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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

THE DESIGN OF WATER SPRAYS FOR PROTECTIVE INSTALLATIONS AGAINST FIRES OF HIGH BOILING LIQUIDS

PART I

EXTINCTION OF A TRANSFORMER OIL FIRE 30 CM IN DIAMETER

by

D. J. Rasbash and Z. W. Rogowski

SUMMARY

A series of tests have been carried out on the extinction of a transformer oil fire 30 cm diameter by water sprays applied from single nozzles situated 8 ft. above the plane of the fire. It was found that an increase in the rate of flow and the velocity of the entrained air stream in the spray decreased the extinction time, but within the range of drop size of practical interest in this problem an increase in drop size increased the extinction time. The fire was extinguished more easily when it was not placed directly underneath the spray nozzles. The predominant mechanism of extinction was by cooling the liquid to the fire point. No evidence was obtained that in these experiments extinction took place by the formation of an oil in water emulsion. It is concluded that nozzles should be designed to project water sprays to surfaces where they may cool the liquid to the fire point. The entrained air velocity of the spray assists fine sprays to do this, but there is probably an upper limit to the size of the fire and to the degree of extraneous disturbance beyond which this factor will not operate satisfactorily.

May, 1955.

Fire Research Station,
Boreham Wood,
Herts.

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SYMBOLS

A	Entrained air velocity of spray	LT^{-1}
D	Mass median drop size of spray	L
H	Heat transfer rate from the flames received as sensible heat by unit mass of oil in the surface	θT^{-1}
K	Cooling capacity of spray	T^{-1}
K_1	Heat transfer rate per unit temperature difference to the spray contained within unit mass of oil	T^{-1}
K_2	Rate of mixing of cold oil into unit mass of oil in the surface	T^{-1}
L	Distance of fire from centre of the spray	L
R	Rate of flow of spray to the fire area	$ML^{-2}T^{-1}$
T	Temperature	θ
C	Specific heat of oil	*
t	Time	T
y	Extinction time	T
ρ	Density of air	ML^{-3}

Subscripts to T

o - surface layers of oil, c - cold oil, s - spray, i - surface layers of oil before spray application, e - surface layers of oil at extinction.

*Dimensions of all symbols involving heat are based on the assumption that specific heat is a dimensionless quantity (1).

INTRODUCTION

Although water sprays have been used for many years in protective installations for fires in liquids with high boiling points, there is as yet no general agreement on the best types of spray to use. Thus in practice a number of different systems are used which rely on sprays with quite different properties and which are reported to give extinction by quite different mechanisms. The Central Electricity Authority, who use such installations extensively to protect apparatus containing transformer oil and lubricating oil, asked the Joint Fire Research Organization to

obtain information on the properties of the sprays to be used. As a first step towards this a series of tests was carried out with single nozzles on a standard laboratory transformer oil fire, 30 cm diameter. The object of these tests was to obtain some detailed information on the effect of the spray properties on the mechanism and efficiency of extinction, prior to tests being carried out on larger fires.

EXPERIMENTAL

Apparatus

A diagram of the apparatus is shown in Figure 1. The nozzle under test was supported 8 ft (240 cm) above a combustion vessel 1 ft (30 cm) in diameter. Water was supplied to the nozzle from a pump through a length of pressure hose, a filter and a straight vertical length of pipe 18 in. (45 cm) long. The pressure was measured at a tapping immediately behind the nozzle. The combustion vessel was mounted on a cradle which allowed it to be moved about in a horizontal plane 8 ft below the nozzle. Underneath the combustion vessel was a large tray which allowed surplus water to be drained away.

Spray nozzles and properties. The nozzles and the pressures at which they were tested are listed in Table. 1.

TABLE 1

Nozzles tested and properties of sprays at fire area

Nozzle designation	Nozzle type	Pressure lb/in.^{2}	Rate of flow to central fire area gm cm^{-2} min^{-1} *	Entrained air velocity ft/min	Drop size mm
A	Swirl	50	1·48 - 1·50	924	0·46
B	Imp. jets	100	1·56 - 2·15	447	0·41
C	Swirl	50	5·65 - 5·96	1440	1·33
D	1 pr. 7/64" Imp. jets	25	0·363 - 0·375	232	0·60
E	"	50	0·424 - 0·443	302	0·52
F	"	100	0·792 - 0·823	334	0·47
G	1 pr. 1/16" Imp. jets	25	0·317 - 0·330	226	0·45
H	"	50	0·439 - 0·481	394	0·40
K	"	100	0·716 - 0·753	426	0·37
L	1 pr. 1/32" Imp. jets	100	0·174	n.d.	0·23

*Range in individual tests.

