# The Extinction of Fires by Water Sprays

by

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## INTRODUCTION

Water spray has long been widely used for the extinction of fires in both liquid and solid fuels. Although there have been numerous ad hoc investigations on the effect of sprays from various nozzles on fires of different types, it is only in recent years that any systematic study has been made using sprays and fires with controlled and measured properties. Work of this nature has been carried out for about ten years at the Joint Fire Research Organization. In this work attention has been paid in particular to the ability of spray to penetrate to the seat of a fire, the mechanism of extinction and the properties of sprays required to extinguish fires of various types. To some extent the work has also permitted an approach to be made to defining critical heat transfer criteria for extinguishing fire. In this paper these aspects of the problem will be discussed and illustrated by experimental results obtained at the above organization and elsewhere. The results of the experiments also suggest certain broad principles on which fire fighting operations should be based, and these will be outlined.

## PENETRATION OF SPRAY TO THE SEAT OF A FIRE

In order for a spray to be able to exert a useful effect on a fire it is usually necessary for the spray to be able to penetrate to the seat of the fire, particularly to the burning fuel. To do this the spray must be either formed near the fuel or it must have sufficient forward force to prevent too much of the spray being either deflected by or evaporated in the flame and hot gases associated with the fire.

The factors which control the penetration of spray to the seat of a fire are the drop size and thrust of the spray, the thrusts of the flames and wind, gravity and the evaporation of spray in the flames. When sprays are applied to fires by hand the effects of the thrust of the flames and the wind, and the evaporation of spray in the flames are usually minimized by applying the spray directly through the base of the flames to the fuel from the upwind side of the fire; the reach of the spray, which is determined mainly by gravity and the forward thrust of the spray, usually controls the penetration to the seat of the fire under these conditions. When spray is applied downward to a fire all the above factors are of importance but particularly the relative thrusts of the spray and the flames. Little information is available from the literature on either of these two factors but work carried out at the Joint Fire Research Organization indicates that they may be estimated from readily measured properties of the spray and the flame. The thrust within a spray is a function of the reaction at the nozzle and the width of the spray; there is also evidence that at some distance from the nozzle it is approximately equal to the thrust of the entrained air current. The latter depends on the flow rate of spray per unit area and the pressure at the nozzles. The thrust of flames is proportional to the buoyancy head. Further information on these relationships is given in the appendix.

Experimental information on the penetration of sprays to burning fuel is available for fires in kerosine burning in a 30 cm diameter vessel using downward application of spray(1). The results were scattered mainly because the penetration was very sensitive to the pattern of the spray at the fire area, a factor which was very difficult to control experimentally. Broadly, however, the penetration decreased as the pattern of the spray became more peaked in the centre of the vessel and as the thrust and the drop size of the spray decreased. The effect of the latter two factors are illustrated in fig. 1 which refers to sprays in which the peak of the spray distribution was contained in the central half of the vessel but in which not more than one fourth of the area of the vessel was covered by a flow rate less than one half of the peak value. In spite of the scatter of the points, the effect of spray thrust, as calculated from the entrained air current, and the drop size on the penetration is clearly seen. There is, however, an indication that at drop sizes greater than about 0.8 mm the penetration was independent of the thrust. If the peak was outside the central area of the vessel the penetration was usually considerably greater.

In the tests referred to in fig. 1 the height of the flame as judged visually was 150 cm before the applioation of spray and was reduced to mean values between 80 and 140 cm during the application of the spray. These heights correspond to upward flame thrusts of 34 and 18 - 30 dynes/cm$^2$ (see appendix). It will be seen from fig. 1 that the thrusts of the spray required to give a 50 per cent penetration for the finer sprays is comparable to these values.

It was observed during the tests that as the thrust of the spray was increased above 20 dynes/cm$^2$ the flames became increasingly unstable. Sprays with higher thrusts than represented in fig. 1 often caused stabilization of the flame as a relatively flat flame above the vessel after a period of instability. The minimum spray thrust at which this phenomenon occurred was 77 dynes/cm$^2$. It would be expected that under these conditions the bulk of the spray, even if it were fine and of a peaked pattern at the fire area, would penetrate to the burning fuel; this might also be inferred by extrapolation of the results in fig. 1. This critical thrust, $T_c$ might be related to x, the height of the flames as judged visually prior to the application of spray, by equation 1.

$$T_c = 0.5 \rho_c g x \qquad \text{......(1)}$$

$\rho_c$ = density of air, g = acceleration due to gravity.

It would be expected that since equation 1 represents the thrust in the air current of the spray required to overcome the buoyancy head of the flames, $T_c$ should scale with flame height for larger sizes of fire than the fire tested.

For a given flow rate of spray in the absence of fire, and for a given pressure, the thrust of the spray in these experiments was approximately independent of the drop size. Therefore, as the drop size decreased the penetration decreased. However, as the drop size decreased the efficiency of unit mass of spray in reducing the rate of burning increased since the finer spray cooled the liquid more efficiently. As a result of these two phenomena a drop size occurred at which there was a minimum rate of burning for a given flow rate and pressure. This drop size depended on the spray thrust, and decreased from 0.8 to 0.33 mm as the thrust increased from 6 to 26 dynes/cm$^2$.

## MECHANISM OF EXTINCTION

There are two main ways of extinguishing a fire with water spray: (1) cooling the burning fuel and (2) cooling the flame. The mechanism of smothering the flame with steam is one aspect of cooling the flame and will be dealt with under that heading.

### Cooling the fuel

To reduce the temperature of the fuel the spray must be capable of abstracting heat from the fuel at a rate greater than the rate at which the fuel will take up sensible heat. Heat will normally reach the fuel by heat transfer from neighbouring hot bodies and from the flame. Information on heat transfer from bodies may be obtained from texts on heat transfer although there are many important cases, for example, on the flow of films of fluid over hot surfaces where information is lacking. There is evidence, which will be given later, that radiation from the flame to the fuel that is being cooled does not normally play a large part in determining critical conditions for extinction, although if only a part of the fire is being extinguished at any one time, radiation from the rest of the flames might become an important factor. In this paper, therefore, particular attention will be paid to estimating critical conditions when the surface receives heat mainly by convective or conductive transfer from the flame. Such estimates may be obtained from known relationships between the rate of burning and the heat transferred from the flame to the surface. The method used may be best illustrated by an example. Equation 2 was found by Spalding to give the rate of burning of liquid fires flowing over surfaces with a vertical dimension (d)[7]

$$\dot{m}'' = \frac{0.45k}{dc} B^{\frac{3}{4}} \sqrt[4]{\frac{gd^3}{\alpha^2}} \qquad \text{......(2)}$$

where $\dot{m}''$ is the average rate of vaporization per unit surface area,
- d is the linear dimension of the surface,
- k, c $\alpha$ are thermal conductivity, specific heat and thermal diffusivity of air at room temperature,
- g is the acceleration due to gravity,
- B is a transfer number equal to $\dfrac{m_{O_2} H/r + c(T_g - T_s)}{Q}$

where Q is the heat transfer to the fuel surface per unit mass of fuel vaporized,
- $m_{O_2}$ is the concentration of oxygen in air (by weight),
- H is the heat of combustion of the fuel,
- $T_g$ is the ambient gas temperature and $T_s$ the surface temperature,
- r is the stoichiometric ratio (weight of oxygen/weight of fuel).

Normally, under steady conditions, the value of Q in the transfer number is equal to $\lambda_f$ the heat required to vaporize unit mass of fuel. However, when a spray is acting on the fuel and heat is being removed from the fuel, Q will be greater than $\lambda_f$.

For most liquid hydrocarbons equation 2 may be reduced with little error to

$$\dot{m}'' = \frac{0.17}{d^{0.25}\,Q^{0.75}} \qquad \text{......(3)}$$

($\dot{m}''$ in g cm$^{-2}$s$^{-1}$; d in cm; Q in cal/g.)

The rate at which heat reaches unit area of the burning liquid from the flame is $Q\dot{m}''$; the rate at which heat needs to be transferred to vaporize the fuel is $\lambda_f \dot{m}''$. Therefore, a steady condition as expressed in equation 3 will be maintained if the spray removes from the liquid a quantity of heat $\gamma$ given by

$$\gamma = (Q - \lambda_f)\,\dot{m}'' \qquad \text{......(4)}$$

Combining equations 3 and 4 gives either

$$\gamma = \frac{0.17}{d^{0.25}\;Q^{0.75}}\,(Q - \lambda_f) \qquad \text{......(5)}$$

or

$$\gamma = \left(\left(\frac{0.17}{d^{0.25}\;\dot{m}''}\right)^{4/3} - \lambda_f\right)\dot{m}'' \qquad \text{......(6)}$$

If the spray is capable of removing heat at a greater rate than $\gamma$ the temperature of the fuel will be reduced. This will result in a smaller value of $\dot{m}''$ and a correspondingly larger value of Q and $\gamma$. The reduction in temperature will also bring about a reduction in the rate at which spray can remove heat from the fuel.

