F. R. Note No. 400

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JOINT FIRE RESEARCH ORGANIZATION

A DISCUSSION OF SOME OF THE FACTORS AFFECTING THE DESIGN AND EVALUATION OF EXTINGUISHERS AND PROTECTIVE INSTALLATIONS FOR FLAMMABLE LIQUID FIRES

by

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1. Introduction

Flammable liquids differ so widely in their properties that all extinguishing agents can be effective against some types of flammable liquid fire. The mechanism of extinction of the different agents and their limitations as well as their advantages must be understood before the most satisfactory method of protection can be chosen. Extinguishing agents will be considered under three headings:

1. Water - which can be used to extinguish fires in which the flammable liquid can be cooled to below its fire point. Fires in liquids miscible with water may in some circumstances be extinguished by dilution.

2. Foam - can extinguish fires by cooling, but its unique feature is that it forms an impermeable physical barrier over the flammable liquid, preventing reignition.

3. CO_2, vapourizing liquids and dry powder - which are active in the vapour phase and do not afford any protection against reignition.

The efficiency of a protective installation in which there are often ample supplies of agent, can be judged on different grounds from that of an extinguisher where the amount available is limited. To be effective against a flammable liquid fire a hand extinguisher should be capable of extinguishing the type and size of spill fire likely to occur. A fixed installation, however, it may often be adequate to control the fire and prevent its extension to other plant, final extinction being achieved by other means.

2. Water

(a) Application by hand. Rasbash and Stark [1] in tests with water sprays applied by hand to an 8 ft diameter flammable liquid fire have shown that the extinction time depends on the spray properties and the fire properties in the following way.

$$t = \frac{24,330\ D^{0.85}\ Y^{0.39}}{R^{0.68}\ \Delta T^{1.67}} \text{ secs.} \qquad (1)$$

where D - mass median drop size of the spray (mm)

Y - preburn time of the fire (min.)

R - flow rate gal/ft^2/min.

ΔT - difference between the fire point of the liquid and ambient temperature

They suggested that the critical rate of application below which extinction is unlikely is given by

$$R_{crit} = \frac{10.5\,D}{\Delta T} \text{ gal/ft}^2\text{/min.} \qquad (2)$$

Equations (1) and (2) are only applicable within certain ranges. Flammable liquids with fire points much below kerosine ($\Delta T \approx 40°C$) would require favourable conditions and considerable experience before extinction was possible. Splash fires develop in the less viscous liquids when the droplet size is too great and these can prolong extinction. The mass median droplet size should be less than 0.7 mm to prevent splash fires in gas oil ($\Delta T \approx 90°C$), whereas much coarser drops of 1.25 mm diameter are required to give splash fires in transformer oil ($\Delta T \approx 160°C$).

Table 1 shows the critical rates of application for some oils, with sprays of varying droplet sizes.

Table 1

Critical rates of application - water

Liquid	ΔT °C	Critical rate of application gal/ft^2/min. Mass median droplet size of water sprays.		
		< 0.5 mm.	0.5 - 0.75 mm	1 - 1.25 mm.
Kerosine	40	0.13	0.19 *	0.26 *
Gas oil	90	0.058	0.087	0.116 *
Transformer oil	160	0.033	0.05	0.066

* Splash fires would be likely under these conditions.

Considering these results in terms of the normal hand extinguisher holding 2 gallons of water discharged at a rate between 1 and 2 gallons per minute, some idea can be gained of the size of fire which could be extinguished. The majority of these extinguishers discharge their water as a jet which would be ineffective; however, the operating pressure is sufficient to give a spray with a mass median drop size at least as low as 1 mm. with a suitably-designed nozzle. If this was done the 2 gallon extinguisher would extinguish a fire in transformer oil of about 15-30 ft^2 in area and probably a fire of about half the size in gas oil. Water may also be applied to flammable liquid fires from the hose reel equipment carried by fire tenders. The normal rate of flow from this equipment is 8 gal/min. and depending on the droplet size of the spray, a fairly large fire at least in the heavier oils could be extinguished. High pressure equipment used by some brigades give higher flow rates (15 - 20 gal/min.), and nozzle pressures greater than 250 p.s.i. and the sprays have a mass median droplet size of about 0.7 mm. It can be seen from Table 1 that this would enable a sizeable fire to be extinguished.