Nozzles A, B and C were proprietary nozzles; the others were single pairs of impinging jets made in the laboratory. With all the nozzles, tests were carried out with the standard fire placed 8 ft directly below the nozzle. At this point measurements were made of the mean rate of flow to the combustion vessel, the entrained air velocity and the mass median drop size of the spray. These spray properties are given in Table 1. With nozzles A and B tests were also carried out with the standard fire placed in different positions in the plane 8 ft below the nozzles. Figures 2 and 3 show the pattern of spray which these nozzles produced in this plane and also shows the positions in which the standard fire was placed in the tests. In Table 2 the distances of these positions from the central point of the spray has been recorded as well as the properties of the sprays at the different positions.

TABLE 2

Properties at different parts of the spray

Nozzle designation	Position	Position relative to centre	Properties of sprays falling on fire area at given positions		
			Rate of flow (range) g cm^{-2} min^{-1}	Drop size mm	Entrained air velocity (vertical component) ft/min
A	a	At centre	1·48 - 1·50	0·46	924·0
	b	2 ft away	0·97 - 1·00	0·79	297·6
	c	3 ft away	1·57 - 1·66	0·93	208·8
	d	3 ft. 6 in. away	0·76 - 0·76	n.d.	no reading
	e	4 ft away	0·52 - 0·57	1·00	no reading
B	a		1·56 - 2·15	0·41	447·0
	b		1·60 - 1·90	0·45	309·6
	c		0·65 - 0·76	0·39	222·8
	d		0·34 - 0·42	n.d.	n.d.
	e		0·21 - 0·23	0·43	124
	f	4 ft. 6 in. away	0·11 - 0·14	n.d.	n.d.

n.d. = not determined.

The standard fire. A commercial sample of Transformer oil was used in all tests. The oil floated as a layer 6 cm deep on water the upper surface of the oil being 2·0 cm from the rim of the vessel. The initial and final boiling point of the oil were respectively 295 and 395°C and the fire point 175 - 180°C. The oil was primed with 40 cc of hexane, ignited with a wax taper and allowed to burn freely for 5 minutes before the spray was applied. Figure 4 gives the temperature at different depths below the liquid surface after 5 minutes burning.

Programme of tests

With the exception of nozzle L, at least three tests were carried out for each nozzle at each of the pressures and positions of the standard fire shown in Tables 1 and 2. Nozzle L, the single pair of 1/32 in. impinging jets showed no sign of controlling the fire in the first test and only one test was carried out. The temperature of the liquid during the application of spray was measured at a point 1 mm from the surface and 8 cm from the edge of the vessel, using a thermocouple sealed in glass(2). In all tests the effect of the spray was observed and the extinction time recorded. In the experiments with nozzles D and E, and in a few other experiments, tests for reignition were made after extinction firstly by bringing a lighted taper close to the surface and then after about 1 - 2 seconds touching the surface with the taper.

Tests for the detection of an oil in water emulsion. In some of the experiments, mostly with nozzle A tests were carried out to find whether an oil in water emulsion was formed during the application of the spray to the fire. The main test used was one in which an estimate was obtained of the electrical conductivity 1 mm below the liquid surface during the period of spray application. For this purpose a pair of electrodes was inserted in the liquid; these electrodes were spheres, each 1·5 mm in diameter, and the distance between them was 9 mm. The wires leading to the electrodes were sealed in glass capillaries which were bent in such a way as to minimize any shorting between the electrodes by water running along the outside of the capillaries.

