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HIGH-EXPANSION AIR FOAM
A SURVEY OF ITS PROPERTIES AND USES

by

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SUMMARY

This note examines the present state of knowledge regarding the use of high expansion air foam, and suggests areas in which development of this agent and its uses may proceed.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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1. Introduction

Water in its bulk liquid form is of limited use in fighting fires in many flammable liquids. For this reason, methods for turning the water into a foam which can float on the surface of a flammable liquid have been developed, "protein-based" foams being the most widely used. In recent years, however, a different type of foam has been developed having different physical and extinguishing properties from those of protein foams. This foam has become known as 'high-expansion' foam in contrast to the normal 'protein' or 'low-expansion' foam, since it is normally used in a highly expanded state. The 'expansion' of a foam is the ratio of a given volume of the foam to the volume of liquid it contains. Where protein foams usually have expansions between 5 and 15, high expansion foams have expansions of up to 1000, or even higher.

The original concept and early development of high expansion foams resulted from the unique problem of fighting fires in mines. Adverse factors restrict the use of conventional methods of extinction for an established fire underground (for example, the range of a water jet is restricted by the low ceiling). There was an obvious need for a method of conveying some fire quenching agent to the active end of a mine fire from a distance, and this agent would have to pass through the heated zone of burnt-out roadway. To meet this need, the Safety in Mines Research Establishment pioneered the first development work on high expansion foam, and over a period of a few years investigated most of the salient features of the production and effectiveness of high expansion foam with respect to underground fires[1-5]. The United States Bureau of Mines followed on from the lead given by S.M.R.E. and brought the technology of high expansion foam to a more advanced state[6-9]. At this stage, the technique interested private enterprise, and two persons who had worked in liaison with the Bureau of Mines developed a portable apparatus suitable for use both above and below ground[10]. This development took place between 1960 and 1963, and since this time more commercial interest has been aroused, and a wide variety of high expansion foam liquids and appliances are now available. The foam itself is extremely light, it is a poor transmitter of sound, light, and thermal radiation and, as far as is known, is a poor conductor of electricity.

2. Mechanism of extinction by high-expansion air foam

The mode of extinction by high expansion foam depends to some extent on the nature of the combustible material. It is possible, however, to generalise briefly on the contributing factors to extinction[11-13]. As high expansion foam contains water, perhaps the most obvious mechanism of extinction is by cooling the material until combustion ceases. Another way in which high expansion foam contributes to extinction is in the production of steam, which then displaces air at the fire and further inhibits combustion. High expansion foam can also limit combustion by reducing the access of adequate air to the fire, for example, where the foam surrounds the base of a burning pile of material. In this way the fire can ultimately burn itself out without spreading; even if the other two methods of extinction do not apply. It should be noted at this point that severe breakdown of the foam will release the air inside the bubbles, but in general, the other factors will offset this effect. Some contribution to extinction will also be made when the inert combination products are trapped under the foam instead of escaping in convection currents, and these products will also assist in smothering a fire.

High expansion foam has one other property which is a major factor in its use for fire control. It is extremely effective as a thermal radiation shield and by reducing the radiative transfer of heat from a fire, the rate at which a fire can spread will be considerably reduced.

3. Methods of production

The usual way in which high expansion foam is generated is to spray a dilute aqueous solution of a suitable detergent or wetting agent onto an absorbent mesh screen (usually fabric) through which air is blown by a fan or other device. The overall result will depend upon the combination of agent, screen and blower used and it is convenient to consider each of the components separately in order to discuss the development work to date.

(a) Agent

Hundreds of foaming agents have, so far, been tested for foaming properties. Most of them are the wetting agents and detergents, which are commonplace in the detergent and textile industries. An important criterion for a good foaming agent is that it should produce a mechanically stable foam which will not permit a high rate of liquid drainage from the bubble walls. Another property for a good foaming agent is that it should be bio-degradable to permit it to be flushed away through the drains. The foam must also be able to carry large quantities of water to the fire, a property which is not necessarily directly related to its rate of drainage. As the nature of the available water used to make the foam can affect its properties, the ideal agent should also be capable of producing foam with waters of varying degrees of hardness, acidity and salt content.

Eisner and Smith[1] in their early work on high expansion foam attempted to make an assessment of the relative merits of different wetting agents. Most of these were proprietary brands of which the exact chemical constitution was unknown. They generally contained some stabiliser or "foaming agent". Two of the agents which were found to be better than others for foam production were compound A (a flake material, mainly dodecyl benzene sodium sulphonate) and compound B (a viscous liquid of unknown composition). Subsequent extinction tests on underground fires were made using a solution of B at about 3 per cent concentration.

