correlation with the fire-extinguishing efficiency of such foam. This can be easily explained based on the authors’ experience in the field of foam fire extinguishing, which indicates that the primary factors influencing the fire-fighting effectiveness of foam are the chemical nature and quality of the foam concentrate, not the features of the devices used to generate it. Moreover, the relatively fast dehydration of the foam is not only a factor of its destruction, but also a phenomenon that intensifies the cooling of the surface of the liquid or solid combustible material, contributing to the cessation of burning. At the same time, if the foam concentrate has film-forming properties, the sufficient speed of liquid release from the foam guarantees the proper course of the

processes of formation and renewal of the film on the surface of the combustible (flammable) liquid, its reliable isolation from the oxygen of the air and, accordingly, acceleration of extinguishing and the increase of resistance to re-ignition of this liquid under the influence of red-hot building elements.

4. The results of the research described in the papers and the provisions of the current standards of the National Fire Protection Association (USA) regarding fire-fighting with foam make it possible to state that compressed foam fire-fighting systems are fundamentally suitable for extinguishing fires at least at all those facilities where effective use of air-mechanical foam generated by conventional methods is possible. The authors see no reason to predict any decrease in the effectiveness of fighting fires in the event of a transition from “conventional” foam to compressed one.
5. The potential limitations for the use of compressed foam fire-fighting systems are the same as for foam fire-fighting systems of conventional design. These include the presence of any substances that release significant amounts of oxygen or other oxidants capable of sustaining combustion, substances capable of entering into a chemical interaction with water (alkaline, alkaline earth and certain chemically active metals, phosphorus (V) oxide, triethylaluminum, etc.). The probable suitability and conditions of use of compressed foam fire-fighting systems for extinguishing live electrical equipment is the subject of separate studies.
6. To date, there are quantitatively substantiated and regulated by the US standard NFPA 11 requirements regarding the parameters of fire extinguishing agent application by compressed foam sprinkler and deluge fire-fighting systems for the protection of facilities with the possible formation of spills of combustible (flammable) liquids. The requirements for the application rate of foam solutions are essentially lower than in the case of foam fire-fighting systems of conventional designs, and are also fundamentally applicable to the protection of facilities with the presence of solid combustible materials, which are characterized by a lower fire hazard. The substantiation of similar requirements for the protection of tanks for the storage of combustible (flammable) liquids requires special research and full-scale experiments.
7. The currently existing European standard for foam fire-fighting systems (EN 13565-2:2018+AC:2019) can be reasonably supplemented with provisions on the protection of facilities with compressed foam sprinkler and deluge fire-fighting systems. Based on the information presented in appropriate scientific publications and NFPA 11 standard, it is proposed to establish (taking into account rounding) the minimum application rate for such systems of 1.8 mm/min (1.8 l/(m2 min)) in the presence of non-polar and 2.3 mm/min (2.3 l/(m2 min)) in the presence of polar combustible liquids. We think it necessary to preserve the value of the duration of foam application as regulated by EN 13565-2:2018+AC:2019 depending on the type and specifics of the fire protection facility.
8. In compressed foam sprinkler and deluge fire-fighting systems which provide fire protection of facilities with the presence of combustible (flammable) liquids, only fluorosynthetic (“AFFF”) or fluoroprotein (“FFFP”) film-forming foam concentrates should be used until the relevant data are obtained. The issue of the possibility and conditions of using “F3” foam concentrates for this purpose (the serial production of which was established relatively recently) is subject to separate research. To determine the effectiveness of foam concentrates of various types in the case of extinguishing solid combustible materials with such systems, separate studies are required. To determine the effectiveness of foam concentrates of various types in the case of extinguishing solid combustibles with such systems, separate studies are needed as well.
9. At the same time as amendments are made to the European requirements for foam fire-fighting systems (standardized by EN 13565-2:2018+AC:2019), it is necessary to make amendments to the standard that regulates the requirements for the components of such systems (EN 13565-1:2019). For this purpose, at the first stage, it is sufficient to standardize the need to conduct tests of devices for generating and applying compressed foam in combination with specific foam concentrates in an order similar to the requirements of UL 162:2022 standard which regulates the procedure for testing foam concentrates and components of foam fire-fighting systems.

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Primary Paper Section: A

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