The electrodes were connected in series with a battery and resistance as shown in Figure 5. A voltmeter of adjustable sensitivity measured the potential difference across part of the series resistance. When a current flowed the reading was for practical purposes proportional to the conductivity in the gap between the electrodes. When the electrodes were placed in a transformer oil - tap water emulsion, stabilised with 1 per cent of a non-ionic agent, the voltmeter reading increased with increase in the percentage of water in the emulsion in the manner shown in Figure 6. The presence of the emulsifying agent did not affect the conductivity of the tap water or the transformer oil. Figure 6 shows that the readings obtained for these emulsions were of the order of tens of millivolts. When used in its most sensitive range the apparatus could detect voltages of 0·2 microvolt, although frequently stray E.M.F.'s and other causes not under control produced zero readings of up to 20 microvolts. In the tests with sprays the apparatus was set on its most sensitive scale and the maximum difference between the readings immediately before and during the spray application noted. Changes in conductivity were measured in most of the tests with nozzle A. Measurements were also made on the changes in conductivity in cold oil when sprayed, and of the conductivity of the sprays alone.

In addition to the above tests visual and microscopic examinations were made on samples which were withdrawn from the liquid surface immediately after application of the spray. Miscibility tests for water and oil were also carried out on these samples. These tests and examinations were usually carried out about ½ minute after the spray application had ceased.

CALCULATION OF RESULTS

Cooling capacity of the spray

A figure representing the cooling capacity of the spray was derived as follows. For any given spray under any given set of conditions it may be assumed that the rate of cooling of unit mass of oil in the surface layers will depend on the rate of heat transfer from the oil to the water drops, the rate of stirring of cold oil into the surface layers, and the rate of heat transfer from the flames to the surface layers in the manner shown in equation 1.

$$-\frac{dT_o}{dt} = \frac{K_1}{c}\left(T_o - T_s\right) + K_2\left(T_o - T_c\right) - \frac{H}{c} \quad \ldots\ldots (1)$$

T_o = temperature of surface layers of oil
t = time
c = specific heat of oil
K_1 = heat transfer rate per unit temperature difference to the spray drops contained within the unit mass of oil
T_s = temperature of the spray drops
K_2 = rate of mixing of cold oil into unit mass of oil in the surface
T_c = temperature of the cold oil
H = direct heat transfer from the flames received as sensible heat by unit mass of oil in the surface

K_1 and K_2 will depend in an intricate way on the properties of the spray. It has been found from the tests without spray that H probably increases as the temperature of the liquid is reduced, but that in any case it is likely to be small compared with the other two items on the right hand side of equation 1. In order to simplify this equation, therefore, this term was neglected and T_s was assumed equal to T_c and equal to atmospheric temperature. With these assumptions T_o was integrated with respect to t over the range of time between the beginning of the spray application and the extinction time giving

$$\log \frac{T_i - T_s}{T_e - T_s} = Ky \qquad \ldots \ldots (2)$$

T_i = initial temperature
T_e = temperature at the moment of extinction
y = time of extinction

In equation 2, K may be regarded as a cooling factor dependent on the spray properties only. Assuming T_i = 264°C and T_s = 18°C in all the tests, K was calculated for the different sprays from known values of T_e and y.

RESULTS

Table 3 gives the results of the tests carried out with the fire directly underneath the nozzles, and Table 4 the results of the tests with nozzles A and B for different positions of the fire. These tables show the extinction time and temperature 1 mm below the surface at extinction and also give some comments on the way the fire behaved when the spray was applied.

Mechanism of extinction

Tables 3 and 4 show that in most tests the temperature 1 mm below the surface at extinction was well below the fire point of the oil, 175 - 180°C. Indeed, in only two tests (No. 9 and 33) was the temperature of the liquid at extinction substantially greater than 180°C. The predominant mechanism of extinction was therefore by cooling to the fire point. This conclusion was supported by the fact that, in nearly all the tests, in the period immediately preceding extinction the flames were quite small and usually covered only a small part of the vessel. With sprays from nozzles D and E reignition occurred in only two tests (No. 32 and 33) without the igniting flame touching the surface and in only one test (No. 28) after the flame had touched the surface. In these reignitions the flame spread slowly across the liquid surface. The few tests which did provide some evidence of extinction without cooling to the fire point were all carried out with comparatively fine sprays.