Investigations were made at the U.S. Bureau of Mines[7] into the foaming properties of various compounds. There were:

(i) Ammonium lauryl sulphate
(ii) Amino fatty acid
(iii) Alkyl-aryl sulphonate
(iv) Alkyl phenol
(v) Alkylated ether
(vi) Alkylated phenol ether

Tests were carried out on this series of compounds to determine their relative drainage properties and also the relative decrease with time of the foam volume. The effects of agent concentration and temperature on the water retention properties for ammonium lauryl sulphate were also investigated. In all these tests, ammonium lauryl sulphate appeared to be superior to the other compounds, particularly in terms of its drainage characteristics. Experiments were made subsequently with a blend of 83 per cent ammonium lauryl sulphate and 17 per cent alkyl aryl sulphonate; foam from this blend contained adequate water (70.2 oz/cu.ft) and could be transported greater distances than foam from ammonium lauryl sulphate solutions. It was found that satisfactory results were obtained with an ammonium lauryl sulphate containing 2 to 3.5 per cent unsulphated alcohol, and not more than 1 per cent ammonium chloride, ammonium sulphate, or other impurities and having a pH between 6.0 and 6.5 and a buffering component to resist change in pH. With some brands of this compound not containing these properties, the water retentivity was rather low and was affected by temperature. The minimum recommended concentration in a solution of ammonium lauryl sulphate for soft water was 0.4 per cent in the final solution applied to the net. Household detergents were not effective foaming compounds for fire control.

As part of a test programme for generating high expansion foam using a turbo-jet engine, selection tests for foaming agents were carried out at the Fire Research Station, Boreham Wood[14]. In the first instance a simple test was made, using a method first devised at S.M.R.E.[15], in which only small quantities of material were used. Essentially, the time for the 'black band' in a film of the agent in solution to descend to the mid-point on a supporting framework (at 45^{o} to the horizontal) was measured. A slow descent indicated a strong, stable film. Thirty agents were tested using this apparatus and as a result seven of these were selected as having a sufficiently slow drainage rate and high stability to warrant further examination on the pilot scale. These were:

(i) Blend of sodium dodecyl benzene sulphonate with non-ionic components.

(ii) Ethylene oxide condensate of sodium lauryl sulphate

(iii) Sodium lauryl di-ethylene glycol ether sulphate

(iv) Blended sulphated fatty alcohols

(v) Sodium lauryl ether sulphate

(vi) Sodium alkyl napthalene sulphonate

(vii) Ammonium lauryl sulphate

The pilot test comprised filling a cylinder, 51 cm diameter (1 ft 8 in) and 366 cm (12 ft) in length with a foam plug, collecting the draining liquid at known time intervals, and thus determining the "half-drainage time" which is the time taken for half of the liquid contained in the freshly generated foam to drain. Again, on the basis of this test, ammonium lauryl sulphate proved to be the most satisfactory agent, although one or two of the others showed some promise. In all tests the solution concentration was kept constant at 1 per cent of active content of agent. The nominal expansion of the foam was 1000:1.

Another series of extensive tests on foaming agents was made by the Walter Kidde Company[10], who in the first instance began to develop for commercial use the concentrate discovered and developed by the U.S. Bureau of Mines[7] (described above). It was found, however, that this material had three notable deficiencies, namely:

(i) It could not make foam with water having a hardness much over 700 ppm. This ruled out its use for many water sources and particularly its use with sea water, which can have a hardness as high as 13,500 ppm. It was also necessary to increase the rate of use of the concentrate with increasing water hardness.

(ii) The viscosity of the liquid increased with decreasing temperature and it became solid at 40°F.

(iii) The water retention stability of the foam was poor.

In the search for a material not having these defects, 400 materials were screened using a foam-making apparatus and despite the fact that no individual substance met the requirements a combination of materials was found which yielded excellent foam of controlled stability with synthetic sea-water. The nature of these components and those used in more recent formulations have been specified in the patent literature[45,46]. In the above discussion of investigations into the relative merits of different foaming agents, mention has been made of one or two adverse factors which can reduce the effectiveness of a good foam. It is also necessary to consider whether the stability and drainage properties of a foam can be improved in any way. Two of the most significant factors which can adversely affect the performance of a foaming agent are associated with the water supply available for foam making; they are the pH of the water and its hardness. It has been shown[7] that a pH variation between 3 and 11 has little effect on the water retention of foam from ammonium lauryl sulphate if soft tap water of 100 ppm hardness is used. With mine water of 1480 ppm hardness water retention of foam from 1 per cent solution increased linearly with the pH of the solution. As the hardness increased, a proportional increase in the solution concentration was required for satisfactory foam production. Above 500 ppm hardness, it was recommended that the water be treated, as an increase in solution concentration did not normally neutralize the hardness. For water with excessive calcium, the addition of sodium phosphate was effective in softening the water. A buffer additive was helpful in resisting changes due to pH.

The drainage rate of a foam may be improved by adding a "viscosity intensifier" to the foaming agent. In the Bureau of Mines work[7], carboxy methyl cellulose and a high molecular weight, water soluble, synthetic acrylic polymer were both effective in this way. The polymer was available in aqueous solution and could be mixed readily with the foaming compound.