In a burning fuel in which the temperature of the fuel has reached steady conditions, $Q = \lambda_f$ and $\gamma = 0$. The application of spray with a lower temperature than the fuel will therefore result in the fuel being cooled. This will continue until either a steady burning condition is established at a particular temperature or one of the two following critical conditions for extinction is reached.

(1) The value of Q may reach the maximum value, $Q_c$ which the flame is capable of imparting to the surface without becoming extinguished.

(2) The value of $\dot{m}''$ may reach a minimum value, $\dot{m}_c''$ below which a flame cannot continue to exist above the surface.

The rate $\gamma$ at which the spray must abstract heat from the fuel at the particular fuel temperature at which these critical conditions occur will be given by one of the equations (5) and (6), and if $Q_c$ and $\dot{m}_c''$ are assumed independent of the linear dimension of the burning surface, then $\gamma_c$ will be expected to decrease slowly as this dimension increases.

By a similar argument to that developed above it is possible to put forward equations giving $\gamma_c$ for a wide range of conditions, indeed for all conditions for which there is a known relationship between the Nusselt number for heat transfer from a gas and other relevant dimensionless groups, e.g. the Reynolds, Grashof and Prandtl numbers. By these means it may be shown that above a certain dimension of the surface $\gamma_c$ will cease to decrease with increase in d, and if the wind is sufficiently strong $\gamma_c$ will be proportional to the square root of the wind velocity and inversely proportional to the square root of d.

A certain amount of information is available for the critical value of Q. Thus for flame quenching in channels(3) and in flame arresters(4) it has been found that for stoichiometric hydrocarbon flames the maximum amount of heat a flame can impart to a surface before it is extinguished is 23 per cent of the heat of combustion of the fuel, i.e. about 2,500 cal/g. Spalding(2) carried out experiments on the circulation of kerosine burning on the surface of a sphere and here again it was found that the fire was extinguished when the heat transferred to the burning surface by the flame was 2,500 cal/g of fuel vaporized. Spalding's experiment is analogous to extinguishing a fire by cooling with water spray, the only difference being that heat was removed by excess fuel rather than by water spray. It would be expected that the conditions under which the maximum fraction of the heat of combustion can reach the surface of the burning fuel would occur when a stoichiometric mixture burns very close to the liquid surface. The temperature of the surface should therefore be near to the value corresponding to equilibrium with a stoichiometric mixture. For kerosine this temperature is 15°C higher than the temperature at which the surface is in equilibrium with the lower limit mixture and is approximately equal to the fire point.

Using 2,500 cal/g as the value for $Q_c$ the following values for $\gamma_c$ may be calculated for fires burning under conditions of natural convection.

| | | |
|---|---|---|
| Pool or spill fires | $\gamma_c = 0.6/d^{0.25}$ | ......(7) |
| Fires on tubes | $\gamma_c = 1.2/d^{0.25}$ | ......(8) |
| Fires on vertical surfaces | $= 1.2/l^{0.25}$ $l < 100$ cm | ......(9) |
| | $= 0.4$ for $l > 100$ cm | .....(10) |

$\gamma_c$ is in cal/cm$^2$s; d, $l$ characteristic dimension in cm.

There is little information on the minimum value of m" below which a flame will not be sustained. It might be postulated that $m_c''$ should be not less than the value required to sustain a lower limit flame at its appropriate burning velocity over the whole surface; this would give $m_c''$ equal to about $1.5 \times 10^{-4}$ g/cm$^2$s for fires in hydrocarbon liquids. On the other hand experiments on the extraction of heat from laminar propane-air flames(5) indicate that a stoichiometric mixture may continue to burn close to a surface to which it is imparting heat at a rate similar to $Q_c$ when the combustion rate is as low as $2.6 \times 10^{-4}$ g/cm$^2$s. The above figures for $m_c''$ are about one-tenth of the rate of combustion of pool fires under steady conditions; they imply that $\gamma_c$ may depend on critical rate of vaporisation when the dimension of the fire is greater than 30 cm, for fires burning in a natural draught.

The analysis so far has dealt only with burning liquids. There are difficulties in applying a similar analysis to wood. The main difficulty as far as the extinction of flaming combustion is concerned is that the heat required to produce unit mass of volatiles is not known. The slow decomposition of wood is an endothermic process, i.e. $\lambda_f$ is negative, but Klason(6) showed that as the rate of decomposition increases the process changes from being exothermic to endothermic. There is evidence that for the rates of decomposition required to sustain a flame over a wood surface, the decomposition is indeed highly endothermic. For the extinction of glowing combustion the analysis would have to be modified to take into account the loss of heat from the surface by radiation and the effect of surface temperature on the combustion rate.

The above considerations are concerned with the rate at which heat must be removed from the fuel in order that the fire may be extinguished by cooling the fuel. The ability of the spray to remove this heat will depend on the properties of the spray and the fuel; this aspect of the problem will be referred to when experimental results are discussed.

Extinction of the flame

The criterion of extinction of a flame by heat abstraction inside the flame is that the combustion products as they leave the reaction zone should not exceed the temperature they would have for lower limit flames; this temperature is about 1580°K for a wide range of flammable vapours and gases. A decrease in temperature approximately to this value is obtained when extinction is obtained by adding nitrogen, water vapour, carbon dioxide or inert dust to flames in stoichiometric mixtures.

The amount of heat which it is necessary to remove from the flame to accomplish this is the difference in heat of combustion of stoichiometric and lower limit mixtures. For most flammable organic compounds and probably also for the volatiles from some common dry woods this is about 45 per cent of the heat of combustion of the fuel. Since with diffusion flames it would be expected that there would be a zone between the fuel and the atmosphere where the stoichiometric mixture occurs, the heat which has to be removed from the flame as a whole is 45 per cent of the heat of combustion of the fuel. It is important, however, that this heat be removed either from the reactants or the reaction zone. If the heat is removed from the combustion products the heat removal will not substantially affect the temperature of the products leaving the reaction zone. In a turbulent diffusion flame it is very difficult to differentiate between the reactants, the reaction zone and the combustion products. However, it would be expected that if a spray is capable of removing all the heat of combustion from the flame, then the flame will be extinguished.

It is interesting to note that the heat removal required to extinguish the flame by cooling the flame is twice as great as the heat which an extended surface on the reactant side of the flame may abstract from the flame before the flame is extinguished. This might be explained by a different balance of heat release and heat loss rates for a vitiated flammable mixture and a stoichiometric flammable mixture close to an extended surface[8]. Owing to the intractability of defining the position and properties of the reaction zone in a turbulent diffusion flame the approach to estimating critical conditions for extinction of the flame by water spray has been made on the basis of heat transfer taking place within the whole flame. If V is the volume of the flame, Z the mass rate of burning and H the heat of combustion of the fuel, then I, the mean rate of the heat production per unit volume of flame, assuming complete combustion of the fuel, is $\frac{ZH}{V}$. If the capacity for heat transfer of the spray within the flame is defined as X, the rate of heat transfer per unit volume of flame to the spray, then three critical criteria for X may be put forward.

(1) Removal of all the heat in the flame neglecting the production of steam as a result of heat transfer to the spray

$$X_1 = I \qquad .....(11)$$

(2) Removal of heat only from the reaction zone and the reactants, but also neglecting steam formation

$$X_2 = 0.45\ I \qquad .....(12)$$

(3) Removal of heat only from the reaction zone and the reactants, but assuming that all the heat transfer for the drops result in steam formation. This will only be the case if the drops enter the flame at the wet bulb temperature (about 75°C). It may be assumed that the steam formed will contribute to the cooling of the flame a quantity $\beta$ per unit mass of steam equal to the whole of the sensible heat of steam from 370–1580°K. The ratio of $\beta$ to $\lambda$, the latent heat of steam, is 1.23. This gives

$$X_3 = \frac{\lambda}{\beta + \lambda}\ 0.45\ I = 0.195\ I \qquad .....(13)$$

A fourth criterion may also be put forward if steam is formed outside the flame either at the burning surface or at surrounding hot bodies. Under these conditions the latent heat of vaporization does not contribute to cooling the flame but the sensible heat of steam up to 1580°K does. If the steam is formed at or sufficiently near to the burning surface to accompany the reactants into the flame then the critical flow rate, W, of water required would be

$$W = 0.45 \frac{ZH}{\beta} \qquad .....(14)$$

If the steam is formed well away from the burning surface and is heated by the combustion products, then W may rise to values equal to $\frac{ZH}{\beta}$.