(b) Fixed installations. Fixed installations employing water are used for protecting oil-cooled transformers and many different risks involving flammable liquids. The fires likely to be met in this sort of application will consist of spill or pool fires and fires in burning liquids on the tubes of a transformer or the pipes and tanks of a plant. The performance of fixed water sprays on pool fires (2) is similar to their performance by hand application described in the previous Section. The ease with which the burning liquids can be cooled to below their fire point when burning on tubes or plant will depend on the temperature of the metal on which they are burning. Rasbash and Stark (3) in tests on a nest of tubes showed that the longer the preburn time the higher the temperature on the tube bank and, consequently, the higher the flow rate required to extinguish the fire. As with all fires which are extinguished by cooling, the lower the fire point of the oil, the higher the flow rate required. The rates of application required to extinguish the [illegible] fires were very much higher than those required for pool fires and the effect of preburn time in the tests is shown in Fig. 1. This shows the importance of early detection of the fire and there appears to be some scope for improvement in the detection methods used for actuating fixed installations (4).

The tests on the tube bank fires showed that the efficiency of the water sprays increased with pressure, particularly up to 50 lb/in².

In deciding what rates of flow are required for a particular installation, one of the most important points is the speed with which adequate mobile equipment can be brought into use. With a reasonable standard of mobile equipment the rates of flow of the protective installation could be reduced to that necessary to cool the plant involved and prevent the spread of fire to other parts of the plant.

3. Foam

The mechanism of extinction of fires in liquids with high fire points by foam is similar to that by water sprays. The water content of the foam cools the burning liquid and it is not necessary to form a foam blanket to extinguish the fire. The critical rates of application to fires in these liquids will, therefore, be similar for both foam and water.

The unique feature of foam as an extinguishing agent is that it can be used to cover the burning liquid with a layer which prevents further heat transfer to the liquid and is impermeable to flammable vapours, thereby preventing reignition of low flash point products. The critical rate of application with foam is therefore, not dependent on the fire point of the liquid in the same way as the critical rate with water.

The time taken to control or extinguish a fire in a low flash point liquid depends primarily on the rate of application and the critical shear stress of the foam; the critical shear stress has little effect on the critical rate of application.

The following relations have been obtained (5) for protein type foams applied to the surface of petrol fires:

Critical rate of application = 0.025 gal/ft^2/min.

$$T_c = \frac{.0056S}{R} + 18 \qquad \text{......(3)}$$

$$T_e = \frac{.0183S}{R} + 49 \qquad \text{......(4)}$$

where T_c - control time or time taken to reduce the radiation from the fire to $\frac{1}{3}$ rd of its original intensity.

T_e - extinction time

S - critical shear stress of the foam (dynes/cm^2)

R - rate of application (gal/ft^2/min.)

The quantities of foaming liquid per square foot of fire area required to extinguish the fire can be calculated from Equation (4) and are shown in Figure 2. for two values of critical shear stress of foam.

Most nonhydrocarbon flammable liquids require special attention as they can cause a rapid breakdown of protein foams. It appears that this breakdown occurs particularly in those liquids which are miscible with water and it has been shown [6] that for miscible alcohols the greater the molecular weight, the more rapid the breakdown of foam. There is some evidence that the higher molecular weight alcohols which are less soluble in water (butyl alcohol) do not have such a destructive effect on protein foams. The critical rates of application of normal protein foams on the majority of solvent fires appear to be unknown but special alcohol-resistant foams have been developed which are suitable for many of them.

3.(a) Hand extinguishers

Because extinction of low fire point liquids with foam depends on a complete physical barrier being formed over the liquid, it is a relatively lengthy procedure at normal rates of application. The capabilities of a hand extinguisher are therefore governed by the total quantity of liquid available and not the rate of application. This is illustrated by considering the 2 gallon foam extinguisher which discharges at a liquid rate of about 2 gallons per minute. The critical rate of application is 0.025 gal/ft^2/min. Thus if a rate of 2 gal/min could be maintained it would be capable of extinguishing an 80 ft^2 area at the limit. However, Fig. 2 shows that the quantity of liquid required to extinguish a fire varies with the rate of application and the critical shear stress, and the minimum quantities required at the most advantageous rate of application are in the region of 0.1 - 0.2 gal/ft^2. Thus the maximum size of fire which can be extinguished with 2 gallons of foaming liquid will be in the range of 10 - 20 square feet.

