THE FIRE PROTECTION OF FLAMMABLE LIQUID STORAGES WITH WATER SPRAYS

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This paper gives an account of the control and extinction of flammable liquid fires by water sprays. It discusses the differences in the mode of extinction of the three main classes of liquid, and the essential design parameters of the equipment for each type. It gives some account of the extinction of 'mixed' fires involving flammable liquid and heated solids, such as surrounding metal structures, and of the protection of exposures against the effects of radiant heating by adjacent flammable liquid fires.

INTRODUCTION

The use of flammable liquids in the chemical industry carries with it the need for the fire protection of flammable liquid storages and process plant. There are several alternative fire-fighting materials which may be used for this purpose, such as dry powders and vaporising liquids, foams, inerting gases - or the oldest of all the fire-fighting materials, WATER.

Water has several advantages over other materials. It is cheap and usually readily available. It is non-toxic and does not give rise to toxic products. It has a high heat absorption capability in terms of its specific heat and latent heat of vaporisation. This makes it particularly useful where the fire involves not only a flammable liquid, but also hot solids such as pipework, metal bulkheads in ships etc, where the hot solids can cause re-ignition of a flammable liquid already once extinguished. Water can also be used to provide an inerting atmosphere when it can be vaporised to 1700 times its liquid volume, thereby displacing air and flammable vapours from an enclosure or in the area adjacent to a burning liquid surface. Even where water alone cannot completely extinguish a fire, it may often be used in conjunction with other materials such as dry powders or vaporising liquids to secure complete extinction. In this role, the water spray reduces the flaming combustion and cools the surroundings, while the other material completes the extinction.

On the debit side, water has a high freezing point and expands on freezing thus exerting great pressure on vessels and pipework in which it may be trapped. It is relatively weighty in terms of its effectiveness as compared with other

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agents, although this may not be a disadvantage in the fixed systems used in the protection of storages and process plant.

It will conduct electricity in the solid stream condition, so should not be used in fires involving electrical equipment. In the form of a spray, this danger is much reduced and is usually negligible, O'Dogherty (1965). Water will not float on oils to form a sealing blanket in the way that foam will, and indeed it will displace oils from an open container to give a running fire. Its ability to form steam can be a disadvantage when it is applied to an oil which forms a hot zone at a temperature above 100°C, as the water droplets falling into the oil will tend to sustain combustion by giving splash fires and may even give rise to a 'froth over'.

Water cannot safely be used in flammable liquid fires where flammable metals are involved - except in some cases as a fine spray using extreme caution. Against this, a magnesium fire may sometimes be extinguished by the use of lubricating or similar oil, thus converting the metal fire to a flammable liquid fire which may in its turn be extinguished by use of a fine water spray.

In total, the advantages of water as an extinguishing material for flammable liquid fires more than compensate for its disadvantages, and give it a range of application in this field which is at least as wide as that of any other fire-fighting material.

FLAMMABLE LIQUIDS TO BE PROTECTED

In the protection of flammable liquid risks in storages or in process plant, water spray systems are used to combat the rapid growth of fires which may occur, since such fires, if not promptly controlled, are likely to grow to catastrophic proportions and cause substantial damage to valuable plant. In the study of water spray performance, it is convenient to divide flammable liquids into three classes, Rasbash and Stark (1960), since the mechanism of extinction involved in these three classes, and consequently the design of the equipment used, differs between them.

In those liquids which are non water-miscible and have fire points of 45°C and above, the liquid may be extinguished by direct heat transfer from it to those water droplets which penetrate the liquid surface. This application includes diesel oil, gas oil and lubricating oils, and also kerosene as a borderline case. It also includes asphalt, bitumen, pitches, transformer oil, heavy fuel oil, vegetable oil and glycerine which have fire points greater than 100°C, and therefore give rise to certain dangers when water is applied to them.

The second class of flammable liquid which may be extinguished by water sprays includes those which are water-miscible and which can therefore be extinguished by raising the fire point to 45°C and above by the admixture of water. This class includes methyl, ethyl and propyl alcohols, acetone, acetic acid etc. Whisky is also included.

The third class of flammable liquid which can be controlled and sometimes extinguished by the use of water sprays includes those liquids which are non water-miscible and have a fire point below 45°C, namely, the low flash point hydrocarbons such as white spirit, solvent naphthas, petrol, benzole, toluol, xylol etc. It also includes some liquids which are partly water-miscible such as ether, ethyl methyl ketone, butyl and amyl alcohol, ethyl acetate etc. For these liquids, direct cooling of the flammable vapours in the flame zone by heat transfer to the water droplets is necessary.

EXTINCTION OF FIRES IN IMMISCIBLE HIGH FIRE POINT LIQUIDS

Liquids having a fire point above 45°C are extinguished by direct heat transfer to the water droplets which penetrate the liquid surface, until the flammable liquid temperature falls below the fire point. The water spray therefore needs to have sufficient impetus to reach the burning liquid against the updraught of the flames. To do this, it must either be formed near the surface or be projected downwards with sufficient force for a large proportion of the spray to avoid deflection and evaporation in the flames. The factors which are important in achieving this are the drop size and impetus of the spray, the updraught of the flames and wind (under outdoor conditions) and the evaporation of the spray in the flames. The impetus of the spray is a function of the reaction of the nozzle and the width of the spray; there is evidence that at some distance from the nozzle it is approximately equal to the impetus of the entrained air current. The updraught of the flames is proportional to the buoyancy head.

The problem may be illustrated by some experimental fires of kerosene burning in a 30 cm diameter vessel using downward application of the spray, Rasbash (1962). Figure 1 shows the percentage of water actually reaching the surface, as compared with that expected to do so from geometrical considerations. It will be noted that this percentage increases approximately linearly with mass median drop size. In practice, a large range of experiments has shown that the mass median drop size must be above 0.4 mm for a spray to penetrate the flames effectively, although results are scattered because the penetration also depends markedly on the distribution of velocity across the spray, becoming greater the more uniform the distribution. At drop sizes greater than about 0.8 mm, the penetration becomes independent of impetus, although some improvement with increasing drop size is still available. At about this size, another phenomenon begins to occur, the problem of 'splash fires' caused by the more massive drops splashing droplets of fuel out of the surface with a resultant continuance of combustion even after the average liquid temperature has fallen below the fire point.

Rasbash (1960, 1962) has demonstrated that there is a 'critical rate' of water application necessary to achieve extinction and this is given by the general equation

$$R_c = \text{Constant } \frac{D^x}{\Delta T^y}$$

where R_c = critical rate in l/min

D = mass median droplet size in mm

ΔT = difference between water temperature and liquid fire point in degC

x, y = are indices approximately equal to 1

It is essential in practice that ΔT should be at least 40 degC as if it is not, the critical rate will have an unduly high value. As an example, for a tray of gas oil of 8 ft diameter which has burnt for 5 min before spray application, the constant in the equation is approximately 1140. Some experimental curves of critical rate against mass median drop size for kerosene and transformer oil are shown in Fig.2. The general constant is dependent upon the type of flammable liquid, the area of the fire and the length of time for which combustion has already taken place. At rates of application above the critical, Rasbash showed that a general equation for the time to extinguish the fire could also be applied, as follows:

$$t = 5.2 \times 10^{5} \times D^{0.85} \times R^{-\frac{2}{3}} \times \Delta T^{-5/3}$$

where t = time to extinguish in s

D = mass median droplet size in mm

R = rate of application in $1/m^2$ s

ΔT = difference between water temperatures and fire points in degC

Where water is applied to depths of flammable liquids in this class which form 'hot zones' at the surface, there can be a substantial danger of the water boiling below the liquid surface and causing the flammable liquid to froth over, thus spreading the fire. For example, if fuel oil in depth burns for some 15–30 minutes a hot zone will form and this could lead to the water spray boiling. This emphasizes the need for rapid detection and extinction of the fire before the hot zone develops.