The quantity I in equations (11) - (13) is an intensity of combustion and depends on the conditions of combustion, particularly the air current in which the flame is burning. For petrol, kerosine, benzole and alcohol fires 30 cm diameter burning under conditions of natural draught, I was found to be independent of the fuel or the rate of burning and equal to 0.45 to 0.50 cal $cm^{-3}s^{-1}$ (9).

The entrained air current in a spray not only affects the intensity of combustion but also affects the critical heat transfer rate required to extinguish flame. There is very little information to allow the assessment of this factor on a quantitative basis, but an indication of what might be expected may be obtained from work on the blow out of flame at obstacles. For example, if the assumption is made that the fundamental burning velocity of the flame decreases in proportion to the heat transfer capacity of the spray, then on the basis of relationships between the blow out velocity and the fundamental burning velocity(10) it may be expected that

$$V_{BO} = 93 - bX^{1.5 \text{ to } 2} d^{0.5 \text{ to } 1} \qquad .....(15)$$

Where $V_{BO}$ is the velocity of the entrained air current that will cause a blow out when the spray has a flame heat transfer capacity X , d is a characteristic dimension of the system and $a_3$ and b are constants.

It is of interest to compare critical heat transfer rates for extinction by cooling the flame and cooling the fuel. It follows from equations (11) to (14) that the critical heat transfer rate for cooling the flame is greater than 20 per cent of the total heat of combustion of the fire. Equation (4) and subsequent remarks indicate that for cooling the fuel the critical heat transfer is less than 25 per cent of the much smaller rate of combustion that would occur under critical conditions. On this basis much lower critical flow rates would be expected for extinguishing the fire by cooling the fuel than by cooling the flame. As opposed to this, however, it is feasible that unit mass of water can, under critical conditions, be the sink of a much greater amount of heat from the flame (about 1300 cal/g) than it can from a solid or liquid fuel (45 cal/g for kerosine and 750 cal/g for wood).

## EXPERIMENTAL INVESTIGATIONS ON THE EXTINCTION OF FIRE

In order to examine the relevance of the above analyses of extinction mechanism, experimental investigations have been divided into two groups covering investigations in which there is substantial evidence that extinction was by cooling the fuel and the flame respectively. For investigations on the extinction of fires in rooms, however, there has not usually been sufficient evidence to decide on the mechanism of extinction and these investigations will be dealt with separately.

Cooling the fuel

Critical flow rate of spray for extinction of pool fires. Evidence has been obtained from experiments with ppol fires that the critical heat transfer rate for extinction of the fire by cooling the fuel is controlled mainly by convection from the flame to the liquid rather than by radiation from the flame. This evidence may be summarised briefly as follows:

(1) With sprays at less than the critical rate a steady fire condition could be established with a temperature near the liquid surface not greatly in excess of the fire point, with a flame size very much less than the size of the flame if no spray were applied, and with the flame reaching down to the surface of the liquid[1]. In these fires the predominant mechanism of heat transfer to the fuel surface was by convection.

(2) The effect of scale on the critical flow rate was as may be expected if convection controlled the critical heat transfer rate rather than radiation.

The reason for the above phenomenon is that when radiation is the predominant mechanism of heat transfer from the flame to the surface, the bulk of the heat reaching the surface is taken up as latent and sensible heat of the vapour leaving the surface and does not manifest itself as sensible heat in the remaining fuel. There is thus little resistance to the cooling of the fuel by water spray. The temperature of the surface is also much higher than the fire point and the capacity of the water spray for taking up heat is correspondingly much greater. Fig. 2 shows critical rates to extinguish kerosine and transformer oil fires by cooling the fuel plotted against the mass median drop size for fires burning in vessels 11, 30 and 243 cm diameter. The curves for the 30 and 11 cm diameter kerosine fires were obtained by extrapolating to the fire point relationships between the flow rate of spray reaching the fuel and the resulting steady temperature near the fuel surface, for sprays of different drop size; the spray was applied in a downward direction[11]. The curves obtained separate tests in which extinction took place by cooling from tests in which no extinction occurred. Although for both fires the critical rate was approximately proportional to the drop size, for a given drop size the rate was slightly less for the 30 cm diameter fire than for the 11 cm diameter fire. If radiation controlled the critical heat transfer rate, the critical flow rate for extinction would be expected to be 100 per cent greater for the 30 cm diameter fire but if convection controlled about 15 per cent smaller. The difference between the points for tests with horizontal application of spray to a kerosine fire 30 cm diameter and for hand application of spray to a fire 243 cm diameter may be accounted for by the different drop sizes of the spray. If radiation controlled the critical heat transfer rate, a ratio of 2.5 would be expected in the critical rate. After taking into account the probable effect of drop size there was in fact no difference in the critical rates. However, the critical rate for horizontal application for the 30 cm diameter fire was about half that for vertically downward application. A possible reason for this difference is that the spray pushed the flame sideways; as a result the drops did not become heated in the flame and have a greater cooling capacity when they reached the liquid.

The effect of radiation is likely to be much greater with pool fires in which the burning surface can "see" all the flame than with other fires. Since radiation from the flame of the fuel being extinguished has a minor effect on the critical rates for extinguishing pool fires by cooling, it is reasonable to neglect it for other fires.

The effect of drop size on the critical rate follows from the fact that the drops are in the liquid for only a limited time and their size is a controlling factor in the rate at which heat is transferred. It would be expected(11) that the heat transfer from the body of the liquid to the drops would be proportional to $D^{-4/3}$. However, the transfer of heat from the surface of the liquid to the interior would be expected to increase as the eddy conductivity caused by the turbulent eddies set up by the motion of the drops on the liquid; this is estimated to increase as $D^{+1/3}$. The actual effect of drop size results from a combination of these two factors.

The driving force for heat transfer in the liquid may be represented by $\Delta T$, the difference in temperature between the surface of the liquid under critical conditions (for practical purposes the fire point) and the temperature of the drops (for practical purposes ambient temperature). It would, therefore, be expected that for a given drop size the critical rate should be inversely proportional to $\Delta T$. Measurements of critical rate indicated in fig. 2 for downward application of spray to a transformer oil fire 30 cm diameter and hand application of spray to a fire 243 cm diameter support this.

Extinction time for pool fires. As long as the flow rate of spray is greater than the critical value, then extinction will take place in a time which depends on the amount of heat present in the burning fuel which must be removed by the spray to reduce the surface temperature to the fire point. With most pool fires this heat content increases as the preburn time increases up to about 10-20 minutes but for hot zone forming liquids, e.g. heavy fuel oils, this heat content may increase indefinitely. Experiments (12)(13) on extinction of pool fires using fixed nozzles sited vertically above the burning liquid (see plate 1) and for hand extinction of an 8 ft diameter fire (plate 2) gave the following relationships.

Fixed nozzle

$$t = 6,800\ (D/M)(Y/\Delta T^{1.75}) \quad \text{.....(16)}$$

Hand application for 8 ft diameter vessel

$$t = 121,600\ D^{0.85}\ F_1^{-0.68}\ Y^{0.39}\Delta T^{-1.67}\ L^{-0.33} \quad \text{.....(17)}$$

where D is the mass median drop size of the spray in mm
M is the flow rate of spray in gallons $ft^{-2}min^{-1}$
Y is the preburn time in minutes
$\Delta T$ is the difference between fire point and ambient temperature °C.
$F_1$ is the total flow to the fire in gallon/min.
L is the total number of tests carried out by the operator
t is the extinction time, sec.

The influence of drop size and of flow rate of spray are as may be expected from considerations of heat transfer between the liquid and the drops. The influence of $\Delta T$, however, is greater than may be expected from a heat transfer basis alone. A reason for this may be that the higher the value of $\Delta T$ the greater was the temperature of the surface of the liquid in excess of 100°C, particularly when application of water spray commenced, and the greater was the steam formation in the liquid during the extinction process. This steam probably accelerated the cooling of the liquid surface by stirring the

* "gallon" refers to imperial gallon in this paper - 1 Imp. gall = 1.2 U.S.Gall.

bulk liquid. An increase in the preburn time increased the extinction time although to a lesser extent for hand application than for fixed application. The experience of the operator as expressed by the factor L in equation (17) was also an important factor in the extinction of fire by hand application.