The increase in water retention of the foam was found to be directly proportional to the concentration of the viscosity intensifier used. With ammonium lauryl sulphate, 0.2 per cent carboxy methyl cellulose in the final solution produced foam with 13 times that of a standard 0.4 per cent ammonium lauryl sulphate solution. Attempts to improve the drainage rate of a foam (made with a blend of sodium dodecyl sulphate with non-ionic components) by adding sodium tri-polyphosphate or ethyl hydroxy cellulose were unsuccessful[14]. It is of interest to note at this point that the drainage rate in moving foam is less than that in the static foam due to the 'tumbling' action of the moving foam which preserves the water present[10].

The practical limitations with the existing foam compounds gives an upper limit of expansion of 1200 : 1. It is possible to produce a foam mechanically with an expansion of up to 2000 : 1 but this is unstable. Although it may be possible to develop a concentrate which would give a stable foam of even higher expansion ratio, there does not appear to be any immediate demand for such a foam.

(b) Screen

The two important features associated with the screen upon which the foam solution is sprayed are the nature of the material from which the screen is constructed and its configuration. The requirements of a screen or net material have been specified as follows.[3] The material should:

(i) create little obstruction to the air-flow;
(ii) catch liquid sprayed with only little trajectory;
(iii) hold sufficient liquid to provide a reservoir for sustaining foam formation during variations of spraying;
(iv) be robust and durable;
(v) form foam at high air speeds.

Many types of material have been tested in different establishments. The simplest screens, having easily-variable dimensions, were made from wire gauzes. In practice, this failed to give a foam capable of filling a test cylinder[1]. It is possible, however, to produce a foam using a metal honeycomb as a screen[7], but generally a collapsible fabric screem is preferable. Various types of textile have been tried, but it is not possible to vary continuously and separately the factors which define a textile. These include: the basic material of yarn and method of construction, whether woven, warp-knitted or lace-knitted, and the weight, thickness and closeness of the completed textile. Initial tests at

S.M.R.E. indicated that thicker materials, lace-knitted from cotton yarn, were by far the most effective[1]. Nylon and rayon materials were not successful. Preliminary tests on materials for the foam-making screen (at J.F.R.O.) showed that an absorbent open mesh cotton fabric was the most satisfactory[16]. The synthetic fibre mesh fabrics tested were not as good as cotton mesh fabrics for making foam but the mesh pattern and the size were not the same as with the cotton fabrics used. Cotton cloth was, in fact, found in later tests to weaken and rupture after an hour or so, and this was ascribed to microbiological attack[17]. On this account, therefore, the synthetic materials appeared to be more suitable provided that a material which was efficient in the foam-making process could be found. This problem has obviously been solved, as in present-day commercial equipment, nylon nets are used.

The different configurations of the net which have been used in various tests are broadly:

(i) Plane net at 90° to the air flow

(ii) " " " 45° " " " "

(iii) Extended cylindrical net at 90° to the air flow

(iv) "Zig-zag" or concertina-ed net with its plane at 90° or angled to the air flow

(v) A conical net

The preferred configuration in the modern commercial equipment appears to be configuration (iv) in the above list.

(c) The Blower

When the idea of using high-expansion foam was conceived at S.M.R.E., the intention was to utilise the natural ventilation current circulating air through the mine as a blower system which would not fail if local electricity supplies failed. All the work at S.M.R.E. was in fact carried out using the existing ventilation system. From this work[4] it was established that one of the important factors involved in the formation of high-expansion foam was the air-speed. It was also shown that a critical limit for this factor existed for a given net and that exceeding this limit would result in "leakage" of air, through and around the net. This in turn would cause a loss of motive pressure, the leaking air would tend to sustain the fire, and the decreased height of the foam plug in the mine would result in quicker drainage. The existence of a critical air speed was also predicted theoretically in this work. Early in the subsequent research at the U.S. Bureau of Mines, it became apparent that the normal ventilating current in mines in the United States would not provide adequate air pressure to drive a foam plug the distance that might be required. Thus a portable high-expansion foam generator was developed which contained a fan having a relatively high pressure potential[6]. Most of the commercial equipment now available employs one of the following methods of air flow:

(i) Propellor fan driven by electric motor

(ii) Propellor fan driven by petrol motor

(iii) Air flow induced by water flow

An all-purpose device has been developed in Russia[18] which can be operated using either a burnt-gas generator, CO_2 cylinder, compressed air or compressed inert gas. A considerable amount of work has taken place at J.F.R.O. where an inert gas generator has been coupled to a foam-making device. This, however, will be dealt with in a later section where the combined use of different agents will be considered.

One factor in the production of high-expansion foam which has not been discussed is the method of injecting the generally viscous foam concentrate into a water supply for dilution before spraying at the net. The four general methods available for this are a direct injection system, a by-pass eductor system, an in-line eductor system and a premix injection system. Details of these four methods have been described and illustrated elsewhere[7].