TABLE 3

Extinction times and temperatures

(a) Fires directly underneath the nozzle

Test No.	Nozzle	Pressure lb/in.^{2}	Flow to fire area g cm^{-2} min^{-1} ·X·	Ext. time sec	K	Ext. temp. 1 mm. below surface °C	Comments
1	A	50	1·35	8·8	·03069	150	Flames blown flat after 2-3 seconds application.
2			1·48	7·8	·03258	155	
3			1·49	7·7	·02897	165	
4			1·50	6·1	·03062	178	
5			1·48	5·0	·03989	182	
6	B	100	2·04	13·0	·01770	163	For first 5-10 seconds flames burnt upwards against the spray, reaching a height of about 150 cm.
7			1.75	13·5	·01549	170	
8			2·03	10·7	·01652	182	
9			1.56	10·7	·01219	200	
10			2.15	15·5	·011.1	179	

·X· Divide by 5 to obtain gallons ft^{-2} min^{-1}

TABLE 3 cont'd

Test No.	Nozzle	Pressure lb/in.^{2}	Flow to fire area g cm^{-2} min^{-1} *	Ext. time sec	K	Ext. temp. 1 mm. below surface °C	Comments	
11	C	50	5·75	6·9	·06324	108	Violent upsurge of flame for 1-2 seconds. Flame flattened. Much splashing. Most of surface cleared after 3-5 seconds.	
12			5·75	6·8	·05875	116		
13			5·75	5·8	·06166	126		
14			5·96	7·5	·06607	96·5		
15			5·65	3·4	·1005	130		
16	D	25	0·363	418·7	·000678	146	Flames burnt upwards against the spray. First clearances after 250-300 seconds. usually small flames left at edge some time before extinction. No reignition.	
17			0·363	410·8	·000643	152		
18			0·375	492·4	·000511	156		
19	E	50	0·424	150·4	·002118	136	Flames burnt upwards against spray. First clearance 65 seconds. Last few seconds flames burning at edge only. No reignition.	
20			0·438	96·3	·001879	180		
21			0·443	96·2	·002061	174		
22	F	100	0·823	25·8	·009484	158	Flames pushed downwards after 10-15 seconds of burning. Clearances after 20 seconds. No reignition.	
23			0·804	27·6	·008872	158		
24			0·792	22·0	·01079	160		
25	G	25	0·330	627	·000329	171	Flame height 80 cm. Clearances after 580 seconds. No reignition. Flame height 100-120 cm. Liquid temperature constant at 200°C after 20 seconds burning.	Fierce sputtering
26			0·320	>720				
27			0·317	>720				
28	H	50	0·481	105	·01991	170	Reignition on touching surface with taper. Flames burnt upwards during spray application. First clearances 75-120 seconds	Fierce sputtering
29			0·481	91·3	·02612	160	No reignition	
30			0·430	146·5	·01489	167		
31	K	100	0·721	36·8	·05152	177	Burnt upwards 25 seconds. No reignition.	Violent sputtering
32			0·716	26·4	·03289	178	Burnt upwards 10-15 seconds. Clearance followed by immediate extinction. Reignition without touching.	
33			0·753	22·0	·02399	191		
34	L	100	0·174	>360			Very violent sputtering. Flame height alternating between 80-140 cm. Liquid temperature 250 - 270°C.	

