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THE EFFECT OF WATER SPRAYS ON A PETROL FIRE 30 CM DIAMETER

by

D. J. Rasbash and Z. W. Rogowski

Summary

A series of tests have been carried out on the extinction of a petrol fire 30 cm diameter with a number of water sprays. The drop sizes of the sprays varied between 0·2 to 0·6 mm, the rates of flow between 0·6 and 4·0 g $cm^{-2}min^{-1}$ and the entrained air velocities between 200 and 500 cm/s. The preburn time of the fire was varied between 1 and 300 seconds. It was found that the extinction time was markedly reduced by an increase in the rate of flow and the entrained air velocity and by a decrease in the drop size. However, it was also found that the most efficient sprays tested often did not give extinction when the preburning time was less than 10 seconds, and for this reason the use of water sprays is not advised as a reliable method for extinguishing this type of fire. The mechanism of extinction of the fire is discussed.

May, 1955.

Fire Research Station,
Boreham Wood,
Herts.

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Symbols

A	- entrained air velocity	LT^{-1}
D	- mass median drop size of spray	L
H	- heat transfer per unit volume of flame	$M\theta L^{-3}T^{-1}$
K	- constant	-
R	- rate of flow to the fire area	$ML^{-2}T^{-1}$
T	- time of preburn	T
V	- velocity of drops	LT^{-1}
h	- heat transfer coefficient	*$MT^{-1}L^{-2}$
k	- thermal conductivity	*$MT^{-1}L^{-1}$
μ	- viscosity	$ML^{-1}T^{-1}$
ρ	- density	ML^{-3}

* Dimensions for quantities containing heat are based on the assumption that specific heat is a dimensionless **quantity.** With this assumption heat has the dimensions $M\theta$

Introduction

In a previous report (1) an account was given of tests which showed the specific effect of the drop size of water sprays on the extinction fires in different liquids including petrol. The present report gives an account of further tests on this fire which shows the effect of the preburn time of the fire and also the effect of the rate of flow and the entrained air velocity of the spray.

Experimental

Apparatus

Sprays tested - The sprays tested and their main properties are listed in Table 1. The manner in which the properties were measured have been described elsewhere (2). Most of the sprays were produced at a pressure of 85 Lb/in^{-2} with the batteries of impinging jets(2) placed 5 ft. 9 in. above the fire area. Sprays 14 and 15 however were produced with a proprietary nozzle consisting of 10 pairs of 1/16 in. impinging jets. This nozzle was placed 8 ft. above the fire area and the pressure used was 100 Lb/in^2. With spray 14 the fire was placed directly underneath the nozzle; with spray 15 the fire was placed 2 ft. to one side. Spray 16 was produced by a proprietary swirl nozzle at a pressure of 100 Lb/in^2 and at a height of 8 ft.

It will be noted that the range of rates of flow tested was from 0·6 to 4 g cm^{-2}min^{-1} (0.12 to 0.8 gal ft^{-2}min^{-1}) and the range of drop

Table 1

Properties of the sprays tested

Spray No.	Jet size mm	Jet size in.x64	Rate of flow to the fire area g cm^{-2}min^{-1}	Mass median drop size (at the fire area) mm	Entrained air velocity (At a point 30 cm above the fire area) cm/s
1.	0·4	1	0·8	0·24	250

Table 1 cont'd

Spray No.	Jet size mm	Jet size in.x64	Rate of flow to the fire area g cm^{-2}min^{-1}	Mass median drop size (at the fire area) mm	Entrained air velocity (At a point 30 cm above the fire area) cm/s
2.	0·8	2	0·6	0·23	210
3.	0·8	2	0.8	0·25	268
4.	0·8	2	1.2	0·27	302
5.	0·8	2	1.6	0·28	344
6.	0·8	2	4.0	0·37	487
7.	1·2	3	0.8	0·35	233
8.	1·2	3	0·8	0·29	233
9.	1·2	3	1·2	0·30	295
10.	1·6	4	1·2	0·40	210
11.	1·6	4	1·6	0·39	338
12.	ca2·8	ca7*	1·6	0·49	376
13.	ca2·8	ca7*	3·7	0·58	428
14.	1·6	4	1·9	0·41	226
15.	1·6	4	1·7	0·45	157
16	7·5	19	3·0	0·59	676

* The wall of these jets was a screw thread and the mean internal diameter was 2·8 mm

sizes from 0·23 to 0·58 mm. The drop size of sprays produced by practical fire fighting nozzles varies from 0·4 mm upwards. The range of drop sizes tested therefore corresponds to the finest fire fighting sprays.