The capabilities of a hand foam extinguisher are obviously affected by the fluidity of the foam and the rate of discharge. The majority of proprietary foam extinguishers produce a stiff foam and the performance could be improved by reducing the critical shear stress of the foam. In chemical foam extinguishers this can be done by reducing the amount of stabilizer used [7].

3.(b) Fixed installations

In a fixed installation there will be adequate bulk supplies of water and foam compound and under these conditions the rate of application is the controlling factor. The recommended rate of application is about 0.1 gal/ft^2/min., about four times the critical rate, and this could be reduced if economic considerations required.

Fixed foam installations have been most used for the protection of liquid storage tanks where the foam is discharged onto the surface of the liquid. Variations in foam properties over quite a wide range are of little practical importance under these conditions. In some incidents the foam equipment has been damaged or destroyed by explosions preceeding the fire, and there are many storage tanks with no fixed equipment. The most satisfactory manner of protecting a tank would probably be to inject foam at the base of the tank from portable foam generating equipment which could be used outside bund walls. The practicability of this method of base injection depends upon the foam properties and the method of injection being designed to limit the petrol content of the foam blanket. It has been shown that if the petrol content of the foam is greater than 10 per cent the fire cannot be extinguished. Although the effect of foam properties is well understood(8) there is not sufficient information (9) on the method of injection to enable the general design criteria to be established for this type of protection.

The use of fixed foam systems for more general plant protection is seldom practised in this country although in some instances, particularly with low fire point liquids, it should show some advantages over water, particularly in the lower flow rates required and the greater degree of control which could be achieved. The most satisfactory way of applying the foam is through a system designed to introduce air at the nozzle so that foaming liquid and not foam is pumped through the pipe work. The foam which is produced by these 'foam sprinklers' is of lower stability than normal fire fighting foam (since less work is done on the foam by the sprinkler heads) but recent tests at the Naval Research Laboratories (10) have shown that it can be very effective. They made tests with a 350 ft^2 pool fire of a low flash point fuel containing some simple obstruction. Foam of expansion about 5 and with a 25 per cent drainage time of less than one minute (normal fire fighting foams drain much less rapidly and have 25 per cent drainage times greater than 5 mins.) was produced by the 'foam sprinklers' at heights up to 20 ft above the surface of the fuel. They found the critical rate of application under these conditions was about 0.1 $gal/ft^2/min$, and this would probably be reduced if a 'foam sprinkler' producing a more stable foam could be designed.

A further advantage of a fixed foam protection system over a water system for plant, which is not evident from tests made on contained pool fires, is that with foam there is much less water to run off and carry burning fuel to drains and other parts of the plant. The disadvantages are those of any system requiring an additive to water, storage tanks are required for the additive and additional equipment for proportioning the foam compound into the water stream is needed. For small fixed foam systems the recent developments of foam compounds which retain most of their properties on pre-mixing with water should make this type of protection more popular.

4. Dry powder, vapourizing liquids and carbon dioxide

The common features of these three agents will be discussed before considering the information which is available to assist in the design of equipment using them.

All three types of agent are active in the vapour phase and they neither cool the high fire point liquids nor provide any permanent protection against reignition of the low fire point liquids. Being active in the vapour phase it is only necessary to get a given concentration of the agent for extinction (11) of the flames and with this proviso, extinction is rapid. This means that the size of fire which can be extinguished is dependent more upon the critical rate of application than the amount of agent available.

However, the 'critical rate' for application by hand is likely to be affected by a number of factors. With low flash point liquids the fire will spread back to areas already extinguished unless the required concentration of agent is maintained as a barrier until the fire is completely extinguished. It might be expected therefore that the critical rate of application would increase as the flash point decreased due to the difficulties in maintaining a barrier over a large fire front.

With these agents it will be more difficult to extinguish fires amongst plant and pipework than on a free surface. Flames are likely to be stabilized behind obstructions and cause reignition when application of the agents is stopped. Since most fires likely to be dealt with by hand extinguishers will have obstructions, it is important that the limitations these will impose should be realised. Some idea of the effect of different types of obstruction on the efficiency of small hand extinguishers is given by tests made at the National Bureau of Standards (12).