* Divide by 5 to obtain gallons ft^{-2} min^{-1}

TABLE 4

Extinction times and temperatures in tests

(b) Position of fire varied in a plane 8 ft below the nozzle

	Nozzle and position	Distance from centre ft	Flow to fire area g cm^{-2} min^{-1}	Ext. time sec	K	Ext. Temp. °C	Electrical conductivity readings (microvolts)	Comments
1	Aa	0	1·35	8·8	·03069	150	n.d.	Flames blown flat after 2-3 seconds.
2			1·48	7·8	·03258	155	0·0	
3			1·49	7·7	·02897	165	0·6	
4			1·50	6·1	·03062	178	n.d.	
5			1·48	5·0	·03989	182	0·0	
55	Ab	2	1·00	7·0	·03499	158	2·8	
56			0·97	6·7	·02951	174	0·6	
57			0·97	5·0	·04775	160	6·0	Flames blown sideways after about 3 seconds, followed by clearance and extinction.
58	Ac	3	1·66	3·5	·06124	168	0·0	
59			1·62	5·3	·06295	132	0·0	
60			1·57	5·1	·03767	176	0·6	
61	Ad	3 ft 6 in.	0·76	6·3	·02917	179	n.d.	
62				8·3	·02630	167	n.d.	
63				7·5	·02673	173	n.d.	
64				7·5	·02600	175	n.d.	
65	Ae	4	0·53	78·6	·005943	102	2·6	Flames blown sideways and began to clear from surface at about 15 seconds. After about 25 seconds only small flame left burning at edge remote from nozzle.
66			0·52	49·3	·008851	108	n.d.	
67			0·57	66·3	·007278	99	1·5	
6	Ba	0	2·04	13·0	·01770	163	n.d.	For first 5-10 seconds flames burnt upwards against the spray reaching a height of about 150 cm.
7			1·75	13·5	·01549	170	n.d.	
8			2·03	10·7	·01652	182	n.d.	
9			1·56	10·7	·01219	200	n.d.	
10			2·15	15·5	·01191	179	n.d.	
48	Bb	2	1·78	9·1	·02897	152	n.d.	Flames blown sideways after 4-6 seconds.
49			1·90	10·7	·02618	147	n.d.	
50			1·60	11·2	·02559	145	n.d.	
51	Bc	3	0·65	7·3	·03750	133	n.d.	Flames blown sideways after 2-4 seconds. Usually clearances after 4-6 seconds. Last 2 seconds usually small flame left at edge furthest from nozzle.
52			0·66	7·7	·03141	138	n.d.	
53			0·76	7·3	·03750	149	n.d.	
54	Bd	3 ft 6 in.	0·34	7·7	·03141	159	n.d.	
55			0·38	7·5	·03784	146	n.d.	
56			0·42	6·8	·02692	172	n.d.	
57	Be	4	0·23	8·7	·02917	155	n.d.	
58			0·23	9·6	·03141	141	n.d.	
59			0·21	7·5	·03741	147	n.d.	
50	Bf	4 ft 6 in.	0·13	6·5	·02831	179	n.d.	As for test 51-59.
51			0·14	8·5	·03027	154	n.d.	
52			0·11	18·3	·01489	149	n.d.	Flame blown sideways. Small partial clearances of flame gradually increasing in size until extinction.

Formation of an oil in water emulsion. Table 4 shows that the maximum reading with the electrical conductivity apparatus obtained during the application of sprays from nozzle A to the fire was 6·0 microvolts. This is about one ten-thousandth of the reading obtained when the electrodes were inserted in an artificially prepared emulsion of oil in water. Table 5 gives further readings obtained when no fire was present. They include readings in which the electrodes were placed in transformer oil and in air and also readings in which the nozzle was placed 2 ft from the liquid surface and the electrodes.

TABLE 5

Electrical conductivity readings in absence of fires
spray pressure 50 lb/in.^{2}

Height above electrodes ft	Horizontal distance of electrodes from centre of spray ft	Rate of flow of spray near electrodes g cm^{-2} min^{-1}	Electrodes in transformer oil		Electrodes in air	
			Maximum reading microvolt	Time of application seconds	Maximum reading microvolt	Time of application seconds
8	0	1·5	6·0	180	1·6	42
8	3	1·7	2·0	60	n.d.	n.d.
2	0	12·9	0·0	13	12·8	16
2	0	12·9	0·0	11	1·2	13

The largest reading (12·8 microvolt) was obtained in a test in which the electrodes were placed in air 2 ft below the nozzle. This reading was probably due to the conductivity between the electrodes through a film of water formed by the spray on the glass covering the leads to the electrodes; it is unlikely that it was due to conductivity within the spray itself. Whenever a reading was obtained with the electrodes in the transformer oil, either with or without a fire, it was recorded about 3 seconds after the application of spray. Tables 4 and 5 show that the readings obtained when the electrodes were in oil were of the same order as the zero fluctuations of the instrument and the readings which could be obtained when spray was applied to the electrodes in air. They were insignificant compared with the readings obtained when the electrodes were placed in an oil in water emulsion even of low water content.