Both the equations (16) and (17) presume that the bulk of the spray reaches the burning liquid. If the downward thrust of the spray was less than the upward thrust of the flames and if the flames could burn vertically upwards against the spray, then the extinction time was prolonged. In this connection it is noteworthy that the size of the flames in the first few seconds of application were usually considerably greater than the size before application of spray, as indicated in plate 1. This was due to the sputtering of fuel into the flame. However, for tests on fires 3 ft and 4 ft diameter in a large roofless structure, the ambient wind was usually sufficient to blow the flames away from the upright position and the force of the spray was not a significant factor in extinction of the fire; if the spray was much wider than the fire. With hand application of spray to an 8 ft diameter fire there was no difficulty in enabling even fine sprays of low thrust to reach the burning liquid, since the fire could be approached on the upwind side and applied directly to the base of the flames. A complicating factor in all these tests was the occurrence of splash fires with coarse sprays; burning fuel was splashed into the flame by the spray and a vigorous flame maintained even though the liquid was cooled well below the fire point. If, when a splash fire was established, the spray were taken away the fire often went out. An example of this is shown in plate .

Fires in oil running over metal work. When sprays are applied to a pool fire which has been burning for some time, there is an initial upsurge of flame and the flames then reduce in size gradually within the extinction time. When burning liquids are flowing over a surface the liquid layer is very thin and the sensible heat in the liquid which needs to be removed is very small. Providing the flow rate of water spray is near the critical rate the flames are reduced in size almost immediately after turning on the water spray and thereafter are reduced in size much more slowly. This is illustrated in plate 4 which shows a fire in transformer oil flowing over a test rig consisting a bank of tubes 5 cm diameter. The rate of flow required to extinguish the fire in a given time depended on the preburn time in this case since during the preburn period the tubes themselves were heated and acted as a reservoir of heat during the application of spray. The effect of the temperature of the tubes on the rate of flow required to control and extinguish the fire is given in Fig. 3. The relationships in Fig. 3 were obtained for sprays projected directly downwards from 5 ft above the point in the tube rig where oil was injected (6 in below the top), but tests in which the sprays were projected from a similar distance from the side of the rig did not give significantly different results, nor was there any difference if the tube bank was horizontal rather than vertical. The drop size of the spray was found to have no significant effect in the range tested (mass median 0.6 to 3.0 mm); there was evidence, however, that an increase in drop velocity increased the efficiency of the spray[14] and the effect of the drop size may have been masked by the fact that the ratio of drop size to drop velocity was constant for the sprays referred to in Fig. 3. The tests covered a wide range of ambient wind conditions. However, Fig. 3 indicates that the critical rate for these varying conditions increased as the temperature of the tubes increased. These critical rates may be taken as lying between curves (1) and (3) in Fig. 3.

A large number of tests have been carried out in the United States in which water spray has been applied to oil fires on sheet metal structures simulating transformers[15][16]. A comparison between the results of these tests and those carried out on the tube rig in England has indicated that to obtain a given extinction performance under given conditions of nozzle pressure, oil fire point and preburn time, a mean flow to unit area of the envelope of the tube rig on the ~~average~~ 2.3 times as great as that to the large sheet metal simulated transformers was required. Equations 8 and 10 indicate that the ratios of critical heat transfer rates to the surface would be about 1.8; the expected ratio of flow rates to the envelopes of the two risks would be between 1.8 and 2.8. If the wind velocity controlled the critical heat transfer rate the expected ratio would be greater. It is unlikely that the condition for heat transfer to the drops in the oil would differ between the oil running down tubes and a vertical surface although it would be expected that the accessibility of spray to the surfaces would be easier for a flat surface than for a nest of tubes. Broadly, however, the comparison does support the theoretical approach.

Critical rate for extinction of a wood fire. Bryan[17] has measured the critical rate for a wood fire consisting of pieces 2 in square section and a total surface area of 80 $ft^2$. The minimum rate at which he obtained extinction with water was 0.16 gallons/minute corresponding to a rate of 0.01 $g/cm^2 min$. Bryan concluded from other observations that extinction was by cooling the wood. Under the conditions he used it may be assumed that the water was entirely vaporised; this would correspond to a heat transfer of 0.1 $cal/cm^{-2}s$ at the wood surface. From information on the heat of combustion of wood volatiles and assuming that critical criteria as described above may be applied to burning wood, it may be estimated that 0.8 $cal/cm^{-2}s$ would have been transferred from the flame to the wood surface under critical conditions. The difference between the measured and estimated values might be taken to indicate that a substantial heat transfer, of the order of 800 cal/g, was required to cause the evolution of sufficient volatiles for combustion.

Direct extinction of flame

To examine the relevance of the theory developed above it is necessary to have an estimate for X, the heat transfer capacity for the sprays. These estimates were obtained using equation 18, a modification of the Ranz and Marshall relationship for heat transfer from gases to drops[18] which was found to hold for water drops evaporating in a bunsen flame[19].

$$\frac{hD}{k} = \frac{1}{1+0.39\beta/\lambda}\left(2 + 0.6\left(\frac{c\mu}{k}\right)^{0.67}\left(\frac{V_D D\rho}{\mu}\right)^{0.5}\right) \quad \ldots\ldots (18)$$

$c, \mu, k, \rho$ specific heat, viscosity, thermal conductivity, density in boundary layer;

D drop size, $V_D$ drop velocity relative to gas stream;

h heat transfer coefficient;

$\beta$ enthalpy increase per unit mass of vapour between surface and flame temperature;

$\lambda$ heat required to vaporize unit mass of the liquid.

In estimating X it was assumed that the concentration and velocity of the drops in the flame were the same as in the approaching spray, and that the contribution of the individual fractions of the different drop sizes could be added. Since the surface area of drops of size D present per unit volume of space through which the drops are passing is proportional to $M_D/V_D D$ where $M_D$ is the flow rate per unit area, it follows from equation 18 that

$$X \propto M\, D_r^{-(1.5 \text{ to } 2.0)}\, V_r^{-(0.5 \text{ to } 1.0)} \quad \ldots\ldots (19)$$

where M is the total flow rate per unit area, $D_r$ and $V_r$ are a representative drop size and drop velocity.

The extinction of fire by water spray by extinguishing the flame has been studied with fires in kerosine petrol and benzole in a vessel 30 cm diameter[20][1]. Extinction of the flame differed from extinction by cooling the fuel in that there was a sudden clearance of a comparatively large volume of flame which led to extinction.

When the spray was applied in a downward direction the flames of the petrol and kerosine fires were not extinguished unless the downward thrust of the spray was greater than 60 and 40 dynes/$cm^2$ respectively. These forces are comparable with the upward force of the flames before the spray was applied. With sprays of greater downward force the flames were extinguished as long as the heat transfer capacity of the spray was greater than about 0.15 cal/$cm^3$s, and as long as the preburn time was not very short. The above value is intermediate between those expected from equations 12 and 13, if I is taken to refer to the upward moving flames before spray application.

For a given type of spray the most important factor in the heat transfer capacity is the drop size of the spray (equation 19) and in the thrust of the spray the rate of flow per unit area of the fire. If the drop size of the spray is plotted against the critical rate of flow for extinction at that drop size, the above phenomenon of critical thrust manifests itself as a flow rate below which the fire is difficult to extinguish with sprays of any drop size. Critical flow rates for extinction of a flame have been plotted in this way in Fig. 4 for the kerosine and petrol fires; points for extinction and non-extinction are shown for the petrol fire. For comparison critical flow rates for the extinction of the kerosine fire by cooling the liquid have been included. Similar relationships obtained by the author for sprays produced by hypodermic needles acting on a kerosine fire 11 cm diameter[21], and by the National Board of Fire Underwriters for sprays acting on a petrol fire 15 cm diameter[22] have been given elsewhere. The critical flow rate below which extinction was difficult was smaller in both cases than those shown in Fig. 4 for the 30 cm diameter fires. This may be mainly attributed to the smaller dimension of the fires and the resulting smaller upward force of the flames, but different conditions of test and different patterns of spray at the fire area also probably played a part. Extinction of the flame has been found to be easier if the peak concentration of the spray is near or even outside the edge of the vessel, since after a clearance of part of the flame, the remnants of flame from which a flash back may occur are at the edge[20]. This phenomenon may account also for comparatively low flow rates for extinction of flame reported by Y. Yazi[23].