The method of application of the agents to a fire is more important than with foam and water. They must be well dispersed above the liquid surface. Carbon dioxide being a gas is naturally dispersed and dry powder is also dispersed with the expanding propellant gas at the nozzle although a wide cone angle spray will require less manipulation than a narrow one. However, vapourizing liquids need to be discharged as a well distributed fine spray to realise their full efficiency, any agent which reaches the flammable liquid being largely wasted. Thus nozzle design is likely to affect the capabilities of vapourising liquid extinguishers much more than those of carbon dioxide or dry powder.

Some of the inherent disadvantages of these agents may be overcome in fixed installations where the nozzles can be positioned and the discharge rates adjusted to deal with obstructions.

4. Dry powder

(a) Application by hand. Most of the commercial dry powders in use at the present time consist largely of sodium bicarbonate. Tests on free surface (11) petrol fires in trays 3 ft x 3 ft showed that the extinction time was related to the area rate of application (the rate of application of powder surface, given by the weight rate x specific surface of powder) rather than the weight rate, for powders within the range of specific surface from 1000 cm^2/gm - 4,000 cm^2/gm.

Since a given concentration of powder must be maintained across the whole fire front, it might be expected that the controlling factor for hand extinction of fires of different sizes using dry powder would be the area rate of application per foot of fire front rather than the rate per unit area of fire. This is borne out by the results given in Table 2, where the available information has been summarised.

Table 2.

Performance of sodium bicarbonate powders on petrol fires of different sizes (hand application)

No.	Origin and reference	Specific surface cm^2/gm.	Size of fire ft	Critical rate of application		
				$lb/ft^2/sec$	$cm^2/ft^2/sec$	$cm^2/ft/sec$
1	J. F. R. O. (12)	3,300	3 x 3	0.017	2.5×10^4	7.5×10^4
2	J. F. R. O. (13)	1,150	3 x 3	0.042	2.2×10^4	6.6×10^4
3	J. F. R. O.	3,500	5 x 5	0.014	2.[illegible] $\times 10^4$	11×10^4
4	H. R. L. (14)	1,400	3 x 3	0.01	0.6×10^4	1.8×10^4
5	H. R. L. ([illegible])	1,400	7 x 7	0.0135	0.85×10^4	5.9×10^4
6	H. R. L. (10)	1,400	13 x 13	0.009	0.55×10^4	7.2×10^4
7	J. F. R. O. ([illegible])	1,400	30 x 30 (2 operators)	$<.0034$	$<0.22 \times 10^3$	$<6.6 \times 10^4$
8	J. F. R. O. ([illegible])	2,700	30 x 30 (2 operators)	$<.0024$	$<0.3 \times 10^3$	$<9.0 \times 10^4$

The fire in series No. 4 consisted of three litres of petrol which would only give a shallow layer on the tray, and this as well as the short preburn time (5 sec) may account for the much lower critical rate than that obtained in Series No. 2. Estimates of the specific surface of the powders used in Series Nos. 4 - 6 have been made from the particle size distribution of the powders, and the rate of application has been estimated in Series No. 6. It can be seen from the last columns of Table 2 that with the exception of Series No. 4, the critical rate of application expressed in cm^2 of powder/foot of fire front/sec. is approximately constant at 5 → 10 x 10^4 cm^2/ft/sec. for a wide range of fire sizes.

There is little published information on the effect of the flammable liquid properties on the critical rates of application of dry powder. There is, however, some evidence that the critical rate is dependent on the heat of combustion and the boiling point of the liquid, increasing with the heat of combustion and decreasing as the boiling point increases.

In the design of extinguishers using dry powder, it would seem necessary to have a minimum discharge time to take into account such factors as the time required for an inexperienced person to start discharging the powder onto the fire effectively. There is some evidence to suggest that this minimum time should be in the region of 6 seconds. The capabilities of the extinguisher would then be governed by the rate of application and the specific surface of the powder.

Powders other than sodium bicarbonate have been investigated. There is a considerable volume of previous work on the efficiencies of fire powders for suppressing dust explosions and methane-air ignitions and this has been briefly reviewed (16). The alkali metals and the halides are placed in different orders of efficiency by workers using different techniques but they emerge as amongst the most efficient agents.