In most tests in which oil was subjected to a high rate of flow of spray the oil turned milky presumably due to the high concentration of water drops in the oil and a froth also formed which was probably due to entrained air being carried into the oil by the spray. Samples of oil taken from near the surface after spray application were all found to consist of a suspension of water drops in oil irrespective of whether the spray was applied to an oil fire or to cold oil. Figure 7 shows an enlarged photograph of the suspension of water drops in oil obtained after spray C had acted on the oil for 30 seconds. It may therefore be concluded that the tests carried out revealed no positive evidence that the application of the spray brought about an oil in water emulsion near the surface, and that no basis was found for ascribing the extinctions to this mechanism. However, further tests on the detection of oil in water emulsions, which may be formed by direct spraying are being carried out and these will be reported later.

Effect of spray properties

The spray properties that were measured were the rate of flow to the fire area, the vertical component of the entrained air velocity and the drop size. As the fire area occupied only a small part of the total

area of the spray it was assumed that the spatial pattern at the area was reasonably uniform. On the assumption that no other spray properties influence the results of a direct estimate of the effect of any one of these properties may be made by comparing the performance of two or more sprays which differ mainly in one property.

Entrained air velocity. Sprays A and B at the centre (a) of the fire area differed mainly in entrained air velocity. For spray A this velocity was greater than the upward velocity of the flames (approximately 8 ft/sec) and as a result the column of flame was pushed downwards by the spray. On the other hand the air velocity of spray B was smaller than that of the flames and during the initial stages of application, the flames could move upwards against the spray. This prevented access of the spray to the burning liquid and prolonged the extinction time. These phenomena are illustrated in Figure 8 which shows the movement of the flames during tests with these sprays.

Drop size. Spray C had a much higher rate of flow and entrained air velocity than spray A(a), but also had a much coarser drop size. It has been found in previous work on liquid fires (3), that an increase in rate of flow, especially if accompanied by an increase in entrained air velocity, considerably enhances the efficiency. The extinction times with spray C, however, was not significantly less than with spray A in position a. This suggests that the effect of the increased rate of flow and entrained air velocity was counterbalanced by the effect of the very coarse drop size. It was noticed that this spray produced much splashing which appeared to maintain the fire after the liquid had been cooled to the fire point. Table 3 shows that the liquid had been cooled to well below the fire point before extinction took place.

On the other hand with the finest sprays tested (nozzles K and L) violent sputtering considerably increased the flames when the spray was applied. With nozzle L the burning was maintained with a violence considerably greater than the normal burning fire. The flame heights fluctuated periodically between 80-140 cm. When the flames were low some of the fine spray could reach the fire; this caused sputtering which increased the height of the flames. The latter in its turn cut down the access of the spray and the flames subsided. This cycle of events continued throughout the whole period of spray application.

Effect of position of the fire

Table 4 shows the spray was much more effective in extinguishing the fire if the latter was not directly underneath the nozzle. Thus for the positions b, c, d, e with spray B, there was a substantial reduction in the rate of flow and the entrained air velocity to the fire area as the distance from the centre of the spray increased. In spite of this the extinction time decreased from position a to b to c and remained constant from positions c to d to e. For spray A, the rates of flow and the downward entrained air velocity at positions b and d were considerably less than at the centre but the extinction times were approximately the same. There is little doubt that the increase in efficiency was caused by the flames being blown sideways by a horizontal component of the entrained air current. This allowed the approach of the spray drops to the burning liquid without the interference of an upward moving flame. The effect was more marked with spray B than with spray A presumably because the latter spray already had a sufficiently high entrained air velocity in the centre of the spray to allow the spray to penetrate the upward moving flame. It is clear that as the edge of the spray is approached there must be some point where the efficiency of extinction must suddenly drop because of insufficient water reaching the fire area. Thus with spray A the extinction time rose from about 8 seconds to one minute on moving the fire 6 in. outwards from position d to e. The drop in rate of flow in this case was from 0·76 to 0·55 g.cm^{-2} min^{-1}. The tests did not show the effect of the edge of the spray so definitely for spray B, but with test No. 66 in position f (4 ft 6 in. from the centre) the extinction time was larger than with any other test with this spray.