During the tests the flames were usually wild with frequent partial clearance and flashbacks. However, with petrol and benzole fires when the preburn time was very short (less than 10 sec) and when sprays with high downward thrust were used, the spray pushed the flame immediately into a flat flame close to the liquid surface which was very difficult to extinguish. The appearance of the flame depended on the drop size and heat transfer capacity of the spray; a spray with a value X equal to 0.44 cal/$cm^3$s gave thin blue flames near the inside edge of the vessel (plate 5 ); with a value of X of 0.14 cal/$cm^3$ s ; a belt of yellow flame covered the whole vessel. Flames stabilized close to the liquid surface were also obtained if spray were applied to the surface at an angle less than 30° to the horizontal. It was estimated that the value of I for flames stabilized in this way was about 2.5 cal/$cm^3$s. It would, therefore, be expected that a value of X equal to about 0.5 to 1 cal/$cm^3$s would have been required to extinguish these flames reliably.

Regression analyses on the extinction time for the kerosine and petrol fires[20] indicated that for sprays with a given value of X the entrained air current had a powerful effect on the extinction time. This effect was much more powerful than might be expected from a relation such as is given in equation 15. This may be attributed to two reasons. Firstly, the entrained air current helped to present the spray to all parts of the flame; associated with this reason it also helped the spray penetrate to the burning liquid, cooling the latter and thus reducing the size of the flame. Secondly, the entrained air current tended to blow away the thick vapour zone which was usually established after burning for about 10 seconds and thus render the flames unstable.

## EXTINCTION OF FIRES IN ROOMS

Tests have been carried out by many authorities on the extinction of solid fuel fires in rooms. It is not yet clear, however, whether these fires are more efficiently controlled by cooling of the fuel or by the formation of steam which cools the flames.

Kawagoe[24] has found that the rate of burning in room fires is, on the average, directly proportional to the ventilation, and the constant of proportionality indicates that the ratio of air to fuel volatiles is the stoichiometric ratio. When fires in rooms are attacked with sprays from an opening in the wall, then additional air would be entrained into the room comparable with the normal ventilation rate through the opening. Under these conditions it may, therefore, be expected that the fire is burning with excess air when extinction is commenced. The critical amount of steam required to smother the flames would then be governed by equation(14). It may be estimated using equation 14 that if steam is obtained by the impact of spray on the burning surface, the critical flow rate of water to form sufficient steam to extinguish the flames is 10 to 15 times greater than that found by Bryan[17] to be necessary to extinguish a wood fire by cooling. However, conditions in practical fire fighting may still frequently be such that steam extinction would require the use of a smaller total quantity of water.

From the intrinsic nature of extinction of the flame by steam and extinction by cooling the fuel, the qualitative effect of various factors on the efficiency of control (i.e. critical flow rate and quantity of water required) may be deduced. These effects are compared in Table 1.

Table 1

Effect of various factors on control of room fires by cooling and by steam formation

| Factor | Cooling the fuel | Steam formation |
|---|---|---|
| 1. Increase in preburn time | Critical flow rate increased somewhat. Quantity increased approximately in proportion to preburn time. | No effect |
| 2. Decrease in ease of access of water spray to burning surfaces. | Quantity increased | No substantial effect if walls are hot. |
| 3. Increase in the fraction of incombustible surface present; total area of combustibles remaining the same. | Critical flow rate increased (due to radiant heat falling onto burning surfaces). | No substantial effect if incombustible surfaces are hot. |
| 4. Increase in ventilation | No effect | Critical flow rate and quantity increased. |
| 5. Linear dimension d | Critical rate proportional to $d^2$ | Critical rate proportional to $d^{5/2}$ |

Available test results have been summarised by Hird et al[25] but owing to the lack of a systematic investigation of the above factors, at least on the full scale, it is not possible to give a firm opinion on the extinction mechanism. The amounts of water used to control the fires varied from 2 to 15 gallons/1000 ft$^3$. The above workers also carried out a comprehensive series of tests in which sprays of varying pressures from 80 to 500 lb/in$^2$ and with flow rates from 5 to 25 gallons/minute were used against a standard fully developed fire in a room of volume 1750 ft$^3$. The tests are illustrated in plate 7. The quantity of water required to control and extinguish the fire was 7 and 17 gallons respectively, and within the variance of the results, was independent of the pressure, the flow rate and whether jets or sprays were used.

## USE OF WATER SPRAYS IN PRACTICAL FIRE FIGHTING

The following broad principles may be put forward on the basis of the experimental work carried out at the Joint Fire Research Organization and elsewhere.

(1) In general the best way of putting a fire out is that spray should be made to reach and cool the burning fuel. The rate at which the spray need absorb heat in doing this is generally far less than the rate of production of heat by the fire. Experimental results are available giving information on critical rates for a few systems. On the basis of equations 7 to 10 or other relationships developed in similar manner, it is possible to extrapolate

these results to other systems as long as heat transfer between the spray drops and the fuel behaves in a similar way. Perhaps the most important consequence of equations 7 to 10 is that critical flow rates per unit area for a given type of system should not increase as the scale increases; under some conditions they may in fact decrease.

(2) If sprays are applied downwards to a fire with a flame moving steadily upwards then for the bulk of the water to reach the burning fuel the downward thrust of the spray should be comparable to the upward thrust of the flame. These two thrusts may be calculated as indicated in the paper. If the sprays are applied laterally or by hand from the windward side of a fire, a much smaller thrust is necessary.

(3) Water sprays in current use are unreliable in extinguishing a fire.that cannot be extinguished by cooling the fuel. However, extinction may frequently be obtained with available fire sprays produced by pressure nozzles (mass median drop size 0.2 - 0.4 mm) particularly if there is no change to stable burning in the air current of the spray. When extinction is not obtained, a large reduction in the size of flame may be achieved.

(4) For most of the fires for which water sprays are useful, e.g. fires in solids and fires in high boiling liquids flowing over solid surfaces, the drop size of the spray is not usually an important practical factor. However, for fires in deep pools of high boiling liquids the efficiency of the spray increases as the drop size is reduced.

(5) The pressure at a nozzle influences a number of factors that affect the extinction of fire. However, where sprays may be reliably used for extinction of fire, an increase in pressure about 100 $lb/in^2$ with a given flow rate of spray has not been found to confer any extra efficiency on the spray providing that the water can reach the seat of the fire. The choice of pressure for a pump, therefore, depends rather on operational factors, in particular the length and diameter of hose line and the flow rate which it is desired to give the operator, than on intrinsic efficiency of the spray in fighting the fire. It should be added here that an increase in flow rate, or a decrease in cone angle, has a greater effect on increasing the throw of a spray[26,27] than an increase in pressure, and that an increase in pressure has a smaller effect on reducing the drop size of a spray when the pressure is above 100 $lb/in^2$ than when it is below 100 $lb/in^2$.

Finally, it is instructive to compare quantities of water which have been found necessary to extinguish experimental fires with those actually used in practical fire fighting. For fires in rooms it has been found experimentally that about 10 gallons per 100 $ft^2$ of floor area is required and, according to the drop size of the spray, from 5 to 15 gallons may be used to extinguish a gas oil pool fire of the same size. According to information provided by Mobius[28] the minimum quantity of water to extinguish fully developed room fires under operational conditions is about 100 gallons. Thomas[30] made an analysis of the amount of water used at large fires based on the number of pumps called to the fire. It may be estimated from this analysis that for large fires approximately 1000 gallons of water is used for 100 $ft^2$ of the fire. Thus, either wastage or operational difficulties in applying water to fires is by far the most important factor governing the amount of water used, and this would appear to be a direction where a substantial research effort is worthwhile.

ACKNOWLEDGMENT

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# APPENDIX

## THRUST OF FLAMES AND SPRAYS

### Thrust of flames

A complete analysis of the movement of flame has not yet been made, but as this movement is controlled by the buoyancy of the flame, it would be expected that the upward thrust would be proportional to the flame height. Analysis of buoyant columns rising from small heat sources indicate[30,31] that the thrust at the centre of the column is given by

$$\rho_z V_z^2 = 1.5 \text{ to } 2.0 \left(\rho_0 - \rho_z\right) g z \qquad \text{.....(20)}$$

where $\rho_z$ is the density of the column at a point z above the source and $\rho_0$ is the density of the ambient air.

In Fig. 5 some calculated thrusts based on measurements of the upward velocity of flames and the flame temperature[9] are plotted against the buoyancy head $(\rho_0 - \rho_f) g x$ for fires in different liquids burning in a vessel 30 cm diameter; $\rho_f$ is the density of the flame and x the height of the point in the flame for which the thrust was estimated. The velocity measurements were made by ovserving the upward motion of the top of the flame and eddies at the side of the flame as recorded by a cine camera; the calculation of the thrust was made for the mean time of burning and the mean height of the flame at which measurements were made. The temperature on which $\rho_f$ was based was a mean temperature across the flame as measured by the Schmidt method. The straight line relation (equation 21) obtained

$$\rho_f v_f^2 = 0.27 \left(\rho_0 - \rho_f\right) \cdot g x \qquad \text{.....(21)}$$

confirms the proportionality expected and indicates that thrust is independent of the nature of the burning fuel. The constant, however, is considerably less than would be expected from equation (20).