Systems for the extinction of liquids in this category are designed to give various rates of discharge and to produce a conical spray of water with an even distribution of droplets in the size range 0.4–0.8 mm travelling at a velocity sufficient to give penetration to the surface of the flammable liquid. The nozzles are arranged in groups in a common pipe system, each group being controlled by automatic controls or by an automatic deluge valve. The positioning, cone angle and rate of application of each nozzle is designed to ensure complete coverage of the fire risk area with economy of water. A range of typical high-velocity open spray nozzles is shown in Fig.3. Typical arrangements of spray systems for automatic operation are shown in Figs 4 and 5.

Figure 4 shows the type of protection installed where the risk is limited in area. The flow of water to the small group of nozzles is controlled by two thermally-operated automatic controls, so that when the fire causes the valves to open, water is discharged simultaneously from all the nozzles.

Figure 5 shows the arrangement for the protection of a larger fire area. The open spray nozzles are mounted on the empty pipework which covers the area of the entire risk. Glass bulb detectors are mounted on an independent pipe system charged with compressed air and located so that wherever a fire originates within the area, at least one bulb will be affected and will allow the air pressure in the pipe to fall. At a predetermined air pressure in the control pipe, the automatic deluge valve will open and will allow water to pass to all the water spray nozzles in the system. In the extinction of high fire point oils, water discharge densities in the range 0.16–1.2 $1/m^2$ s (0.2–1.4 gal/ft^2 min) are supplied according to the fuel and the conditions, with nozzle pressures of 2.75 bar (40 lbf/in^2) and more.

The use of water sprays for the control and extinction of fires in non water-miscible high fire point liquids, subject to reservations in regard to 'splash' fires and frothing over, is probably the widest and most successful application of this material.

EXTINCTION OF FIRES IN WATER-MISCIBLE LIQUIDS

Liquids in this category may be extinguished by diluting the surface layers with a fine spray of water until the fire point of the mixture is sufficiently high for extinction to occur. After extinction, the surface layers will contain a high percentage of water, and reignition will not be possible for some time until the lower layers of liquid have mixed with the diluted layers to lower the water concentration. When water sprays are applied to alcohols, the flame is pushed into a flat thin flame adjacent to the liquid surface. A flame-free area then forms on the surface and this increases until only a few small flames are present, burning at the edge of the vessel. It is often difficult to see when combustion has ceased due to the low luminosity of the flames. The mass median drop size of the spray should be less than 0.4 mm. Where the depth of liquid to be extinguished is large, the amount of water required for extinction is often prohibitively large, since the liquid will have to be diluted to several times its initial volume before it is rendered non-flammable. For example, while whisky may be extinguished by admixture of 1½ volumes of water per volume of whisky, the ratio for ethyl alcohol is 7:1 and for acetone it is 30:1. This will lead to difficulties of spillage if the volume of the container is not sufficient, or if the liquid cannot be tapped off from the base of the tank. Another problem is the need to reprocess the flammable liquid to remove the water after extinction.

Some liquids which are only partly miscible with water and which have a low fire point are very difficult to extinguish with water, and the fire can only be controlled. This applies to ether, methyl ethyl ketone and others. Densities of discharge of 0.12-0.30 l/m^2 s (0.15-0.35 gal/ft^2 min) are usually required for control or extinction of fires in this class of liquid, and for this purpose medium velocity spray systems operating at nozzle pressures of 1.4 bar (20 lbf/in^2) upwards are used.

EXTINCTION OF FIRES IN IMMISCIBLE LOW FIRE POINT LIQUIDS

The extinction of fires in these liquids, with fire points below 45°C, requires the direct cooling of the flame zone by heat transfer to the water droplets passing through it, with some assistance from the air entrained by the spray. It has been estimated that for a kerosene flame, about 0.7 cal/s would need to be extracted from each cubic centimetre of the flame to obtain extinction by cooling, and about 0.1 cal/s per cubic centimetre, if extinction were entirely by steam formation. Hence, water sprays can abstract between 0.1 and 1 cal/s per cubic centimetre before extinction is likely to occur, the actual value depending on the degree of vaporisation taking place.

The effect of drop size on extinction time has been examined, and varies with the liquid to be extinguished. Figure 6 shows that extinction time for liquids in this category reduces sharply with reduced mass median drop size, although if the drop size is too small the finer sprays may show the disadvantage of 'sputtering' at the liquid surface, which increases the violence of the fire during the early stages of extinction. With petrol and benzole, the spray must penetrate to the lower part of the flames, but not necessarily to the liquid itself. If it does penetrate the liquid, it does not cause sputtering as the liquid is not hot enough. It is interesting to note that in tests with alcohol, reduction of the drop size from 0.5-0.3 mm decreased the mean extinction time from 500 to 10 s, possibly because the coarser drops caused more mixing of the surface and lower layers of alcohol to occur, with a consequent delay in extinction.

In general, the ease of extinction is greatly influenced by the mode of application of the spray, the preburn time, and the conditions of burning. The mass median drop size should be about 0.3 mm, and its effect is often increased markedly by air entrainment. Increasing the rate of flow by increasing the nozzle pressure and drop velocity, will entrain more air and assist extinction. Nevertheless, the extinction of liquids in this class is often difficult with water sprays, although a useful cooling of the surroundings may be achieved. This leaves open the possibility for a combined use of water spray with, say, dry powder or vaporising liquid to complete the extinction.

Spray systems used for low fire point liquids, whether miscible or immiscible with water, utilise 'medium velocity' spray nozzles of the open or closed type (Fig.7). Variations in design give a range of orifice sizes and deflector angles to ensure the most economic combination of nozzles without wastage of water. Control of the system is usually by automatic controls or by automatic deluge valves.

WATER SPRAYS FOR USE ON FIRES IN OIL-FILLED EQUIPMENT

The use of water sprays against oil-cooled equipment such as transformers, turbo-alternators, switchgear etc., has been mentioned earlier in connection with the use of high-velocity spray nozzles on fires in immiscible flammable liquids with fire points above 45°C. A further note on the difficulties of these 'mixed' fires of hot metal and flammable liquid is appropriate. When a fire breaks out, it is usually the result of an electrical breakdown which causes an explosion, and leaves a situation in which the burning oil is being pumped by the cooling system over the outside of a complicated array of pipes and other metal surfaces, which rapidly become hot and help to sustain the fire. Early detection of such a situation is very important, as it greatly helps the subsequent extinction process if the metal has not been allowed to become hot.