4. Specifications for suitable foaming agents

As the use of high-expansion foam is not yet universal, and its full potential is not yet realised, it is difficult to specify the required properties of a given foaming agent or piece of apparatus. Some ideas about specifications have been forthcoming from development work on high-expansion foam, and others can be derived by analogy with those applied to ordinary low-expansion foam.

A series of requirements for a foaming agent suggested by S.M.R.E. after some early work on high-expansion foam[3] in mines were summarised as follows:

(i) Viscosity of the agent should not exceed 20 poise, even at temperatures of $5^{o}C$.

(ii) The agent should be suitable for forming a 3 per cent solution in water

(iii) It should dissolve in water when stirred only for a few seconds

(iv) The viscosity of a 3 per cent solution should not greatly exceed 50 centipoise

(v) The surface tension of the solution should not exceed 40 dyne cm^{-1}

4. Specifications for suitable foaming agents (Cont'd.)

(vi) The back pressure exerted in the mine ventilation shaft by the friction of a 150 ft plug of foam should not exceed by a factor of 1.5 that exerted in the mine roadway by similar foam plugs of available foam agents.

(vii) The agent should be capable of forming ½" bubbles at an expansion of about 600, and should not lose more than half its water content in 2 minutes, from a 2 ft high column.

(viii) The half-drainage time of the foam should not be made less than 2 minutes by impurities in the water used, within the following ranges:

pH	7.0 - 8.5
Na	0-4000 p.p.m.
Total hardness	0-700 p.p.m.

(ix) The properties of the agent should be unaffected by its storage for periods of a few years at temperatures between 5 and 40°C. In addition, it is desirable that the agent should be cheap and should introduce no fire or physiological hazard.

When considering these suggested requirements, it should be borne in mind that as the problem under consideration was the fighting of fires in mines, elements of the requirements (notably (vi), (vii) and (viii)) are appropriate for this particular usage, but not necessarily generally applicable. In particular a half drainage time of 2 minutes may be too low for general fire fighting use, since such foams have been found to be ineffective in extinguishing liquid fires and in maintaining a cover over ordinary solid fires for a sufficient time to bring about extinction[32]. A half-drainage time of 10 minutes is probably more appropriate. The above requirements coincide with those suggested by the U.S. Bureau of Mines regarding stability, viscosity at different temperatures, corrosive nature, preservation of foaming quality with time etc. In the absence of any specific standards for high-expansion foam, the properties of a commercially-developed agent[10] have been kept within most of the existing American standards for air-foam liquid concentrates (Section III, U.L.162. "Standards for Safety-Air Foam Equipment and Liquid Concentrates", Underwriters Laboratories, Inc., May 1960). These are:

(i) Induction Factors. Liquid concentrates must be capable of introduction into water flowing under pressure in pipe lines or hose lines, bu vacuum-induction methods as well as pressure-induction methods. (The commercial liquid standard induction rate is 1.5 per cent instead of suggested standards of 3 per cent - 6 per cent).

(ii) Storage Temperature. Minimum temperature classification - 20°F (commercial liquid does not obey this), + 20°F, and + 35°F.

(iii) Ageing. Air-foam liquid concentrates shall show no material evidence of chemical or physical change when subjected to two conditioning cycles, each consisting of storage for 14 days at the minimum temperature claimed for the liquid concentrate, followed by storage for 24 hours at 150°F.

(iv) Corrosion effects on containers. Liquid concentrates shall not be unduly corrosive to the steel or other metals forming the containers im which they may be shipped and stored. (In this respect, the commercial liquid and also ammonium lauryl sulphate solution must be kept in plastic-lined or plastic containers becuase of their corrosive nature).

(v) Flash Point. This should not be less than 150°F, as determined by the Tag closed-cup method.

(vi) pH Value. The pH values of liquid concentrates must be determined for use as an aid in identifying container corrosion factors, and in identifying the liquid concentrate.

(vii) Physical Effects on Personnel and Property. Air foams from liquid concentrates shall not be injurious to persons or equipment.

(viii) Precipitation. Air-foam liquid concentrates of ordinary types in recommended percentages shall be readily soluble in either fresh or salt water. The precipitate, if any, should not interfere with the proper operation of foam-liquid pick-up and proportioning equipment. (This specification has not been applied to the commercial liquid).

(ix) Specific Gravity. This should be determined for use as a means of identification.

(x) Packaging. Gives specifications for containers.

It would appear, therefore, that a comprehensive list of requirements could be drawn up, based essentially on the U.L. standards for air-foam liquids, amplified where necessary to include the range of properties found desirable in the development of high-expansion foam (for example, to specify a range of acceptable viscosity in the induction specification). It would also be necessary to include in the list of requirements, two of the more important factors. These are the "half-drainage time", and the "half-life time", or time for the foam volume to reduce to half its original value. It might also be possible to include a requirement for the minimum amount of water delivered per unit time to the fire. Specific gravity, pH, flash point, viscosity and surface tension may be determined with standard laboratory equipment. Many tests for the half-drainage time on the laboratory scale[7,15], and on the pilot scale[1, 10, 14], have been devised and used. Because of discrepancies between the laboratory scale and the pilot-scale equipment, it would be preferable if a pilot-scale unit were used in specification tests for the half-drainage time. The determination of the "half-life" of the foam is a relatively simple matter. A tank of 620 l capacity has been used for this purpose and found satisfactory[14]. A large volume of foam has to be used in this test to reduce wall effects and to approach the condition of full scale foam production.