On the basis of equation (21) it is possible to calculate the upward thrust of the flame knowing the flame heights. The latter has been related by Thomas to the rate of burning and the main dimension of the fuel layer for solid fuel fires[32].

### Thrust of a spray

A spray after leaving a nozzle very soon becomes a suspension of drops moving in an air stream. The air stream is generated by the transfer of momentum from the drops and is of importance in determining the velocity of the drops and the motion of the spray as a whole. The total forward thrust of a spray may be measured by the reaction at the nozzle. Measurements of the entrained air current of sprays directed downward from a number of nozzles[33] have shown that for sprays of mass median drop size less than 1.0 mm the bulk of the thrust is transferred into momentum of the airstream by the time the spray has reached a plane 6 ft below the nozzle; most of the remaining thrust may be accounted for by momentum of the drops moving at the velocity of the air stream. For very coarse sprays (mass median dropssize 1.5-3.5mm) about 50 per cent of the initial thrust is converted into momentum of the air current.

The reaction of a jet is the product of the flow rate and the velocity at the nozzle, both these factors being proportional to the square root of the pressure. The reaction of a spray nozzle, however, is less than the product mentioned above due mainly to the presence of lateral motion in the spray. Fig. 6 shows the ratios of the reaction of a number of spray nozzles to that of corresponding perfect jets and indicates the extent to which the reaction is reduced as the cone angle increases and as the spray pattern becomes less peaked in the centre. Knowing the reaction at the nozzle, an approximate estimate of the mean forward thrust in a plane is given by R/A where A is the cross-sectional area of the spray in the plane, and if the assumption is also made that the thrust has been entirely converted into movement of the entrained air stream then the air velocity $V_a$ may be given by:-

$$\rho_o v_a^2 = \frac{R}{A} = a_1 \rho^{0.5} \frac{F}{A} \qquad .....(22)$$

where $a_1$ is a constant depending on the nozzle
$\rho$ is the nozzle pressure
F is the flow rate

Equation (22) gives, of course, a mean value of $v_a$. There is evidence, however, that the distribution of entrained air velocity in a plane perpendicular to the spray axis, when both entrained air velocity and distance from the axis are expressed in dimensionless terms, is approximately independent of the distribution of flow rate within the spray. In addition the distribution of the entrained air velocity is similar to the distribution found in a turbulent air jet. These points are illustrated in Fig. 7 which shows an almost identical distribution of the entrained air for two sprays with widely different spray pattern. The radius of the spray referred to in this figure were radii where the entrained air velocity and water flow rate were respectively 1/100 of the values in the centre of the spray.

For sprays with a similar pattern over a given area it follows from equation 22 that for a given part of the spray

$$v_a \propto P^{0.25} \; M^{0.5} \qquad .....(23)$$

where M is the local flow rate per unit area. A relation similar to this has been found to hold for a wide range of values of P and M for sprays projected downward from a battery of impinging jet nozzles[26].

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Symbols

| | | |
|---|---|---|
| $a_1\ a_2\ a_3\ b$ | - | constants |
| $c_f$ | - | Specific heat in gas boundary layer |
| d | - | Linear dimension |
| g | - | Acceleration due to gravity |
| h | - | Heat transfer coefficient |
| k | - | Thermal conductivity |
| l | - | Linear dimension |
| $m_{og}$ | - | Concentration of oxygen in the air |
| $\dot{m}''$ | - | Rate of burning per unit area per unit time |
| r | - | Stoichiometric ratio (weight of air/weight of fuel) |
| t | - | Time |
| $v_a, v_D, v_{B.O.}$ | - | Velocity of entrained air, of spray drops, and velocity to blow out flame. |
| $v_f, v_z$ | - | Upward velocity in flame, in buoyant hot column. |
| x | - | Height of flame |
| z | - | Height of buoyant column. |
| A | - | Cross sectional area of spray. |
| B | - | Transfer number (after Spalding) |
| D | - | Drop size. |
| F | - | Total flow rate of spray |
| H | - | Heat of combustion |
| I | - | Intensity of combustion in flame |
| $M, M_D$ | - | Total flow rate of spray per unit area, flow rate of drops size D. |
| L | - | Number of tests carried out by operator. |
| P | - | Pressure to produce spray with pressure nozzles. |
| $Q, Q_c$ | - | Heat transfer to fuel surface per unit mass of fuel vaporised, critical value of Q. |
| R | - | Reaction of nozzle. |
| $T_g\ T_s$ | - | Gas temperature, surface temperature. |
| $\Delta T$ | - | Difference in temperature between fire point and ambient. |
| V | - | Volume of flame |
| W | - | Critical flow rate of water to extinguish flame by steam formation. |
| $X_1\ X_2\ X_3$ | - | Critical values of X. |
| $X'$ | - | Heat transfer to spray within unit volume of flame in unit time. |
| Y | - | Preburn time |
| Z | - | Rate of fuel consumption in fire. |
| $\alpha$ | - | Thermal diffusivity |
| $\beta$ | - | Sensible heat of steam or vapour. |
| $\gamma$ | - | Heat taken up as sensible heat in fuel per unit area of surface per unit time. |
| $\lambda, \lambda_f$ | - | Heat required to vaporize unit mass, of liquid, of fuel. |
| $\mu$ | - | Viscosity in boundary layer. |
| $\rho, \rho_f, \rho_0, \rho_2$ | - | Density in boundary layer, in flame, ambient air, in buoyant column. |
| $T_c$ | - | Thrust of spray |
| $\gamma_c$ | - | Critical value of $\gamma$ |

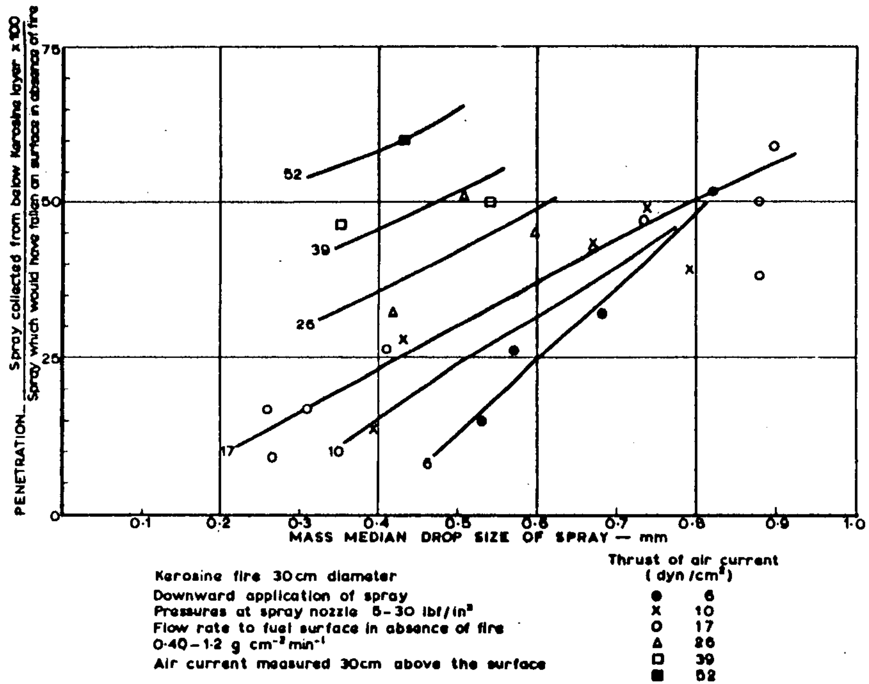
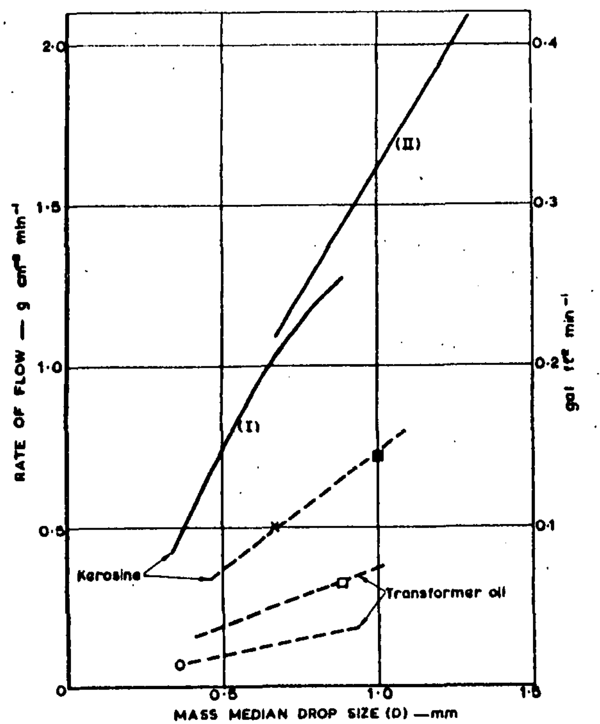
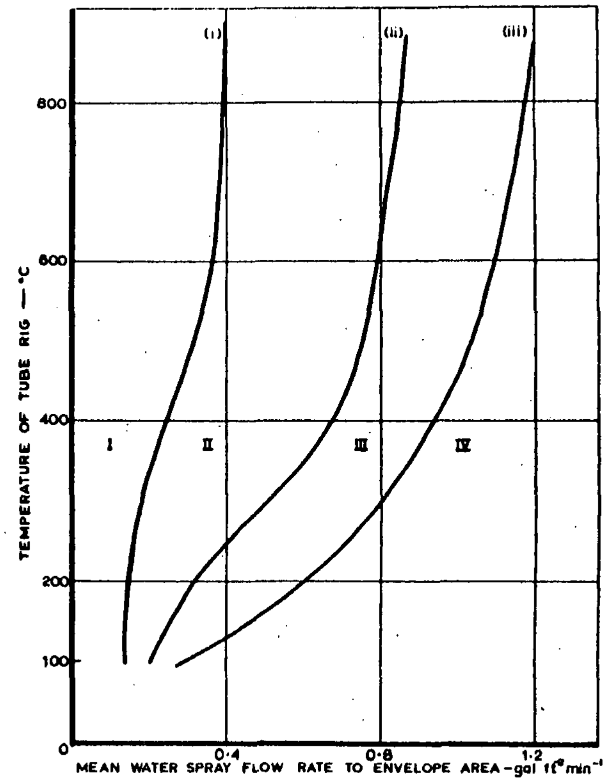