Standard fire - The fire tested was the standard 30 cm diameter petrol fire. A layer of petrol 6 cm deep floated on water and the ullage in the containing vessel was 2 cm. A detailed description of the fire has been given elsewhere (3).

Test programme

Sprays were applied to the fire after the following preburn times: 1,2,4,6,10,15,30,120 and 300 seconds. Sprays 5 and 6 were tested at all these preburn times. The preburn times at which sprays 3,11,12,13 and 14 were tested are shown in Table 2. All the other sprays were tested at preburn time of 300 seconds.

Table 2

Preburn times in tests with sprays

Spray No.	Preburn times
3	1, 4, 300.
11	120, 300.
12	2, 120, 300.
13	120.
14	2, 300.

The results for sprays 5, 11 and 12 at preburn times of 120 and 300 seconds are taken from an earlier report (1).

Results

The results of tests with sprays 5 and 6 at preburn times up to 30 seconds are shown in Table 3.

Table 3

Extinction time (seconds) with sprays 5 and 6
at low preburn times

Spray	Preburn time							
	1	2	4	6	8	10	15	30
5	>60 >60	>480 >60	>60 34.2*	>60 2.5, 0.9	3.2 1.9	4.6 3.2	2.6, 1.7 3.7	3.3 5.7
6	0.2 0.3	>30 8.2*	1.0 1.5	>30 0.7	1.0 1.3	>30 0.7	0.7 1.6	1.2 2.0

* Extinction took place, after thin stable flame formed.

At preburn times greater than 6 seconds for spray 5, and 10 seconds for spray 6, the fire went out very rapidly in all tests. At lower preburn times the fire was not extinguished in a number of tests. In all the tests in which extinction did not take place a stable thin blue flame formed close to the vessel surface immediately after the application of the spray. A photograph of this thin flame is shown in Fig. 1. The flame was most pronounced at the edges of the fire area; except for momentary flickers across the surface the centre of the fire are was usually free of flame. Once this stable flame had formed the fire did not go out, except in two tests. (see Table 3). In most of the other tests in which extinction was obtained, the spray appeared to make the flames unstable by causing partial clearances prior to extinction; in these tests the flames did not lose their original yellow colour and when there was a clearance the part of the flame left was as a rule even more yellow than the normal flame.

None of the other sprays tested at a preburn time of less than 6 seconds gave extinction within a time of application of 60 seconds. Spray 3 resulted in the formation of a flame very similar to that formed by sprays 5 and 6 but there was a pronounced yellow colour in the flames. Spray 12 resulted in the immediate formation of a flat stable yellow flame which stretched across the whole vessel. With spray 14 the shape of the flames alternated between flat and vertical during the spray application and there were occasional partial clearances.

Table 4 gives the results of tests at preburn times of 120 and 300 seconds. Most of the extinctions which took place were preceded by partial clearances of the flame some of which lasted for several seconds.

It is difficult to obtain from Table 4 directly an estimate of the effect on the extinction time the rate of flow and the entrained air velocity. However, sprays 14 and 11 differed mainly in the entrained air velocity, that of spray 11 being the greater, and it will be noted that the latter spray gave the more rapid extinction.

Table 4

Extinction times (seconds) with sprays at
high preburn times

Spray No.	Preburn time (seconds)	
	120	300
1	-	123, 189.
2	-	>420
3	-	65, 75, 75, 62, 68, 150.
4	-	33.0
5	9.3, 10.6, 9.2, 7.8	12.4, 10.0
6	1.9	1.5
7	-	280
8	-	50.5, 164, 110
9	-	254
10	-	>420
11	5.9, 49.6	39.8, 45.2
12	215, 249	152, 235
13	15.2	-
14	-	70, 198, >240
15	-	>240, >240
16	-	3.0, 6.0, >30

Statistical analysis of the results

A quantitative estimate to the effect of the spray properties on the extinction time was obtained by carrying out a regression analysis on the results. A disadvantage of this method, however, was that it was not possible to include tests in which extinction did not take place. For this reason all results of tests at preburn times of 10 seconds and less were excluded from the analysis since in a large number of these tests extinction was not obtained. The results of this analysis are expressed in equation (1).

$$\text{Log } Y = -2{\cdot}13\ (\pm\ 0{\cdot}81^{*})\ \text{Log } R + 4{\cdot}31\ (\pm\ 1{\cdot}13)\ \text{Log } D - 2{\cdot}99\ (\pm\ 1{\cdot}38)\ \text{Log } A + 0{\cdot}35\ (\pm\ 0{\cdot}24)\ \text{Log } T + 10{\cdot}64 \quad \ldots\ldots\ldots\ldots\ldots(1)$$

* 95% confidence limits

Y = extinction time (seconds)
R = rate of flow ($g\ cm^{-2} min^{-1}$)
D = mass median drop size (mm)
A = entrained air velocity - (cm/sec)
T = time of preburn (seconds)

Equation 1 shows that an increase in rate of flow and entrained air velocity and a decrease in drop size brought about large reductions in the extinction time. An increase in preburn time also increased the extinction time, but less markedly.