5. Applications of high-expansion air foam

The possible applications of high-expansion foam in fire-fighting are numerous, and as its history is relatively short, the number of actual fire outbreaks where high-expansion foam has been used is small. Small and large scale testing on fires of different nature has been carried out, however, and much useful information has been gained as to its applicability under different circumstances. Review articles on its properties and applications have recently appeared in French and German Journals[39, 40].

In the initial stages, the development of high-expansion foam was concerned solely with the extinguishing of fires in mines. The considerable number of full-scale experiments carried out in Britain and the U.S.A.[1-8] advanced the state of the art to a point where it could be used successfully on two mine fires in the U.S.A.[9, 19]. In mine fires, the foam is applied as a 'plug' which moves along the mine roadway towards the fire. High-expansion foam has also been used in circumstances which are somewhat analogous to the fires in mine situations. A fire in a sewer under construction in Scotland was successfully extinguished[20]. Methane gas was burning at the bottom of a shaft 75 ft deep which was linked to other shafts by sewer tunnels. High expansion foam was applied from above via a discharge tube after water jets and normal foam had been tried without success. It was necessary to 'top up' the foam in the shaft at intervals, but the fire was eventually extinguished. Again, it has been reported that a fire in a subway under construction has been fought successfully with high expansion foam[21].

Liquid fuels and their associated hazards are responsible for a large number of fire outbreaks, and the effectiveness of high expansion foam in fighting this type of fire has been demonstrated. Among the Class B materials which have been extinguished successfully with high expansion foam are[10]:

A. High flash point liquids
- (i) Crankcase drainings
- (ii) Diesel oil, Jp-4, RP-1
- (iii) Crude petroleum
- (iv) Very hot (boiling diesel) oil

B. Low flash point liquids
- (i) Various paint and lacquer thinners
- (ii) Gasoline, benzene, toluol, heptane
- (iii) Hydrazine
- (iv) Ethyl alcohol, acetone, isopropyl alcohol, MEK.

C. Liquefied gases
- (i) Propane and butane
- (ii) Liquefied natural gas (control only)

In the above series of tests, a fire in a 1500 ft^2 area of high flash point oil was extinguished in 8 minutes by a truck-mounted unit which used about 100 g.p.m. of foam concentrate. It is of interest to note that in connection with the protection of liquid natural gas storages, one of the largest high expansion foam systems to be commissioned to date is at Le Havre in France where 15 generators, each giving 44,000 cu. ft min^{-1} of 1000:1 foam, protect three tanks holding 9×10^6 U.S. gallons. The delivery ship is also protected[43]. It has been noted in the above series of tests that fires of water solubles require substantially greater foam application rates to obtain control. Supporting evidence for this is available elsewhere[13], where fires of acetone, unsymmetrical dimethyl hydrazine and methanol were found more difficult to extinguish than fires involving benzene, xylene and hexane. This supports the need for a specification or Code of Practice indicating the minimum and optimum rates of application of foam for different types of fuel. Tests on simulated fires, including fires in flammable liquids, have also been carried out by the City of Coventry fire brigade[22]. One of the more outstanding examples of the use of high-expansion foam in fighting actual fires with liquid fuel involved was an instance in Los Angeles when a locomotive cut in two a petrol tanker on a level crossing[23]. On arrival, the fire fighters found a flaming tangle of train, truck, and trailer, plus burning and arcing high tension wires. Lines with fog applicators were used to control the fire, but the overturned tanker caused problems. A fog applicator used on this spread the burning gasoline to the railway ties (sleepers). High expansion foam was then used, and in 2½ minutes the high expansion foam had extinguished the flames.

One of the uses of high expansion foam which has considerable potential is in the fire protection of buildings, especially where large spaces are involved. The use of fixed installations for this purpose has been discussed, and some tests have been made in this direction[24]. Although the number of actual case histories is small, it is likely that it will be used more extensively in the future for a greater range of enclosed spaces, for example, in ships. Three instances in which a recently acquired foam unit has been used successfully have been reported[25,26,42]. In the first of these, a fire involving a 900 gallon tank of tar oil ignited the roof of the building and the fire spread to the rest of the building. The contents of the building included large quantities of tarred rope, sisal, and flammable liquids. The flames from the fire were 50 ft high and the whole of the factory area of 26 ft x 50 ft was involved. Radiant heat from the fire was so intense that materials 25 ft away burst into flame. A foam generator (31,000 g.p.m. foam) was used to prevent the fire spreading to an office block, the wall of which had already shown signs of collapse. The foam "pushed the fire away from the building" and a wall of foam some 8 to 10 ft high was built up, and completely prevented the fire from affecting the offices. The second fire was in a paper works with 1630 tons of baled waste paper and pulp stacked, in some instances, to a height of approximately 60 ft. Two stacks involving 76 tons and 255 tons were involved, and a considerable amount of smoke was created. There were hazards due to

(i) indiscriminate storage of paper and waste (baled),

(ii) sprinklers "tending to cause horizontal fire spread and to increase the amount of smoke, although they helped to control the fire",

(iii) danger to personnel due to collapse of stacks.