Fire tests of a qualitative nature have been reported by Lee and Shaub (17) who showed that potassium bicarbonate and borax were equally as effective as sodium bicarbonate. Neill (14) has recently reported comparative tests on sodium and potassium bicarbonate which are claimed to establish the considerable superiority of potassium bicarbonate. It is likely, however, that this is due partly to the fact that the specific surface of the potassium bicarbonate was considerably higher than that of the sodium bicarbonate. The quantitative results available are summarised in Table 5.

Table 3

Performance of different types of powder on petrol fires

Type of Powder	Origin and reference	Specific surface cm^2/gm	Size of fire ft.	Critical rate of application cm^2 ft/sec.
Sodium bicarbonate ($NaHCO_3$)	Table 2	Table 2	Table 2	5 - 10 x 10^4
Potassium bicarbonate ($KHCO_3$)	Naval Research Laboratory (14)	1900 1900	3 x 3 10 x 10	* 1.2 x 10^4 5.7 x 10^4
Sodium Chloride ($NaCl$)	J.F.R.O.(13)	2300	3 x 3	6.9 x 10^4
Borax ($Na_2B_4O_7 10H_2O$)	J.F.R.O.	1120	3 x 3	6.7 x 10^4
Anhydrous Borax ($Na_2B_4O_7$)	J.F.R.O.	2150	3 x 3	14.5 x 10^4
Cement	J.F.R.O.	4000	3 x 3	30.6 x 10^4
Pulverised fuel ash	J.F.R.O.	5000	3 x 3	~45 x 10^4

* The same comments apply to these results as to those in Series 4 of Table 2.

Comparing the critical rates of application, it can be seen that a number of materials are in the same bracket of efficiency as sodium bicarbonate, but none emerge as strikingly superior.

(b) Fixed installations

Investigations of the use of fixed dry powder systems for protecting flammable liquid surfaces have been reported by Guise and Lindloff (18). Comparative results with vaporizing liquids and CO_2 were obtained on a 4 ft diameter fire (Fig. 3) where the dry powder appeared superior to all but trifluorobromomethane (CF_3Br). The critical rate of application on the 4 ft diameter fire was about 7 gm/ft^2/sec and that on the 50 ft^2 fire reported (13) about 20 gm/ft^2/sec. The critical rate on the 4 ft diameter fire may be compared with that on a fire of a similar size reported by Hird and Gregsten (13). In these tests the powder was applied by hand and a critical rate of about 13 gm/ft^2/sec was obtained with powder of a similar specific surface to that used by Guise and Lindloff.

Tests have also been reported (18) in which the concentration of powder necessary to extinguish [illegible] liquid fires in enclosed spaces by 'total flooding' with powder was determined. It was found that with larger fires and longer preburn times a lower rate of flow of powder was required for extinction. This is probably due to the fact that with a large fire in an enclosure with small openings there is only sufficient air for flaming combustion near to the openings. This would mean that the requirements for a 'total flooding' system with powder would be very dependent on the degree of ventilation of the enclosure.

Vaporizing liquids and CO_2.

Vaporizing liquids such as carbon tetrachloride and methyl bromide, have been in use for many years but recently there has been considerable progress in the development of more efficient and less toxic agents. Some indication of the extinction efficiency of this type of agent can be obtained from their effects on the flammability limits of n-hexane and the peak values and other properties of some vaporizing liquids and carbon dioxide are given in Table 4, most of which is reproduced from a paper by Kingman and Coleman [19].

Table 4

Properties of some vaporizing liquids

Compound	B.P. °C	Density		Peak value with n-hexane	
		Liquid g/ml 20°C	Vapour g/l N.T.P	Percentage by vol.	Percentage by weight
Carbon dioxide CO_2	-78.5†		1.98	28.0	42
Methyl bromide CH_3Br.	4.5	1.73*	4.25	7.1	23
Carbon tetrachloride $C.Cl_4$	76.8	1.60	6.84	9.7	51
Chlorobromomethane $CH_2Cl.Br$.	69	1.93	5.78	6.35	28
Trifluorobromo - CF_3Br. methane	-57.8	1.58	6.66	4.9	29
Difluorodibromo- methane CF_2Br_2	24.5	2.29	9.39	3.55	26
Tetrafluorodibromo- methane $C_2F_4Br_2$	47.5	2.18	10.62	3.22	26
Ethyl Bromide C_2H_5Br.	38	1.42	4.86	6.1	23