Discussion

Mechanism of extinction

<u>The effect of heat transfer between the flames and the drops</u> - Discussion on the part played in the extinction process by heat transfer between the flames and the drops may be based on equation (2) which has been found to represent the heat transfer which takes place between a flame and a single drop (4).

$$\frac{hD}{k} = K\left(2 + 0.53\left(\frac{VD\rho}{\mu}\right)^{0.5}\right) \qquad \ldots\ldots\ldots\ldots (2)$$

h = heat transfer coefficient
D = drop size
k = thermal conductivity in the boundary layer
K = constant somewhat less than unity
V = velocity of the drops
ρ = density of gas in the boundary layer
μ = viscosity of gas in the boundary layer

Consider a spray passing through a flame. The heat transfer rate per unit volume of flame H will depend on the rate of flow (R) across unit area of the flame, the drop size (D) and the drop velocity (V). Equation (2) indicates that the heat transfer coefficient will be proportional to $D^{-(0.5 \text{ to } 1)}$ the exponent varying according to the velocity of the drops; in addition to this the surface area of drops available for heat transfer will increase as D^{-1}. Therefore the total heat transfer rate should be proportional to $D^{-(1.5 \text{ to } 2)}$. Again the heat transfer coefficient will be proportional $V^{0 \text{ to } 0.5}$ the exponent varying with the drop size. On the other hand the time of residence of the drop in the flame will be inversely proportional to V; as a consequence at constant rate of flow (R) the number of drops which will be present in unit volume of flame at any one moment will be inversely proportional to V. The heat transfer rate per unit volume of flame should therefore be proportional to $V^{-(0.5 \text{ to } 1)}$. Finally the increase in R will bring about a proportional increase in the number and therefore the surface area of the drops and H will be proportional to $R^{1.0}$. Thus it may be expected that the heat transfer from unit volume of flame to the drops will be represented by

$$H \propto R^{1.0} D^{-(1.5 \text{ to } 2.0)} V^{-(0.5 \text{ to } 1.0)} \qquad \ldots\ldots\ldots\ldots (3)$$

The equation may be compared with equation (4) obtained from equation (1)

$$Y \propto R^{-2.1} D^{4.3} A^{-3.0} \qquad \ldots\ldots\ldots\ldots (4)$$

If heat transfer between the flames and the drops is the predominant cause of extinction then it would be generally expected that the extinction time would decrease as the heat transfer rate increases. It would not be expected that there would be a simple inverse relation between these two factors since the flame would probable be extinguished when the heat transfer at the appropriate places in the flame exceeds a certain limit. This limit as well as depending on the flame properties would depend upon the amount of steam formed during the heat transfer process. When a spray acts on a flame, the properties of both the spray and the flame varies from moment to moment due to turbulence; under these conditions a mean extinction time is likely to represent the mean time which elapses before the limiting amount of heat transfer is obtained.

Consideration of the effect of rate of flow and drop size on the heat transfer within the flames and the extinction time fulfils the above expectations. Thus equation 1 and 4 show that the rate of flow and the drop size affect the heat transfer in opposite ways to their effect on the extinction time. Moreover the ratio of the exponents of rate of flow and drop size on the heat transfer equation is about the same as their ratio on the extinction time equation.

Some complication arises however, when considering the effect of the entrained air velocity. For fine sprays this velocity will be the main component of the velocity of the drops. If this were the only relevant consideration it would be expected that the extinction time would increase as the entrained air velocity increases, since equation 2 shows the heat transfer per unit volume of flame to decrease as the velocity of the drops increase. That this is not so indicates that the entrained air stream has important effects on the fire other than governing the drop velocity. A part of these effects is no doubt the ability of sprays with high entrained air velocity to push inside the uprising flame and allow the spray access to all parts of the flame in contact with uprising vapour. It is doubtful, however, whether this factor explains completely the effect of the entrained air stream. Thus, from a knowledge of the spray properties, it was possible to estimate the value of H for sprays 5 and 6; these were respectively 0·44 and 0·31 cal $cm^{-3}sec^{-1}$. Both these sprays had entrained air velocities (344 and 487 cm/sec, respectively) well in excess of that of the upward moving glames (about 250 cm/sec) in neither case therefore was the resistance of this flame likely to prove a barrier to the motion of the spray, yet the extinction times obtained were considerably less with the spray with the higher entrained air velocity and the lower heat transfer rate.