Foam was applied at ground level so that the seat of the fire was covered in foam, and this had the added effect of clearing away the smoke. The generator was moved to balcony level and foam was applied so that a blanket of foam covered the stacks involved (still burning) and the surrounding gangways which prevented the spread of the fire. Once the smoke was clear an access way was made. Foam was applied intermittently when smoke from hot spots broke out and eventually the stacks were dismantled and the fire put out. In the third, a fierce basement fire was effectively extinguished with no damage to goods stored on the ground floor. The effectiveness of high expansion foam in dealing with fires of different types, but particularly those in enclosed spaces has also been demonstrated in Russia, where it has been used in simulated and actual fires in buildings[18,41] and on fires in various parts of a ship, particularly below decks[27]. Some success has already been achieved using high expansion foam on an actual fire in a capsized vessel[37]. In Russia the technique of using high expansion foam differs from that generally employed in Western countries. Men are sent into the foam-filled spaces with breathing apparatus and guide lines, to extinguish the fire. In the West, the tendency is to allow the foam to control the fire by filling the spaces for an adequate time, and then sending men in to extinguish the remaining fire when the foam has collapsed. The Russians have extinguished fires in basements up to 290 m^2 (3000 ft^2) in area and divided into 3 or 4 sub-basements (N.B. Area of basements at the large Covent Garden and Smithfield fire was approximately 25,000 and 60,000 ft^2 respectively). It is important, of course, that the foam penetrates to all places where the fire is burning, and this may be difficult in multi-storey or multi-compartment buildings. Many other tests have been carried out using high expansion foam on fires involving materials and equipment of particular risk or value. For example, its effectiveness and possible deleterious effects have been tested for fires involving record storage[21,28] or electronic equipment, and for fires involving radioactive materials and simulated nuclear fuels[21,30,31]. It would appear from these tests that damage to records and electronic equipment by the use of high expansion foam is minimal. Other burning materials which have been successfully extinguished with high expansion foam are wood, rubber, and clothing[10,12].

Most successful applications of high expansion foam to date have been outlined above. There are, of course, limitations and snags concerned with the use of high expansion foam. Some are specific to a particular type of fuel or fire situation, while others are more general. Two prevalent problems are those of re-ignition of materials covered in foam, and of the continued burning of materials and fuels while covered with a foam layer. The problem of re-ignition seems to occur in deep-seated fires generally, but more particularly in fires involving wood and paper i.e. where smouldering can occur[5,10,26]. The problem of continued burning under a blanket of foam seems to occur with non-hydrocarbon and water soluble fuels[13,32] and theories to account for this have been suggested[13]. In the latter case, the continued application of foam to the fuel at a rate greater than the critical rate of water application will extinguish the fire[13]. In the case of re-ignition of materials under a foam blanket, the only sure way of dealing with this situation seems to be repeated applications of foam until the seat of the smouldering or fire can be tackled with hand lines. Another problem, which has been mentioned briefly above, is the rate of water application (as high expansion foam) to a fire in a given material. If this is not greater than a certain critical rate, it is possible that a fire may be controlled but not extinguished[7]. This problem would arise in situations where either the foam at the point of generation did not contain sufficient water, or the foam (due to drainage during movement) upon arrival at the fire location did not contain sufficient water for extinction.

Other problems exist which are associated with the flow properties of high expansion foam[33]. If the foam is produced at a low level in a building, it will pile up at the opening and flow by maintaining a constant angle of repose (due to a balance in friction loss and head pressure). It may be necessary, therefore, to raise the foam at the inlet to a considerable height before an object remote from the inlet is covered to sufficient depth in foam. There will also be limits to the vertical and lateral spread of foam, from a given machine, against head pressure and friction losses. This problem would be intensified where there is no escape route for the air in an enclosed space as the pressure due to steam generation and the entrapped air would increase even further. Also, the rate at which a given machine would produce foam initially would decrease as the foam blanket advanced across the floor of a building when introduced at a low level. Some of these problems could be partially solved by introducing the foam (where possible) at an elevated level. This is convenient with fixed installations[24] but there are associated problems when portable equipment is used. In this context the application of foam at elevated levels by projection (through windows) from a portable unit mounted on an elevated platform has beem investigated[34]. Although satisfactory remote control of the apparatus is possible, a 'throw' of 60 ft from the generator to an opening in a building can only be achieved by a reduction in the expansion from 1000 : 1 to 500 : 1.