† Sublimes

* at °C

The most extensive work on the application of these agents to fires has been reported by Guise [20] who used a 4 ft diameter fire and an arrangement of 4 fixed nozzles evenly distributed about the tray to apply the agents at different rates of application. A summary of much of the information is shown in Fig. 3 which is reproduced from Guise's report. Information on the application of these agents by hand to fires of different sizes has been reported by Coleman and Stark (21). Much of their work was done with chlorobromomethane and they extinguished fires from about 1 ft^2 to 100 ft^2 at a range of rates of application. They found that the extinction efficiency depended greatly on the method of application, a wide angle flat spray which could cover the whole fire front being most effective. The results of Coleman and Stark on a 4 ft diameter fire are compared with those of Guise in Fig. 4. The critical rate of application for fixed application is about four times greater than for application by hand to the same size of fire. Some advantages would be expected for hand application since the agent can be applied to overcome any deficiencies in coverage. The critical rate for carbon tetrachloride obtained by Coleman and Stark is however of the same order as that obtained by Guise for fixed application. This is an unexpected result and will be discussed later.

The similarity in the method of extinction between vaporizing liquids and dry powder would suggest that the critical rate of application for fires of different sizes could be expressed in a similar way, that is, in terms of the rate of application per foot of fire front. The available information for hand application is summarised in Table 5.

Table 5

Critical rate of application for CB and CTC (hand application)

Agent	Size of fire	Critical rate of application	
		$gm/ft^2/sec.$	gm/ft/sec.
Chlorobromomethane	2 ft diam.	< 13	< 20.5
$CH_2Cl.Br.$	4 ft diam.	2.1	6.6
	10 ft x 10 ft	2.5	25
Carbon tetrachloride	2 ft diam.	17	26.5
$C.Cl_4$	4 ft diam.	> 6.8	> 68

The estimate of the 'critical rate' for the 4 ft diameter fire with CB is probably more accurate than for the other fires since many more tests were done under these conditions.

Table 5 shows that there is insufficient experimental evidence for preferring either criterion. It would seem, however, more logical to expect the critical rate to be reasonably constant for fires of different sizes in terms of the rate of application per foot of fire front. The estimated critical rate expressed in this way for carbon tetrachloride on the 4 ft diameter fire is considerably higher than would be expected by comparison with the results with chlorobromomethane. This was the conclusion which could be drawn from a comparison with the results of Guise, and it may be that further experiments are required on this scale.

Coleman and Stark (21) showed on the 2 ft diameter fires that, at rates of application up to about two or three times the critical rate, extinction took considerably longer with carbon tetrachloride than with chlorobromomethane. Guise also found this to a lesser extent when the agents were applied through fixed nozzles. In relating 'extinction efficiency' with peak flammability data he took as his criterion of efficiency the minimum quantity of agent used to extinguish the test fire. The relation between this 'extinction efficiency' and the 'peak values' expressed as percentages by weight is shown in Fig. 5. When expressed in this way the results for methyl bromide are difficult to explain. It has the lowest 'peak value' but appears as the least efficient agent.

The 'peak value' might be expected to be related more to the critical rate of application than the quantity of agent required to extinguish the fire. At the 'critical rate' the concentration of agent in the fire zone is likely to be just sufficient to inhibit combustion. The 'peak values' are plotted against the critical rate of application in Fig. 6. The results for methyl bromide are still anomalous although the correlation is better than that obtained in Fig. 5. When plotted in this way, carbon dioxide appears more efficient than would be expected. There are of course a number of factors which make unlikely any accurate correlation of peak flammability data with fire test results for a range of agents with widely different physical properties. One of the most important of these is the effective utilisation of the agent which is likely to be greatest for gases and very low boiling point liquids. This might explain the higher efficiency of carbon dioxide and the trifluorobromomethane indicated by Fig. 6, but is no explanation of the anomalous results Guise obtained with methyl bromide.

These correlations are of course for agents applied by fixed nozzles and there is some evidence of a discrepancy between these and the results for hand application.