Statistical analysis of the results

A quantitative estimate of the effect of the spray properties on the extinction time and on the cooling capacity of the spray was obtained by carrying out regression analyses. The results of tests, 45, 46, 47, 60, 61 and 62 were not included in these analyses; these tests were conducted at the edge of sprays A and B and it was difficult to adjust the analysis to follow the very sharp increase in extinction times obtained. The few tests in which there was clear evidence that the liquid was not cooled to the fire point were also ommitted, as were those in which there were not readings of both extinction time and extinction temperature. These subtractions left a total of 50 tests.

Extinction time. The analysis showed that 86 per cent of the variation of the extinction time about the mean extinction time could be accounted for by equation 3.

$$\log y = -1{\cdot}11 \log R + 1{\cdot}08 \log D - {\cdot}00065\, A - {\cdot}388\, L + 2{\cdot}28 \quad \ldots\ldots 3$$

y = extinction time (seconds).
R = rate of flow to the fire area (g cm^{-2} min^{-1}).
D = mass median drop size of the spray (mm).
A = entrained air velocity (ft/min).
L = distance of fire from the centre of the spray (ft).

Equation 3 may be taken as broadly representing the effect on the extinction time of the spray properties and the position of the fire, under the particular conditions of the tests, and gives a quantitative expression to the qualitative conclusions reached above.

It follows from equation 3 that for a given entrained air velocity and position of the fire

$$y \propto R^{-1{\cdot}11}\, D^{1{\cdot}08} \quad \ldots\ldots 4$$

Equation 4 broadly implies that for a given extinction time the rate of flow will be directly proportional to the drop size of the spray.

It was also found that the more complicated equation 5 could account for 92 per cent of the variance.

$$\log y = -0{\cdot}99 \log R - 0{\cdot}00149A - 0{\cdot}42\, L + 78 \log 10D - 102 \log^2 10D + 43{\cdot}8 \log^3 10D - 16{\cdot}43 \quad \ldots\ldots 5$$

The range of drop sizes in those extinction tests that were analysed was from 0·4 to 1·3 mm. Equation 5 indicates that within the range 0·4 to 0·8 mm the drop size had little effect on the extinction time, but that there was a sharp increase in extinction time for sprays of drop size greater than 0·8 mm.

Cooling capacity

It was found that 91 per cent of the variance of the cooling capacity of the sprays could be accounted for by equation 6

$$\log K = \log \left(\frac{1}{y} \log \frac{246}{Te - 18}\right) = 1{\cdot}04 \log R - 0{\cdot}99 \log D + 0{\cdot}00088A + 0{\cdot}41L - 3{\cdot}024 \quad \ldots\ldots 6$$

It will be noted that the regression coefficients in equation 6 are very similar in value to those of equation 3 but are of opposite sign. This implies that the more efficient was the spray in cooling the liquid i.e., the greater the value of K, the more rapid was the extinction. This may have been expected from the fact that only extinctions in which the liquid were cooled to the fire point or below were [illegible]

However, in some tests cooling took place to well below the fire point before the fire was finally extinguished. The differences that exist between the regressions coefficients of equations 3 and 6, apart from their opposite sign, are attributable to variations in this extra amount of cooling.

DISCUSSION

With all the sprays the predominant mechanism of extinction was by cooling the liquid to the fire point. One or two of the finer sprays occasionally brought about extinction without cooling the liquid to the fire point; this is in line with previous tests (4) carried out with sprays within the range of drop size of 0·28 to 0·49 mm in which extinction was obtained fairly frequently without this degree of cooling. The extinction mechanism in these tests may be by extinction of the flames or by the formation of steam at the hot liquid. However, from the practical point of view it is unlikely that sprays which are sufficiently fine to extinguish the fire reliably without cooling to the fire point can be easily developed and even if this were not so they would not necessarily be advantageous since this degree of cooling is very desirable in any case, in order to counteract possible reignition from stray ignition sources.

It follows that nozzles to be used in practice for protective installations against high boiling liquids should be designed so that spray may penetrate to places where liquid is likely to burn rather than to fill any volume which flames are likely to fill. In general there are two main causes which would prevent sprays penetrating to the burning liquid, firstly the counter current of the flames and secondly extraneous wind. On the other hand there are two factors in the design of the nozzle system which influences the penetration, firstly the position of the nozzles relative to the risk and secondly the forward momentum of the spray streams. It is clear that in a protective installation these latter two controllable factors must be adjusted so as to overcome the effect of the flame and wind motion.