As the flow of foam is directionally uncontrolled, it is possible that the foam may spread to occupy areas not affected by fire, or be wasted by flowing out through open doorways, broken windows and other openings. It is possible to control the flow of high expansion foam by the use of nets as barriers[35], but it is not always possible to erect these in suitable positions under fire conditions. Difficulties can also arise where it is necessary to take the foam to a fire via any form of ducting, particularly where this can not be kept horizontal and straight[20].

Under certain circumstances, foam can be broken up by heat and the droplets of water formed escape to the floor through the foam. It is then possible that the air carried to the fire by the foam is contributing more to the maintainance of combustion than the water in the foam is contributing to cooling. A demonstration of this problem was observed when foam advanced upwards towards the ceiling joists of a basement which were fully alight[33]. Foam rose quite rapidly to within 18 in of the ceiling and then its rise was halted quite dramatically. The top surface of the foam continued to undulate, or wave, but the top level of the bubbles continued to burst rapidly as it was moved upward. Other fires where high expansion foam may not be suitable are fires in the open (due to lack of control of the light foam in a wind), fires involving sprays or jets of fuel[36], and conditions where the steam produced may react chemically with carbon or carbon monoxide to form water gas (which contains hydrogen), although there is no evidence of dangerous amounts of hydrogen being produced to date. Another problem is that where it is necessary to use water fog to protect the operatives of foam-generating machines from heat radiation the fog may break down the foam[23].

The conduction of electricity by high expansion foam could give rise to another hazard but the work carried out so far in this direction, has shown that the problem is not as acute as that when bulk water is used. In France, for example, it was found that the specific conductivity of a high expansion foam was found to be 14 megohm/cm/cm^2, that the foam would only conduct a weak electric current and that electric motors and circuits operating at 220 volts did not appear to be damaged by the foam and in fact operated successfully within it[39]. In Germany, the specific conductivity of a high expansion foam (1000 : 1) was found to be 0.77×10^{-6} Siemens/cm (1 Siemen = 1/ohm = 1 Ampere/Volt) compared with a value of 870×10^{-6} s/cm for a 1.5 per cent solution of the foaming agent in water, and 410×10^{-6} s/cm for tap water[40]. It can be seen that the specific conductivity of the foam is approximately one-thousandth of that for the foam solution. The conductivity will, however, depend on the concentration and nature of the foam compound.

Again, in Russia, the electrical conductivity of the foam has been found to be small[41]. Preliminary experiments have shown that the electrical conductivity of a foam with an expansion ratio of 200–500 is such that a voltage of 6 kw at a distance of 3 m does not create a life hazard. The electrical hazard to personnel may increase, however, when considerable drainage has occurred, and until further information is available, maximum safety precautions (switching off mains electricity, high voltage equipment) and the use of rubber boots should be taken. Other disadvantages of high expansion foam as far as personnel are concerned are that it cannot be seen through, and is a poor transmitter of sound also[41].

Personnel under high expansion foam would soon find breathing difficult if not impossible, unless they were wearing breathing apparatus. It is also unlikely that the filling of a building with high expansion foam would assist the rescue of persons trapped in the building.

6. The comparison of high expansion foam and other extinguishing agents

So far, no comparison of the properties of high expansion foam with other agents has been made. A brief comparison will therefore be made in this section and the possibilities of combined usage discussed.

Water is the most commonly used extinguishing agent, and has the advantage of being cheap, readily available, usable in different forms (fog, spray, jet, etc) and generally can be directed easily onto the fire area from a considerable distance. The disadvantages of using water in its usual bulk form are that jets have limited throw and generally speaking water in the form of jets and sprays cannot be made to flow round obstacles. The application of large quantities onto a large fire area thus necessitates the multiplication of appliances. Moreover water cannot be used for certain flammable liquid fires and for fires where there is an associated electrical hazard. Also the amount of damage caused by the water in extinguishing a fire is often comparable with the amount of fire damage, especially with fires involving paper, clothing, packing materials, textiles and similar commodities. High expansion foam can be generated at a very fast rate by a single appliance and will cover a larger area more quickly than a single bulk water unit. It will also extinguish flammable liquid fires, help to clear away smoke (which water as a rule does not), and does not appear to have the same electrical hazard properties that water does[39,40,41]. The amount of water required to make sufficient high expansion foam to fill a given area or volume would be much less than that used by a single water appliance. Compared with water, however, high expansion foam is not susceptible to the same control of direction and does not have the same free range as a water jet.

Ordinary low expansion or protein foam will effectively extinguish liquid fuel fires, but considerable spoiling results from the use of this type of foam. Low expansion foam cannot be built up into a protective wall for personnel against radiation. High expansion foam would not normally be considered as an alternative to dry powder as an extinguishing agent for flammable liquid fires, as it does not give the same rapid "knock-down" on such fires in the open.