In oil-filled transformers, for example, an array of sprinklers is sometimes used as a detection system, mounted on a pipe under air pressure, so that flame impinging on any sprinkler will release the pressure and allow an automatic control valve to operate and permit the flow of water under pressure to high-velocity spray nozzles. Other forms of detection may also be used. Rasbash has shown that the rate of flow of water required to control a 'mixed' fire, eg a fire in an oil-filled transformer, depends on how long the fuel burns before detection, the exposed area of the transformer, the wind conditions, etc. Sprays must be arranged in such a way that there is no possibility of flames becoming stabilised in the down-wind areas behind the pipes. The rate required may be calculated within the range 0.16-1.0 l/m^2 s (0.2-1.2 gal/ft^2 min), as illustrated in Fig.8. Under most circumstances, the 'area' used for calculation is the smallest peripheral area needed to enclose the transformer, without covering all its hidden surfaces, and the density of water distribution selected depends on the speed of detection, wind, etc. A figure of 0.4 l/m^2 s (0.5 gal/ft^2 min) is usually adequate.

PROTECTION OF EXPOSURES BY WATER SPRAYS

Water sprays find an important application in the protection of exposed oil-cooled equipment and storage tanks against a risk of fire spread from an adjacent fire. In addition to the use of high-velocity spray systems against oil-cooled equipment mentioned in the previous section, medium-velocity spray nozzle systems are used in the protection of petroleum or LPG storages.

In the protection of large storage tanks of low fire point liquids such as crude oil, refined spirit etc., a density of water coverage of 0.16 l/m^2 s (0.2 gal/ft^2 min) is recommended, Thomas and Law (1965), National Fire Protection Association Standard No.15 (1973), for the exposed surface. In practice, this is readily possible for small tanks, but the requirement becomes extremely onerous for the really large storage tanks of up to 122 m (400 ft) diameter now being brought into use. It may be argued that these are all floating-roof type tanks and not likely to explode or catch fire under exposure conditions, but fixed roof tanks are also being built up to about 60 m (200 ft) in diameter and larger sizes may be built in the future. Figure 9 shows the quantities of water needed to protect tanks of 22 m (70 ft) height and up to 92 m (300 ft) diameter, from a fire in an adjacent tank. The data is based upon the recommendation of 0.16 l/m^2 s (0.2 gal/ft^2 min) which is approximately the same as the NFPA Code No.15 recommendation of 0.25 US gal/ft^2 min, and includes the water needed to provide the foam necessary for extinction of the original fire. (Curves 'A'). The exposure requirement is far larger than the extinction requirement, and for an 80 m (260 ft) diameter tank would be of the order of 150 tonnes of water per minute. This would require approximately 1000 kW to lift and distribute it through a spray system and its associated pipework. In practice, considerable savings could be made by protecting only the roof, and that part of the walls 'seen' by the adjacent fire at the level of the ullage space, while depending on the run-off from higher levels and the heat capacity of the fuel in the tank to protect the lower level during the extinction of the initial fire. The curves 'B' relate to this condition.

An area in which knowledge is not yet exact enough is in the measurement of heat radiation from a large fire, yet this knowledge is of vital importance in deciding the water protection requirement and the tank spacing. A selection of recent published figures on the heat flux from hydrocarbon fires gives the following results extrapolated from experimental fires of various sizes:

	Btu/ft^2 h	kW/m^2
Blinov and Khudiakov (1957), Hottel (1959)	9,550	30.1
Peterson (1967) (kerosene)	10,800	31.2
Webster, Burne (1948) (petrol)	13,400	42.3
Gordon, McMillan (1965)	13–21,000	41–66.2
Duggan, Gilmour, Fisher (1943)	20,000	63.0
NFPA (1973)	20–33,000	63–104.1
Fu (1972) (kerosene)	59,000	189

The height of the flames from a tank fire must be known to calculate the radiation to adjacent tanks, but no two publications agree on the correlation between flame height and fire diameter over the range of sizes required. The effect of wind in deflecting the flames from the vertical is also likely to be a significant factor.

Until these matters can be clarified, the protection of large storage tanks against adjacent fires is bound to be a somewhat empirical study, and in consequence, there is a danger that in 'playing safe', unnecessarily large water spray installations may be called for. The matter may be made less onerous if assistance can be gained in other ways, namely by using tank surfaces of high 'wetability', or wetting agents in the water to improve the spread of water on the tank surface. A highly reflective surface may also reduce heat absorption by the exposed tank.

Another area of knowledge which would repay fresh study lies in the best way of applying the water to the surface. At the present time, protected tanks are usually fitted with an array of pipework at the ullage level which sprays onto the outer wall and roof of the tank. Apart from the difficulty that the pipework is severely exposed to flame and heat from the original fire, the flames are likely to carry away a large proportion of the spray, or evaporate it before it reaches the exposed surface of the tank to be protected. A few years ago, one oil company devised a centrally-mounted pourer on the axis of a coned roof tank so that the water poured directly onto the roof plates and ran down to the periphery of the roof and hence to the walls. The idea was not immediately successful for a number of minor reasons. First, the experimental flow rate was only a fraction of that required in practice. Second, the tank was built with lap-welded joints which faced upwards towards the apex of the cone. The plates therefore acted as a series of watersheds to break up the film on the surface into rivulets. Once the rivulets were established, the surface tension of the water on the steel surface was sufficient to prevent spread even though the rate of flow was subsequently increased. Finally, the method of water discharge at the axis of the tank was not selective enough to determine to which side of the tank the water ran - although in practice it is probable that an all-over coverage with a greater concentration on the exposed side would be the pattern likely to be required.

Corrie (internal communication) has been pointed out that the method of placing tanks in rows in each direction may not be the best from the fire aspect, and a study of tank farm layout is likely to produce safer arrangements from the point of view of exposure and bunding.

ACKNOWLEDGEMENTS

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REFERENCES

Blinov, V.I. and Khudiakov, G.N. Dokl. Acad. Nauk. SSSR, 1957, 113 1094-8.

Corrie, J.G. (Internal Communication, 1974) Fire Research Station, Borehamwood.

Duggan, J.J., Gilmour, G.H. and Fisher, P.F. Natn. Fire Prot. Ass. Q., 1943, 37 (2) 132-9.

Fu, T.T. US Department of Defence. Wright-Patterson Air Force Base Technical Report AG FS RS 72-2. 1972.

Gordon, W. and McMillan, R.D. Fire Technol., 1965, 1 (1) 52-61.

Hottel, H.C. Fire Res. Abstr. Rev., 1959, 1 (2) 41-4.

National Fire Protection Association Standard No.15. Boston, Mass., 1973.

O'Dogherty, M.J. Fire Research Technical Paper No.13. London, 1965. HM Stationery Office.