In determining the efficiency of new types of vaporizing liquid it would seem that if the 'peak value' from flammability data is less than about 30 per cent by weight, then it may not be a very good guide to the agents efficiency.

As with dry powders, there is little published information on the effect of the flammable liquid properties on the critical rates of application of vaporizing liquids. However, it seems that the agent which reaches the flammable liquid surface can have some inhibitory effect with low flash point fuels and will be rapidly vaporized by high flash point fuels.

In the design of extinguishers using vaporizing liquids, it would be necessary to have a considerably greater minimum discharge time than with dry powder. Coleman and Stark [21] have reported extinction times up to 15 seconds with trained operators using chlorobromomethane at about three times the critical rate of application on 4 ft diameter petrol fires. A minimum discharge time of about half a minute would seem necessary. The capabilities of the extinguisher would then depend on the rate of application and the type of agent used.

Guise's results [18] are applicable to the use of vaporizing liquids for fixed installations. Fixed installations utilizing carbon dioxide have of course been the most common and the requirements for different types of risk and grades of protection are well established [22].

General considerations

There are a number of factors which will govern the choice of a particular type or size of extinguisher or type of fixed installation which have not been discussed. Some of these, such as the question of the toxicity of the agent and its products of combustion, depend on the conditions under which the extinguisher will be used. For others more general considerations are possible. For instance, the majority of extinguishers are likely to be used by untrained people who may well never have used an extinguisher before. It is well established [23] that the time taken to complete almost any task is reduced with subsequent attempts. This certainly applies to extinguishing fires, and Rasbash and Stark [1] have shown in extinguishing oil fires with water sprays that a trained person can extinguish the same fire in a third of the time of an untrained person. This fact has been recognised by the Underwriters' Laboratory in their new method of rating extinguishers for flammable liquid fires. The rated area of flammable liquid fire for a particular extinguisher is 2½ times less than the area which can be extinguished by a skilled operator.

The effects of nozzle design on the capabilities of an extinguisher are likely to be more important with untrained personnel than with skilled operators.

Conclusions

Some of the factors affecting the design and evaluation of both hand extinguishers and protective installations for flammable liquid fires have been discussed.

One of the important differences between the two is that whereas, with protective installations, adequate bulk supplies of agent are normally available, only a limited supply can be carried in a hand extinguisher. This means that although the critical rate of application will almost always be the main design criterion for protective installations, the quantity of agent available will be more important for some agents in hand extinguishers.

The results of the discussions on hand extinguishers are summarised in Table 6.

Table 6

Factors governing efficiency of hand extinguishers

Agent	Factors affecting size of fire which can be extinguished by hand extinguisher	Critical rate of application	Estimate of quantity of agent/ft^2 of fire for extinction	Most efficient method of application
Water	1. **Fire point of liquid** 2. **Drop size of spray** 3. **Quantity and rate of application**	$R_{crit} = \frac{10.5\,D}{\Delta T}$ gal.ft^{-2}min^{-1} Assuming drop diameter of 0.7 mm. Kerosene - 0.19) Gas oil - 0.0[illegible]) gal.ft^{-2}min^{-1} Transformer oil - 0.05)	(1 min. preburn) Kerosene - 4 - 5 lb. Gas oil - 0.7 - 1.2 lb. Transformer oil-0.3-0.6lb.	As a very fine spray which will reach the liquid surface.
Foam	1. Quantity of agent 2. Type of flammable liquid - unsuitable on liquids miscible with water.	0.025 gal/ft^{-2}min^{-1}	1 - 2 lb.	So that the foam can flow over the surface and is not projected straight into the flammable liquid
Dry powder	1. Rate of application 2. Pattern of discharge 3. Specific surface of powder 4. Properties of flammable liquid	**Petrol** 5 → 10 x 10^4 cm^2/ft of fire front/sec.	0.1 - 0.3 lb.	Wide angle spray which requires less manipulation
Vaporizing liquids and CO_2.	1. Rate of application 2. Pattern of discharge 3. Type of agent	C.B. 1.5 → 5.5 x 10^{-2} lb/ft of fire front/sec CTC 5 → 15 x 10^{-2} lb/ft of fire front/sec	CB 0.1 - 0.3 lb.	Wide angle flat spray for vaporising liquids

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