Inert gases (such as carbon-dioxide, nitrogen and exhaust gases) extinguish fires mainly by reducing the oxygen concentration of the atmosphere to a level below which combustion ceases. They are particularly useful in large areas where high-piled materials susceptible to smouldering are stored. The damage to the goods involved in the fire by inert gas is, in the main, negligible, but there is no real control over the direction and spread of an inert gas, particularly where there are secondary sources of air and draught in the building. Nevertheless if an inert gas is transparent, it would be possible by entering into the gas and opening and closing appropriate doors to direct the gas. There is also a special toxic hazard where carbon-dioxide is employed. Under suitable conditions, however, large volumes can be filled rapidly and inert gases can be used in instances where water constitutes a chemical hazard or special risk (e.g. metal fires, fires involving high voltages, liquid fuel fires). High expansion foam will also fill large volumes quickly and there is no intrinsic hazard to personnel in its use other than its effects of curtailing vision and hearing.

High expansion foam is not universal in its application, although there are several risks where it could usefully be used instead of, or in conjunction with, other agents. A programme of testing the use of the exhaust gas from a jet engine for the generation of high expansion foam on a large scale has been in progress at J.F.R.O. for some time and trials have been made on the effectiveness of this combination. The use of carbon-dioxide in high expansion foam has also been examined. The use of small amounts of inert gas or vaporizing liquids in the atmosphere used to generate high expansion foam may produce satisfactory methods for extinguishing fires which would normally prove troublesome with air foam alone. For example, this method is likely to be suitable where smouldering can occur, where burning can continue beneath a layer of air foam, or for three-dimensional liquid fires. It has already been demonstrated[44] that the combined use of high expansion air foam and a sprinkler system will extinguish a deep-seated paper fire under conditions where the individual methods would not.

Attempts to add soluble salt to the foaming liquid to improve the extinguishing efficiency of the foam have so far proved unsuccessful[7]. It would appear, therefore, that some of the major developments to be made in the use of high expansion foam lie in this sphere of combined usage.

7. Possible future studies of high expansion air foam

Despite its relatively short history, high expansion foam has already been used in an extensive variety of ways for controlling and extinguishing fires. There still exists a number of unknown factors in the behaviour and properties of high expansion foam, and it will be necessary to carry out more research and development work on the subject before its full potential is realised[1]. Some of the items which should profit from further investigations are listed below:

(i) Detailed examination of the flow properties of the foam

(ii) Examination of the transmission of heat radiation by the foam

(iii) Effect of variations in the nature and concentrations of foam compounds and stabilisers

(iv) Effect of ionic salt concentration on foaming properties of different compounds

(v) Effectiveness of doping the foam with inert gases, vaporizing liquids and other additives in dealing with fires of different natures

(vi) Effect on foam structure and stability of different gases (i.e. the inert gases) in the atmosphere within the foam, where diffusion and solubility may be important

(vii) Investigation of the possibilities of projecting the foam instead of leading it through ducts

(viii) Further investigation of electrical hazards associated with high expansion foam including effect of drainage in static foam

(ix) Investigation of the critical conditions for foam to cover and extinguish fire

(x) Use of generator without external power supply, i.e. including water turbine or compressed air turbine.

It is not, of course, possible to predict all the future uses of high expansion foam but some will probably be in the general directions outlined below:

- (i) combined use with other agents or systems e.g. sprinklers, inert gases etc.
- (ii) more extensive use of high-rate generators as automatic fixed installations in buildings and ships
- (iii) operation from special appliances such as elevated platforms, and helicopters
- (iv) use on fires in the open, possibly using a foam of lower expansion than normal (say 500 instead of 1000)
- (v) use where expensive equipment and machinery is involved for example (see ref. 38)
- (vi) more extensive use for tackling inaccessible fires in basements, cable ducts and in penetrating spaces where water availability is restricted, or undesirable.

Conclusions

High expansion foam has been shown to be a practical and useful agent in fighting many types of fires. It will control fires in ordinary combustible materials, and can extinguish them if it can reach the seat of the fire. It will also control and eventually extinguish flammable liquid surface fires. High expansion foam can be generated at rates sufficient to fill large spaces and buildings quickly, and has proved particularly useful fighting unventilated and inaccessible fires such as in coal mines, underground ducts and basements. The foam will travel round obstacles into regions which otherwise may be inaccessible, affords an effective shield against heat radiation and has no adverse affect on personnel who can move through the foam to continue fire-fighting manually where necessary. The combined use of high expansion foam with other agents and with sprinkler systems should, in the future, extend its potential use considerably and will almost certainly provide the answer to the few types of fire where ordinary high expansion air foam is unsuccessful. The use of automatic foam units in large buildings should prove a substitute for, and certainly a good alternative to, many existing installations. It will be particularly useful where complicated and expensive machinery is involved and also in situations where water damage could prove as costly as fire damage.

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