The effect of the entrained air stream on extinction

A possible explanation of the effect of the entrained air stream is that it confers an instability on the fire arising out of mixing with the vapour zone. The rate of vaporization of petrol during normal burning of the fire was of the order of 1 mole/min (3); therefore mixing with about 100 mole/min of air would reduce the vapour concentration to below the lower flammable limit. An entrained air stream of 300 cm/sec is equivalent to a flow of air to the fire area of 600 mole/min. There was thus ample air in the air stream associated with the sprays to dilute the vapour zone to below the lower limit.

The rate of mixing between the air stream and the vapour would depend on the thickness of the vapour zone. If the vapour zone were of a thickness considerably greater than that of the boundary layer formed when air moves across the liquid surface, the mixing would take place by turbulent diffusion and would be very rapid. Under these conditions the vapour might be diluted through the range of combustion mixtures more rapidly than flame can propagate through these mixtures; this might be the cause of the frequent clearances of flame which were observed during the tests. On the other hand if the vapour thickness were of the same order as the boundary layer thickness the mixing would take place mainly by the much slower process of molecular diffusion, and clearance of the flame by vapour dilution would be much more difficult.

The above considerations can account for a number of observations in this and previous reports. Thus it was found (1) that when spray 12 acted on a petrol fire after burning for 2-8 minutes, there was a considerable disturbances of the flame with frequent clearances for a period of 10-20 seconds; after this time a stable flat flame across the vessel was formed. In this report it was observed that the same spray when applied to a fire which had been burning for only 2 seconds, pushed the flames immediately into the stable flat shape. It has been observed with the particular fire used that a perceptible thickness of vapour zone forms after 7-10 seconds of burning; the thickness of the vapour zone increases to about 5 cm as the preburning time is further increased (3). It is likely that at preburning times less than 7 seconds rapid mixing of the vapour zone and the entrained air stream does not take place, and this results in the flames being pushed immediately by the spray into a stable flat shape. It is also possible to explain in this way the differences observed in the case of extinction of the fire when sprays 5 and 6 were applied before and after 6-10 seconds preburning time. At preburning times greater than this the extinctions would have been assisted by the instability in the fire caused by rapid mixing between the entrained air stream and the vapour. At lower preburning times this feature favouring extinction was absent since the flames passed immediately into the stable form shown in Fig. 1.

Spray 14 behaved quite differently from spray 3, 5, 6 and 12, when applied to the fire after a low preburning time. With this spray a stable flame was not formed and occasional clearances and flash backs were noted during the spray application. In this respect the behaviour of the fire was no different from its behaviour when the same spray was applied after a preburn time of 300 seconds. An explanation for this is that the entrained air velocity of this spray (226 cm/sec) was less than that of other sprays and also less than the normal upward velocity of the flames (250 cm/sec). There was therefore not sufficient momentum in the spray to push the flame across the vessel, although sufficient air may have occasionally penetrated the vapour zone to bring about flame clearances.

It may therefore be concluded that the extinction of the fire, depended on the combined action of vapour dilution by the entrained air stream and heat transfer from the flames to the drops. Useful information of the relative importance of this factor might be obtained if tests were carried out on the effect of an air stream alone.

Practical implications

Within the range of sprays tested no spray was found to be able to extinguish the petrol fire both rapidly and reliably. The two sprays (5 and 6) which would extinguish the fire most rapidly were not reliable when the preburning time was less than 6 to 10 seconds. Within this preburning time a stable flame burning close to the liquid surface was formed when the spray was applied; this flame was very difficult to extinguish.