FIG. 1. PENETRATION OF SPRAY TO THE FUEL OF A FIRE




(I) 30 cm diameter Kerosine fire spray applied downwards
(II) 11 cm diameter Kerosine fire spray applied downwards
x 30 cm diameter Kerosine fire spray applied 10° to horizontal
■ 243cm diameter Kerosine fire spray applied by hand
□ 30 cm diameter transformer oil fire spray applied downwards
o 243cm diameter transformer oil fire spray applied by hand

FIG. 2. CRITICAL FLOW RATES FOR EXTINCTION OF POOL FIRES BY COOLING THE LIQUID




I No control
II More than 50 per cent of rig cleared of flame in 30s
III More than 50 percent chance of complete extinction in 45s
IV Estimated certain extinction in 45s
Spray pressure 90 lbf/in$^2$
Drop size 0·6 – 3·0 mm
Envelope area of rig 90 ft$^2$
Transformer oil — flow rate 5·25 gal/min

FIG. 3. CONTROL AND EXTINCTION OF OIL FIRES ON TUBE RIG

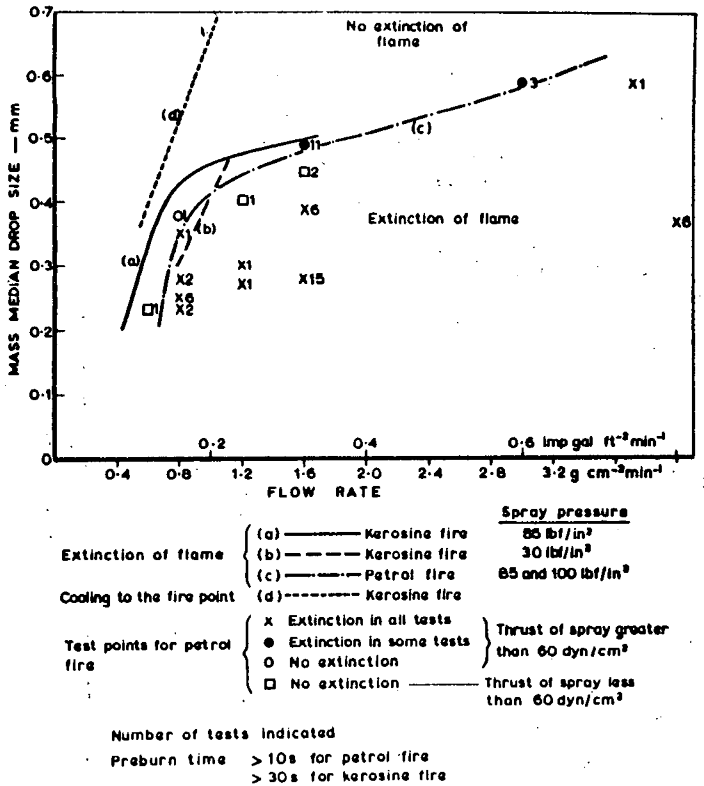
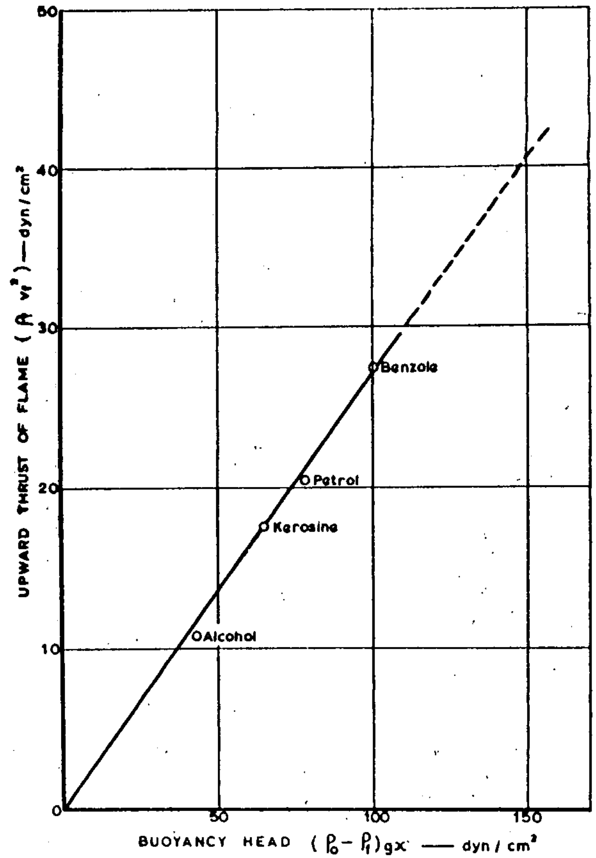
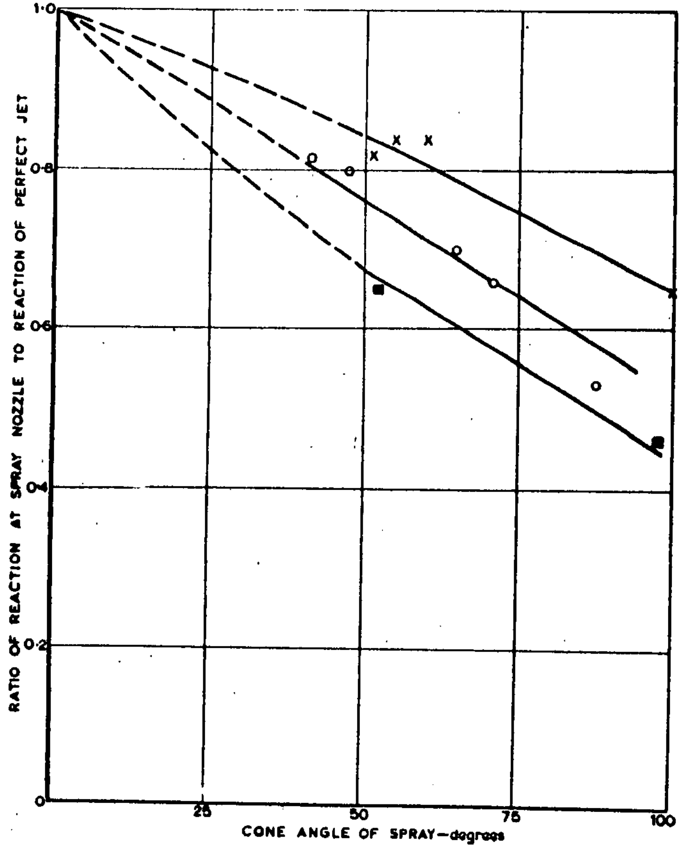



FIG. 4. CRITICAL FLOW RATES FOR EXTINCTION OF KEROSINE AND PETROL FIRES 30cm DIAMETER, DOWNWARD APPLICATION OF SPRAY




N.B. X refers to the height in the flame at which $v_f$ was measured and not maximum height of flame.