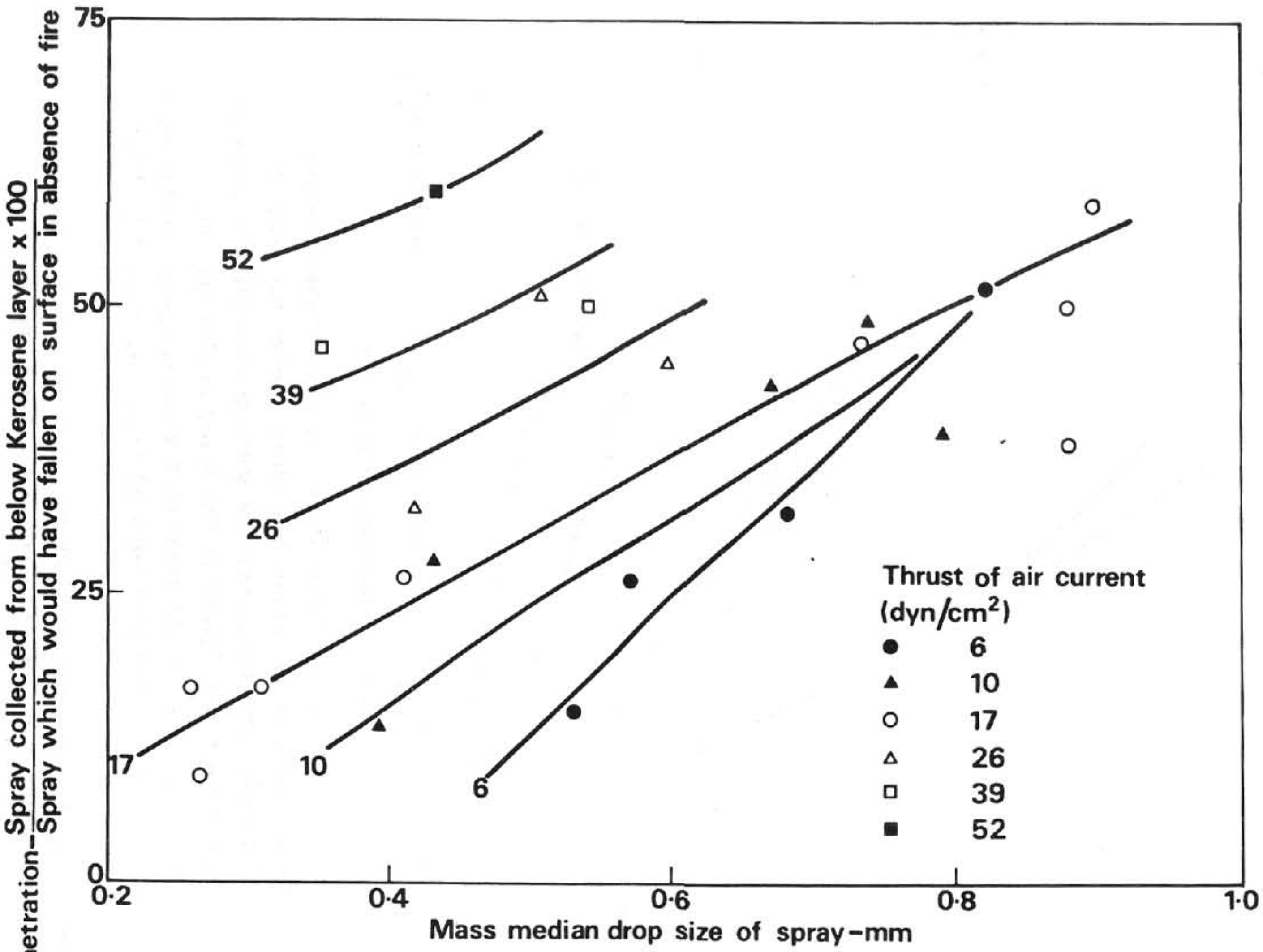
Peterson, H.B. et al. US Department of Defense, Naval Research Laboratory Report 6573. Washington, 1967.

Rasbash, D.J. and Stark, G.W.V. Instn Fire Engrs Q., 1960, 20 (37) 55-64.

Rasbash, D.J. Fire Res. Abstr. Rev., 1962, 4, (1 and 2) 28-53.

Thomas, P.H. and Law, M. Joint Fire Research Organisation Fire Research Note No.609/1965.

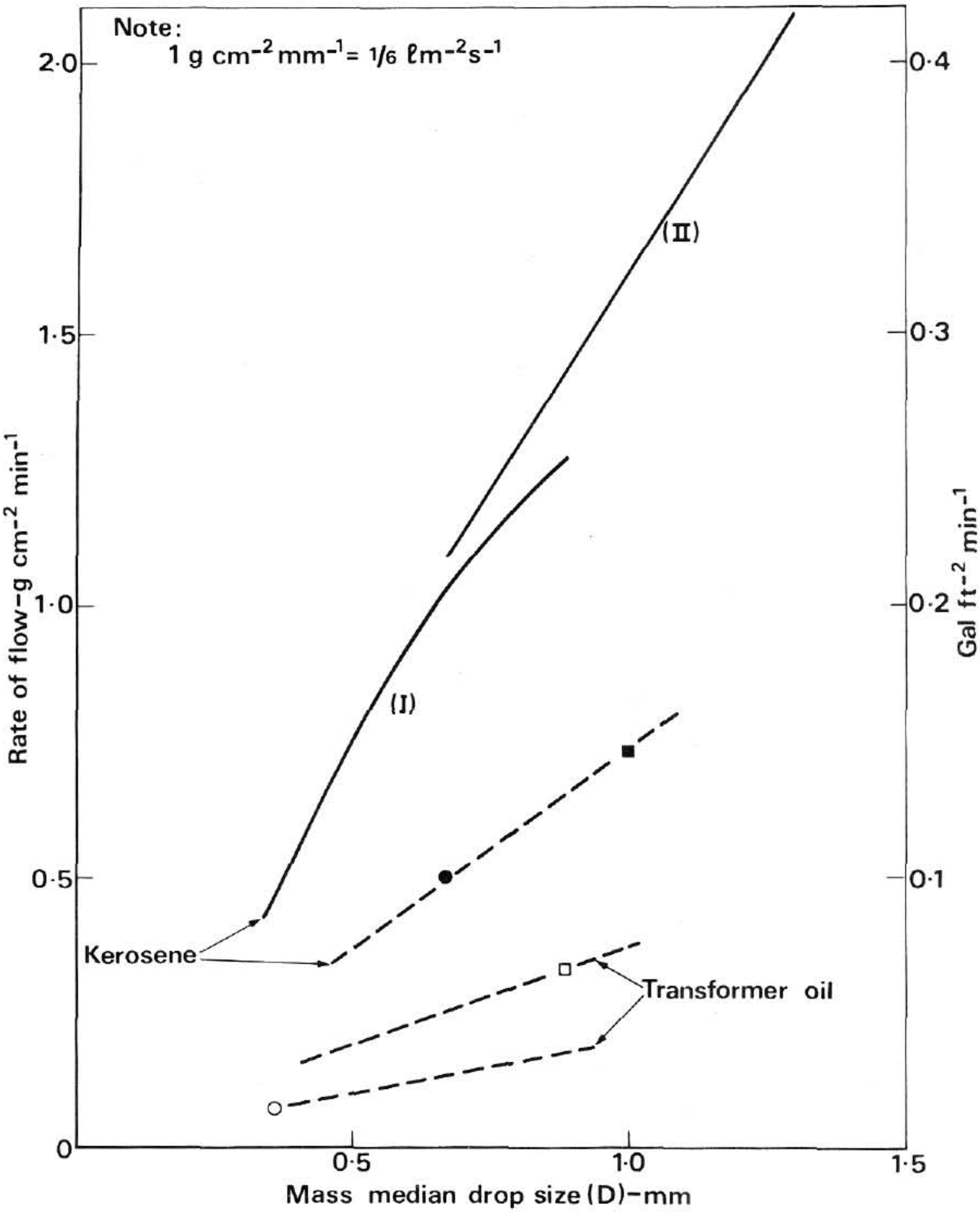
Webster, C.T. and Burne, R.V. Joint Fire Research Organisation FPE Note No.2/1948.