Within the range of conditions under which extinction did take place, the time of extinction was markedly decreased by an increase in the rate of flow, the entrained air velocity and the fineness of the spray. It is possible that if these factors were increased well beyond the range used in the present tests a reliable spray might be produced. However, practical considerations would preclude such spray from being widely used. Thus it must be borne in mind that when water sprays are used against a petrol fire the spray must more than cover the complete area of the fire if it is to be effective. The present tests indicate that the flow rates which would be required for a completely reliable water spray would be well in excess of 1 gallon $ft^{-2}min^{-1}$; very high flow rates would therefore be required for a fire of any practical size. Other means of extinguishing petrol fires require flow rates far less than this; thus the critical rate for foam is 0·02 - 0·03 gallon $ft^{-2}min^{-1}$(5) and for chlorobromomethane 0·01 gallon $ft^{-2}min^{-1}$(6). Any convenience likely to accrue from the use of water spray alone as a medium of extinction would probably be more than counter balanced by the very high flow rates that would be required.

It must be added here that Coleman and Stark (6) found that the use of flat sprays applied directly to the base of the flames was very efficient in extinguishing petrol fires with chlorobromomethane. These authors also found that carbon tetrachloride was much less efficient than chlorobromomethane when used in this way and it must be expected that water sprays would be less efficient still. However, it may be possible that extinction might be reliably achieved with reasonable flow rates if water is applied in this way. Tests to investigate this point are in hand.

References

(1) D. J. Rasbash and Z. W. Rogowski F.R. Note No: 162.

(2) D. J. Rasbash and Z. W. Rogowski , F.R. Note No: 58.

(3) D. J. Rasbash, Z. W. Rogowski and G. W. V. Stark - Awaiting publication.

(4) D. J. Rasbash and G. W. V. Stark , F.R. Note No: 26.

(5) R. J. French, P. L. Hinkley, J. F. Fry F.R. Note No: 21.

(6) E. H. Coleman and G. W. V. Stark F.R. Note No: 152

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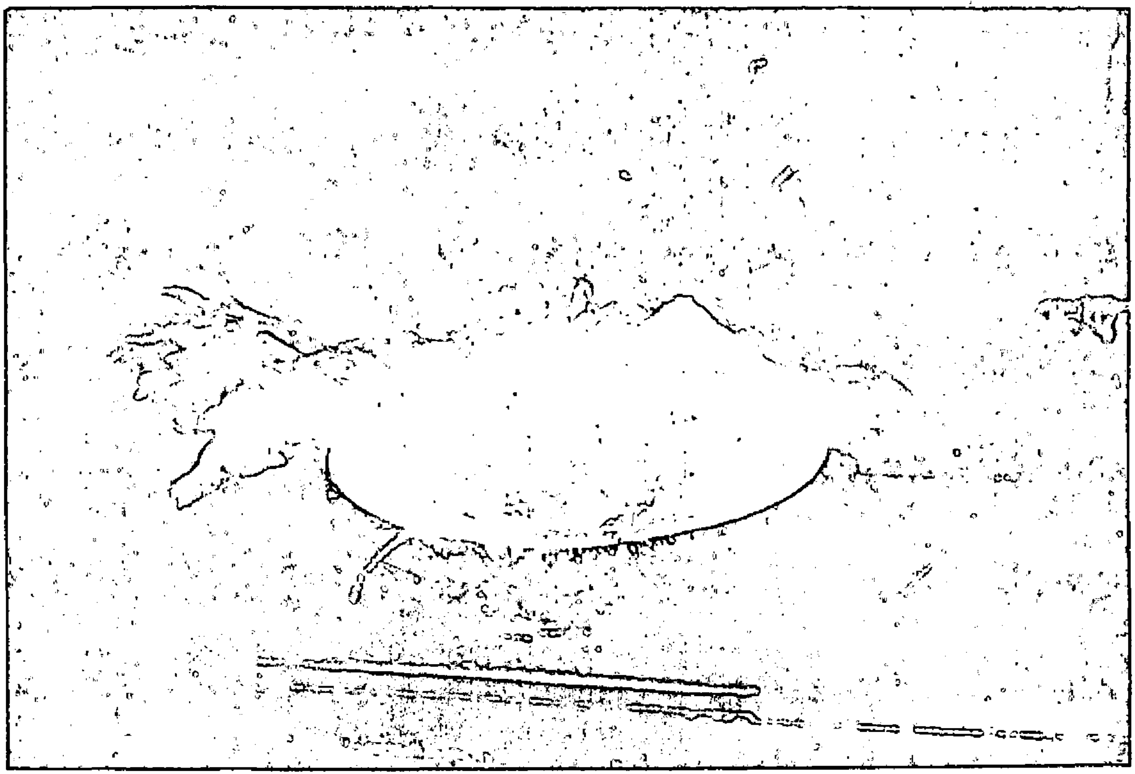

FIG.1. ACTION OF SPRAY 5 ON A PETROL FIRE PREBURN TIME LESS THAN 6s.