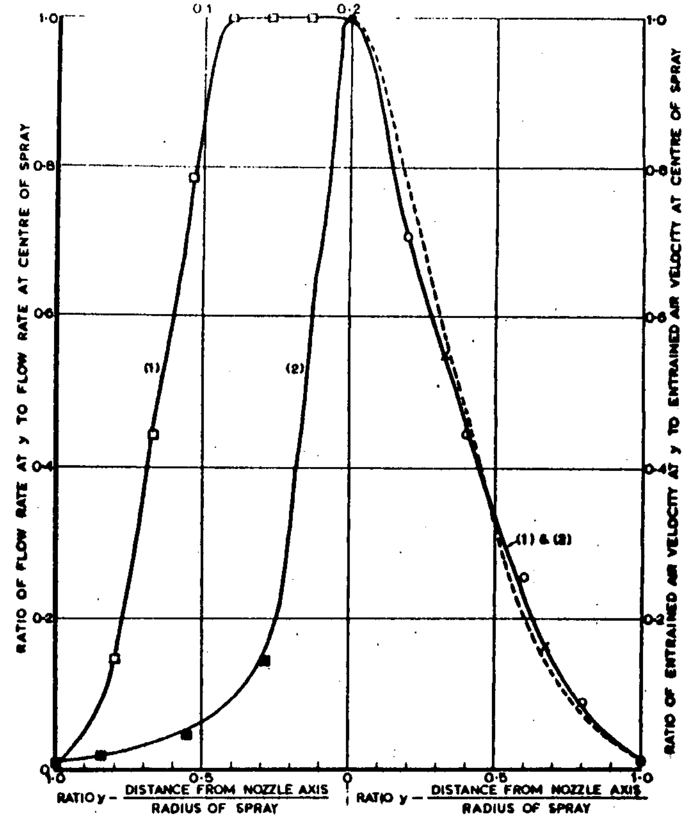
FIG. 5. RELATION BETWEEN UPWARD THRUST OF FLAMES AND BUOYANCY HEAD — FREELY BURNING LIQUID FIRES 30cm DIAMETER




X Peaked sprays *
O Moderately peaked sprays
■ Sprays with uniform pattern *
Spray flow rates 10–35 gal/min
Pressure 25–90 lbf/in²

* N.B. Fig.7 gives pattern of a spray falling into this category

FIG. 6. REACTION OF SPRAY NOZZLES



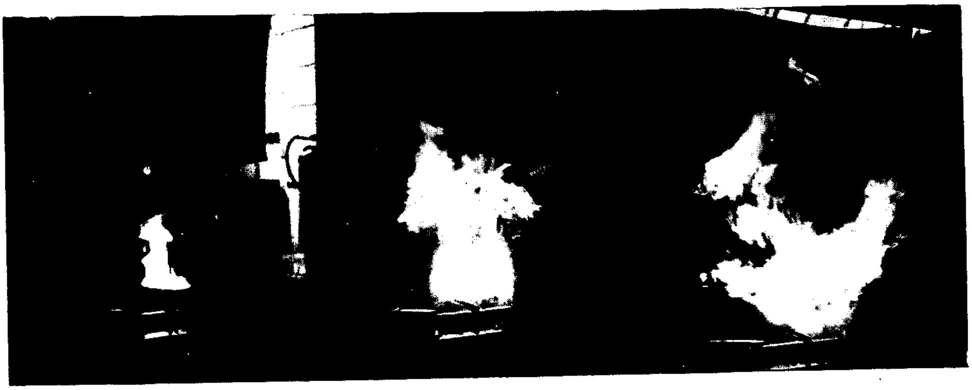

□ Nozzle (1) uniform pattern
■ Nozzle (2) peaked pattern

FLOW RATE PATTERN 7'6" BELOW NOZZLE

O Nozzle (1)
X Nozzle (2)
---- Curve for free air jets*
* See reference 34

ENTRAINED AIR VELOCITY PATTERN 6'0" BELOW NOZZLE

FIG. 7. COMPARISON OF DISTRIBUTION OF ENTRAINED AIR CURRENT AND WATER FLOW IN SPRAYS FROM GIVEN NOZZLES



BEFORE SPRAY APPLICATION | ½ s | 1 s

4 s | 6 s | 8 s

EXTINCTION OF FIRE IN TRANSFORMER OIL BY DOWNWARD APPLICATION OF SPRAY FROM FIXED NOZZLE (EXTINCTION TIME 8·8 s)

PLATE 1

BEFORE SPRAY APPLICATION

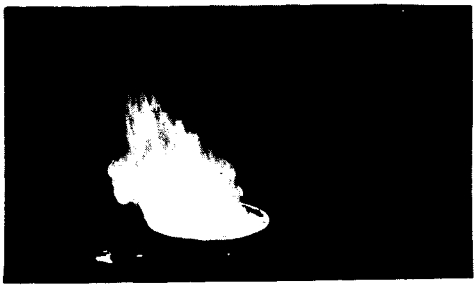
EXTINCTION AT NEARSIDE OF RIM

FIRE UNDER CONTROL

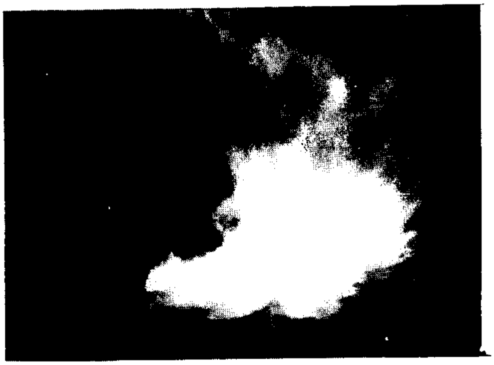
JUST BEFORE EXTINCTION

EXTINCTION OF FIRE IN HEAVY FUEL OIL BY HAND APPLICATION OF WATER SPRAY. SPRAY FLOW RATE 1·4 GAL/MIN.

PLATE 2



BEFORE APPLICATION OF SPRAY



SPLASH FIRE DURING APPLICATION OF SPRAY

1 SECOND AFTER REMOVAL OF SPRAY

SPLASH FIRE CAUSED BY THE ACTION OF A COARSE SPRAY ON BURNING DIESEL OIL

PLATE 3

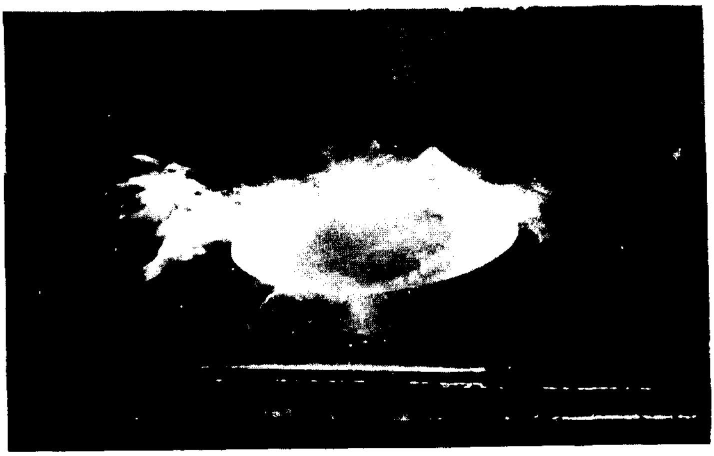
APPLICATION

5 s

30 s

CONTROL OF FIRE IN TRANSFORMER
OIL ON A BANK OF TUBES

PLATE 4



STABLE FLAME CAUSED BY ACTION OF FINE SPRAY ON PETROL FIRE. DROP SIZE OF SPRAY 0.28 mm. FLOW RATE 1.6g $cm^{-2}$ $min^{-1}$

PLATE 5

STABLE FLAME CAUSED BY ACTION OF SPRAY ON PETROL FIRE. DROP SIZE OF SPRAY 0.28 mm. FLOW RATE 1.6g $cm^{-2}$ $min^{-1}$

PLATE 6

ATTACK WITH A WATER JET ON A FULLY DEVELOPED FIRE IN A ROOM

PLATE 7