Kerosene fire 30 cm diameter
Downward application of spray
Pressures at spray nozzle 0·35–2·1 bar (5–30 lbf/in²)

Flow rate to fuel surface in absence of fire 0·40–1·2 g cm⁻² min⁻¹
Air current measured 30 cm above the surface

Figure 1 Effect of mass median drop size on the penetration of a water spray to flammable liquid surface



(I) 30 cm diameter Kerosene fire spray applied downwards

(II) 11 cm diameter Kerosene fire spray applied downwards

● 30 cm diameter Kerosene fire spray applied 10° to horizontal

■ 243 cm diameter Kerosene fire spray applied by hand

□ 30 cm diameter transformer oil fire spray applied downwards

○ 243 cm diameter transformer oil fire spray applied by hand

Figure 2 Effect of mass median drop size on critical rate of application for Kerosene and transformer oil

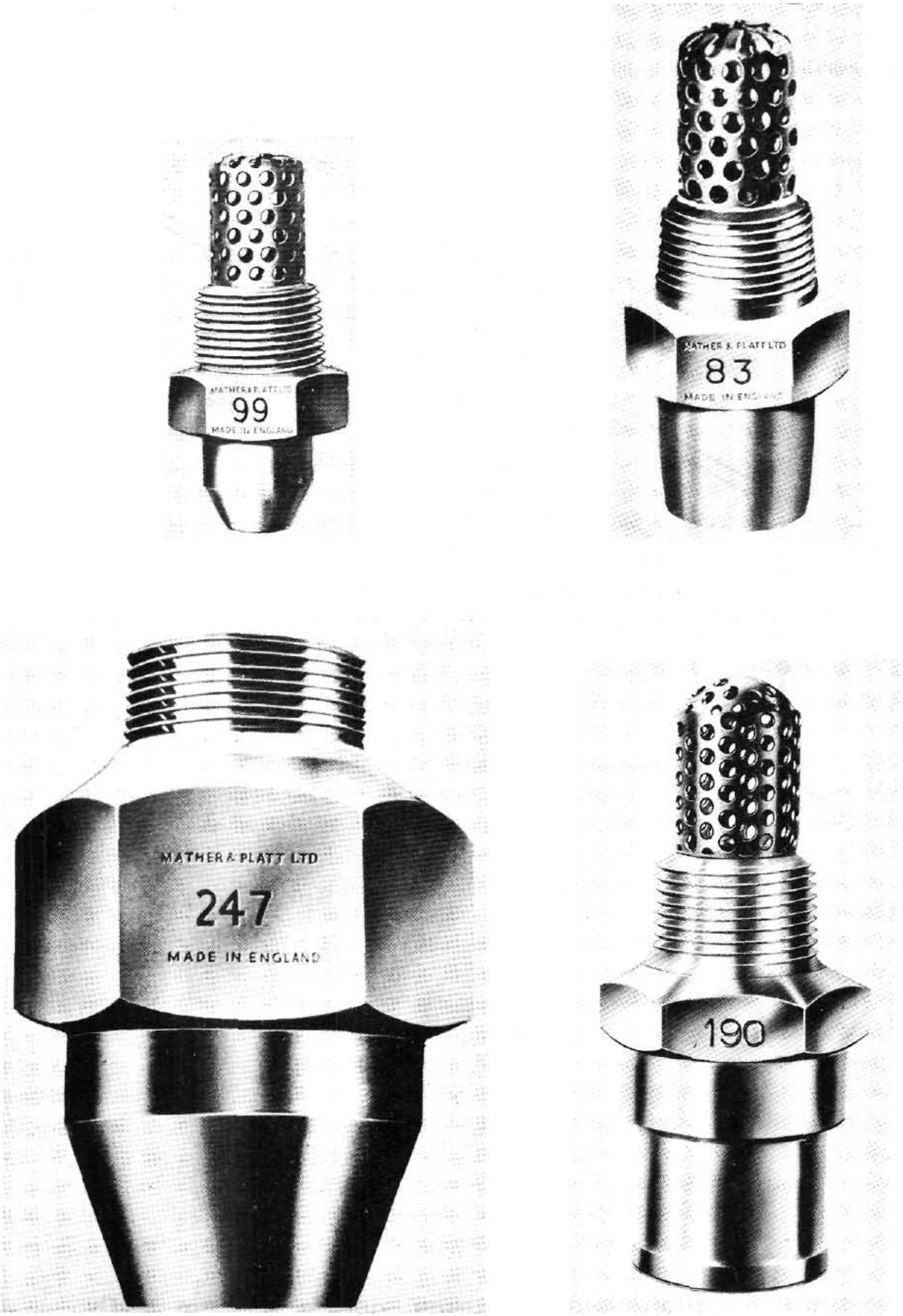


Figure 3 High–velocity open spray nozzles

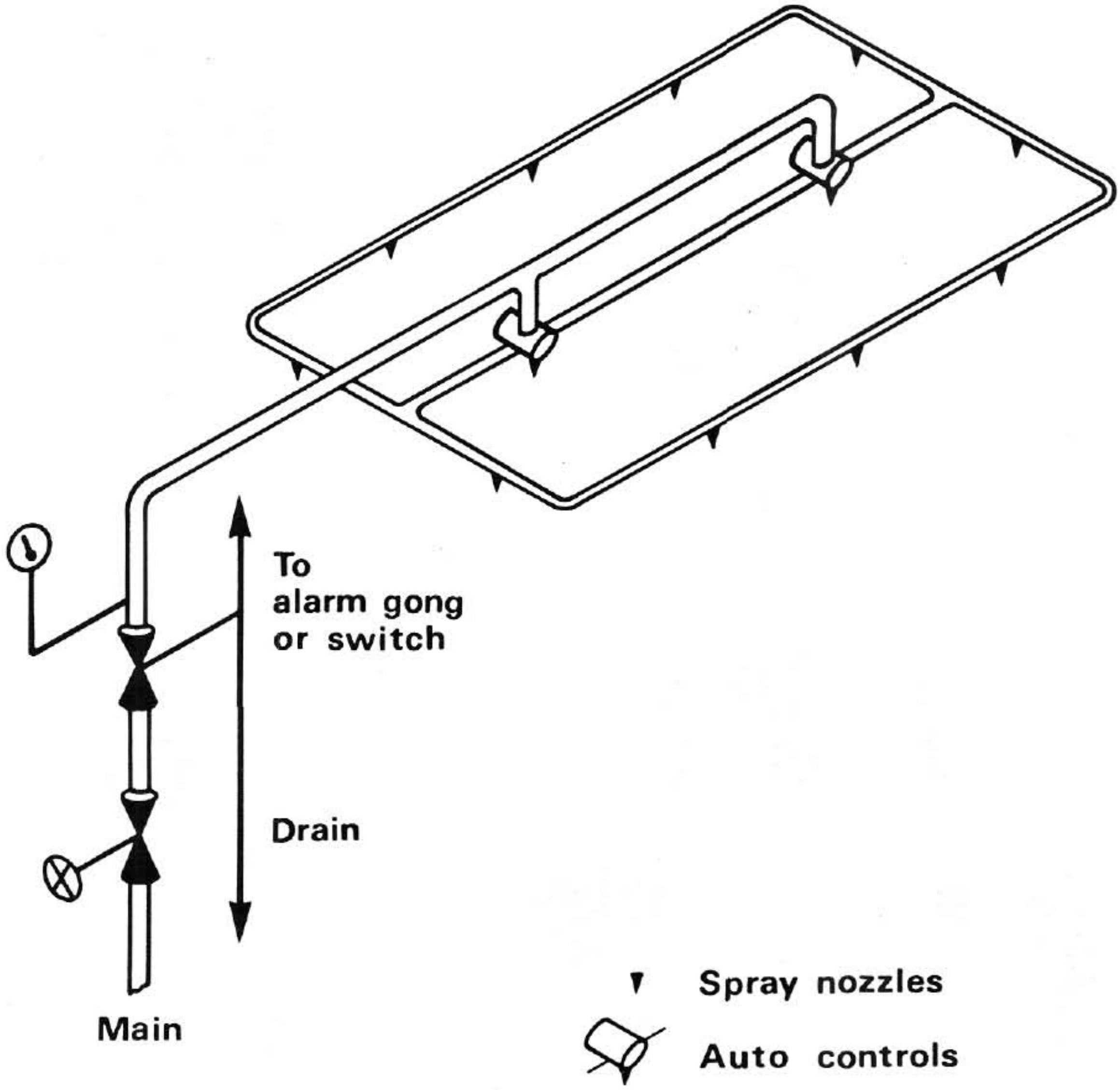


Figure 4 High-velocity spray nozzle system with automatic controls

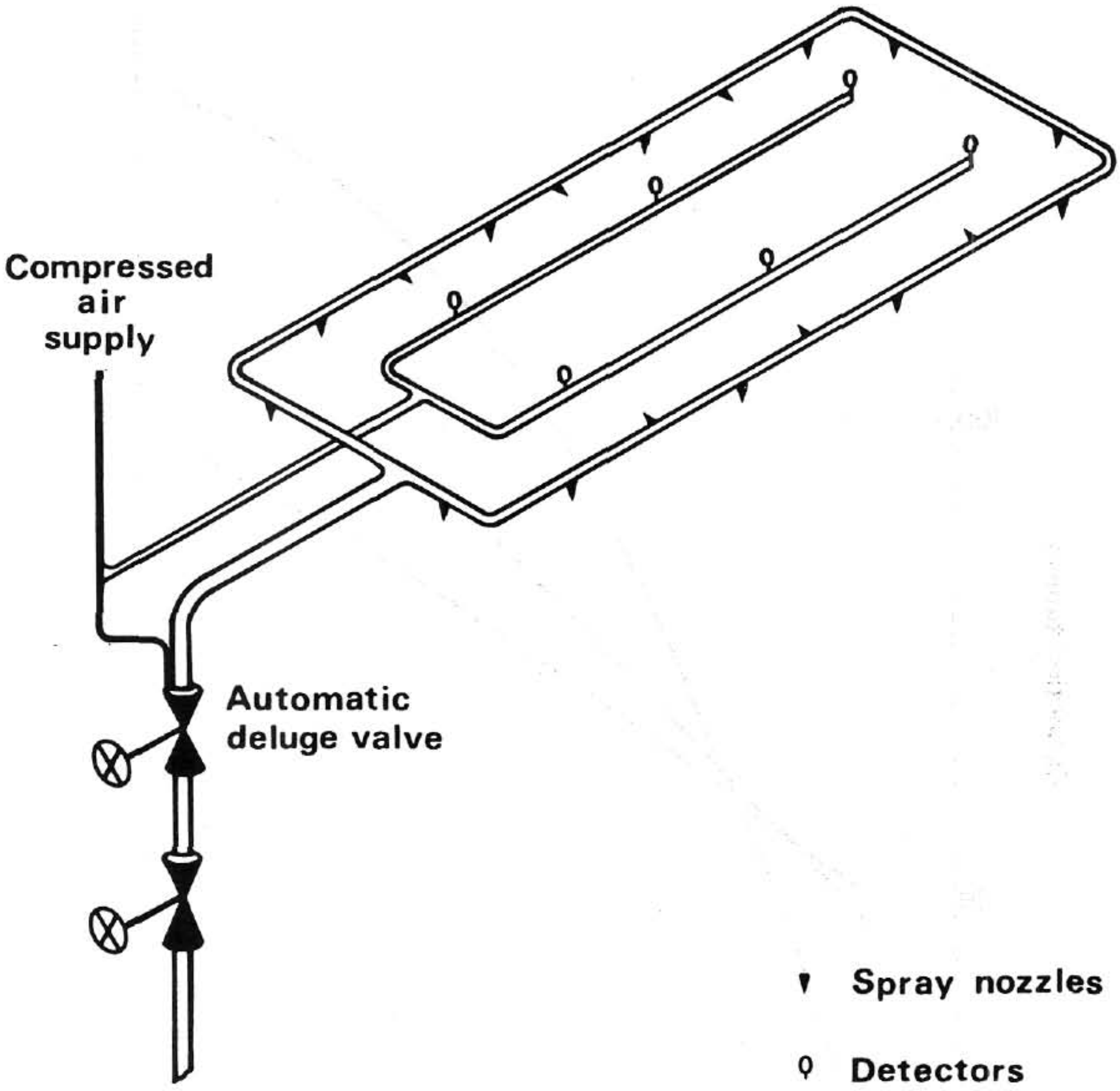
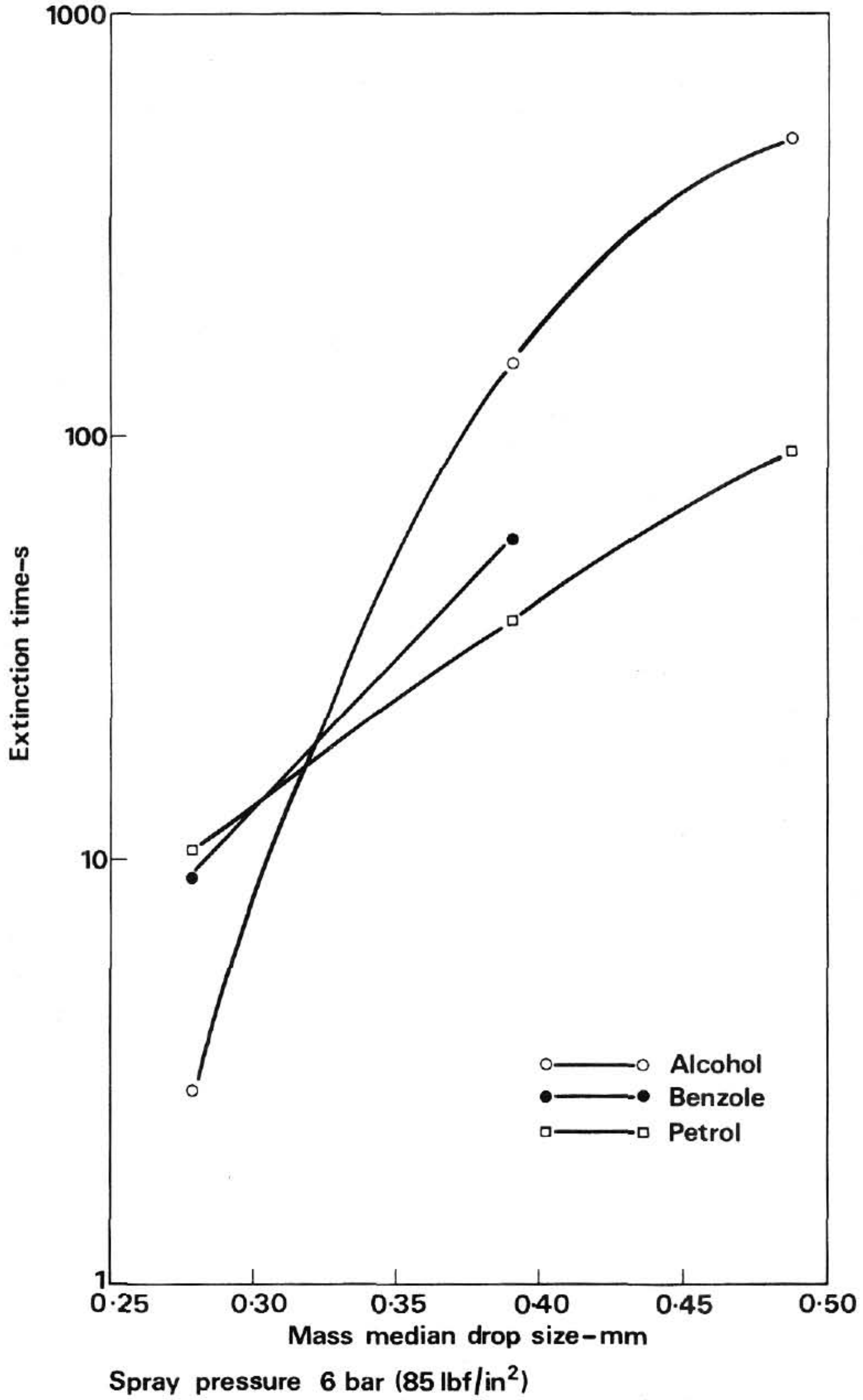
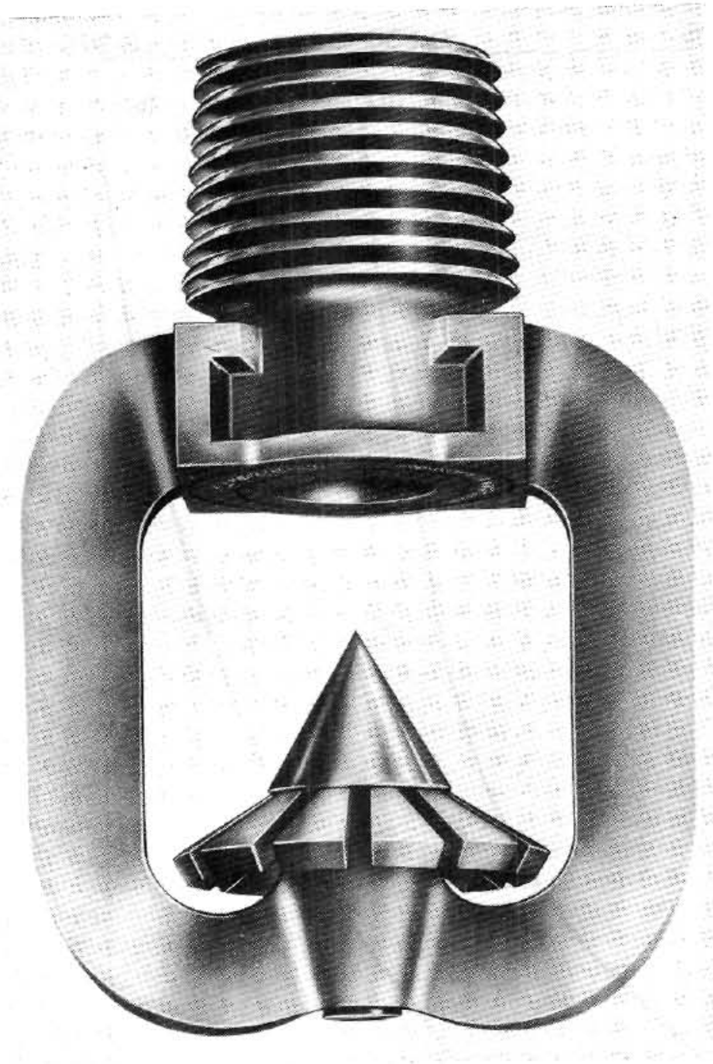


Figure 5 High-velocity spray nozzle system with automatic deluge valve



Spray pressure 6 bar (85 lbf/in^2)
Rate of flow 1·6g cm^{-2} min^{-1} (0·267 ℓ m^{-2} s^{-1})
Preburning time 2–8 min

Figure 6 Effect of mass median drop size on extinction time of volatile liquids



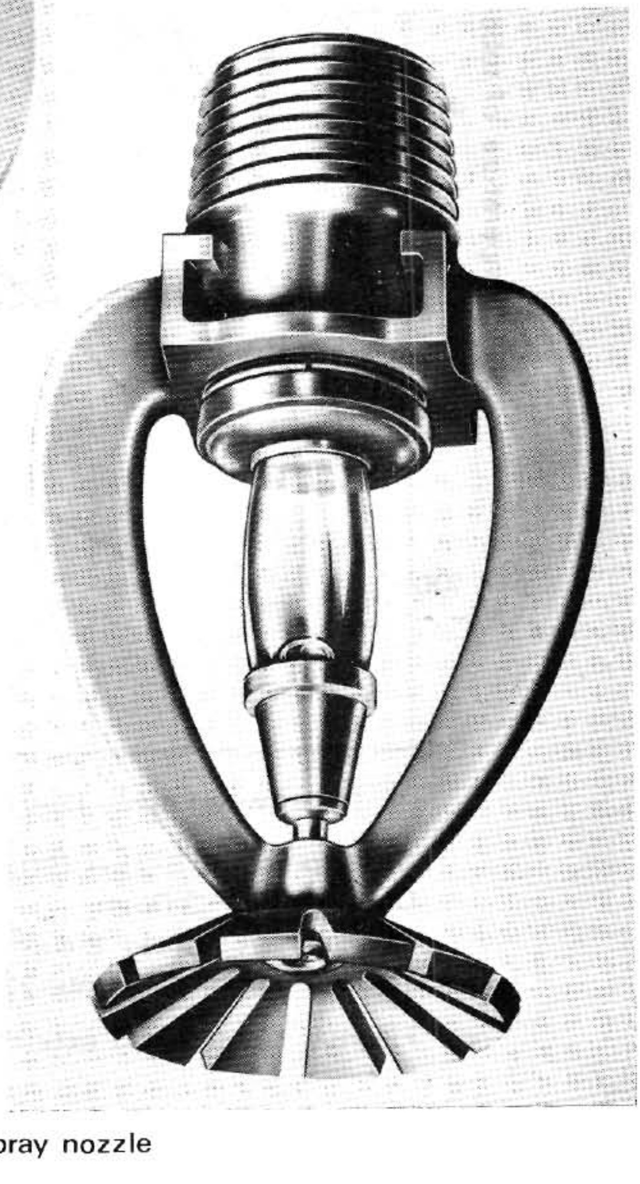
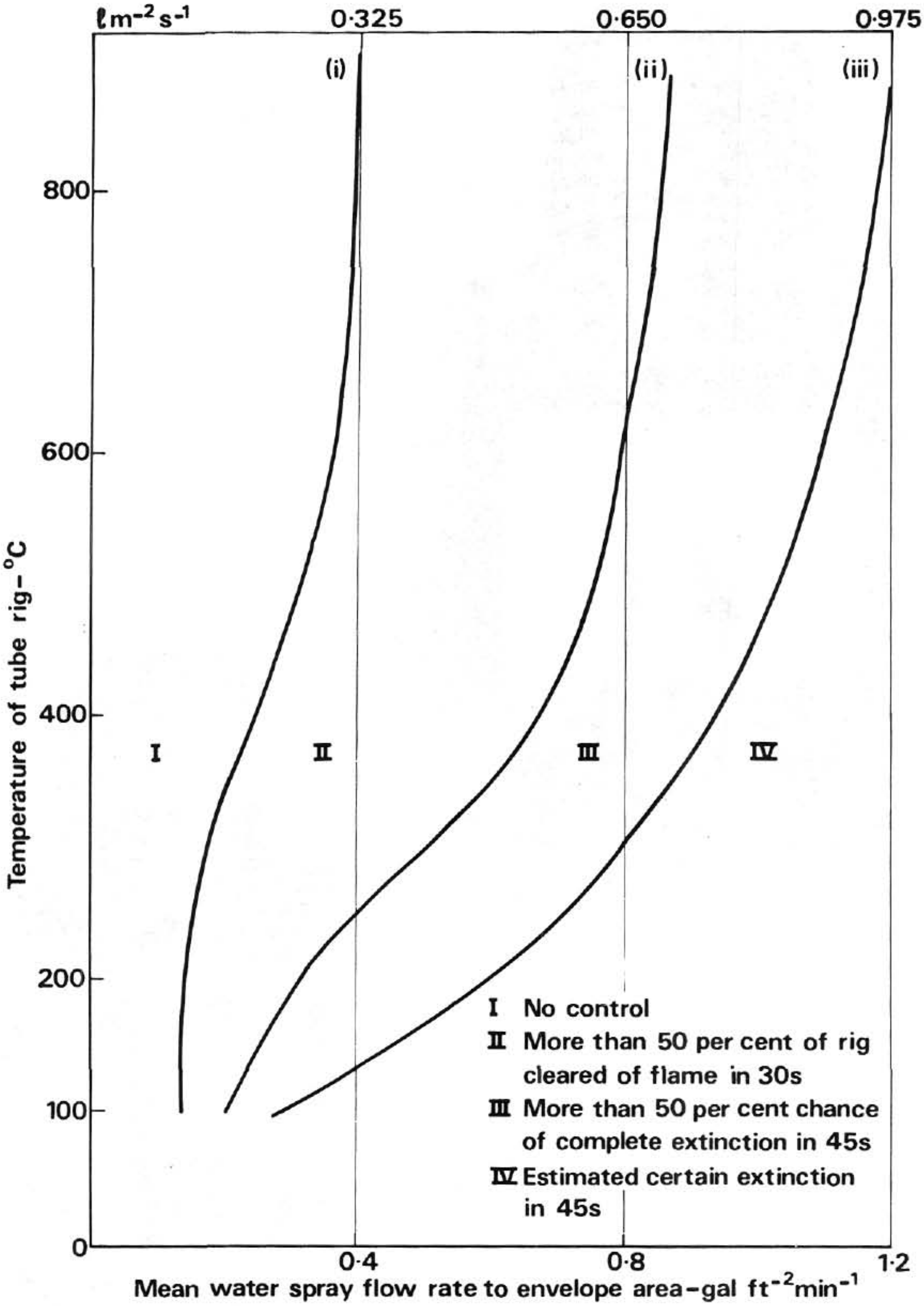


Figure 7 Medium–velocity open and sealed spray nozzle



Spray pressure 6·3 bar (90 lbf/in^2)
Drop size 0·6 – 3·0mm
Envelope area of rig 8·4 m^2 (90ft^2)
Transformer oil–flow rate 23 g ℓmm^{-1} (5·25 gal/min)

Figure 8 Control and extinction of oil fires on a transformer rig

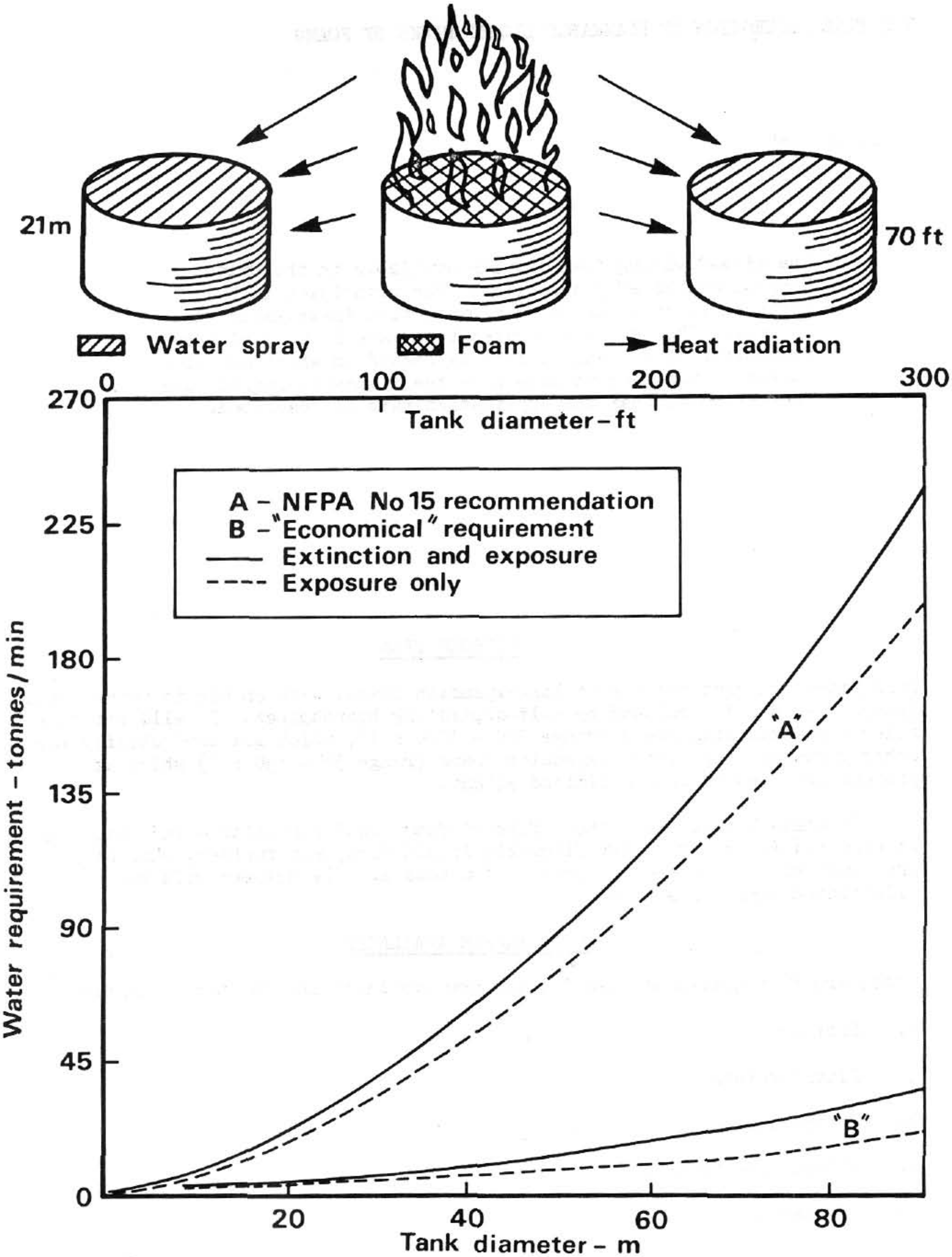


Figure 9 Water requirement for the extinction of an oil fire and the protection of an adjacent exposed tank