Position of the nozzles

If the nozzles are placed so that the projected spray misses the direct counter motion of the flames then the spray produced will reach the burning surfaces much more easily. In general flames travel upwards and the nozzles should be installed to spray sideways on to a risk. However, although this principle may be used in the general siting of nozzles, it may be physically impossible to apply it in a number of cases. Moreover, the motion of the flames may depend on wind conditions and therefore there is an unknown element in the direction the flames will take. It follows that complete reliance cannot be placed on the positioning of the nozzles alone.

Momentum of the sprays

The total momentum flux within a spray will be the product of the rate of flow and the velocity at the nozzle. The concentration of the momentum flux will be determined by the cone angle of the spray; the larger the cone angle the larger will be the area through which the spray passes and as a consequences the smaller will be the momentum flux per unit area. An increase in cone angle will also decrease the total amount of useful momentum flux since the larger the cone angle the smaller will be the velocity component at the nozzle in the forward direction of the spray. The pressure at the nozzle has an important influence on the momentum flux in that it is the main factor effecting the velocity at the nozzle.

As the spray passes through the air an increasing quantity of the momentum which is initially in the spray drops will be transferred to the bulk motion of an entrained air stream. The rate at which this momentum

will be transferred will depend on the frictional resistance offered to the drops, and for unit flow or for unit momentum flux, this resistance decreases as the drop size of the spray increases. Thus with fine sprays the bulk of the momentum is transferred to the entrained air stream fairly soon; measurements on a series of sprays produced by impinging jets (5) showed that with sprays of drop size less than 0.6 mm the entrained air stream accounted for the bulk of the spray momentum after the sprays had travelled five feet. With coarse sprays, however, the momentum transfer from drops to entrained air will be less, and a correspondingly larger fraction of the initial momentum will be retained.

From the point of view of the penetration of the spray it is better that drops retain as much as possible of their initial momentum. Thus consider a spray of drops projected towards an area at a rate of flow of R units per unit area and at an initial velocity of V units. If all the initial momentum of the spray were converted into the momentum of an entrained air stream then the mean velocity A of the air stream will be given by

$$A = \sqrt{\frac{R}{\rho}}\,V \qquad \ldots\ldots 7$$

(ρ = density of the air).

For sprays used in practice R will be of the order of 1 ft/sec and V about 100 ft/sec; thus A would be about 10 ft/ sec. If this entrained air-stream encountered a contrary air stream somewhat greater than itself it would be deflected. However, if the drops still retained a large proportion of their initial momentum then, although they may be subject to a greater deceleration when they encountered a wind of 10 to 20 ft/sec, they would still retain their forward motion.

Thus although in practice it will be a desirable feature to design nozzles in such a way as to conserve the entrained air stream there will probably be an upper limit to the usefulness of this stream in carrying fine spray forward to a burning surface. Spray systems which have to work under conditions which are beyond this limit will have to employ sprays with sufficiently coarse drops to allow a sufficiently larger fraction of the initial momentum of the drops to be retained in the drops. It would appear from the present series of tests that this would be accompanied by a diminution in the innate efficiency of the spray in extinguishing the fire, and that the rate of flow would have to be increased in approximately direct proportion to the increase in drop size. It is clearly a matter of practical importance therefore to determine whether this effect of drop size is of similar importance in larger size fires and also to obtain some measure of the conditions under which the entrained air stream accompanying a spray may be relied upon to carry fine sprays to the burning liquids.

ACKNOWLEDGEMENT

Mr. M. Perry and Mrs. J. Freer assisted in the experimental work and Mr. A Kelly in the statistical calculations. The authors are indebted to Mr. D. W. Millar for discussions on the statistical methods used.

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(2) D. J. Rasbash and Z. W. Rogowski. F.R. Note No. 36.

(3) D. J. Rasbash and Z. W. Rogowski. F.R. Note No. 58.

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

(5) D. J. Rasbash. F.R. Note No. 181

ERH

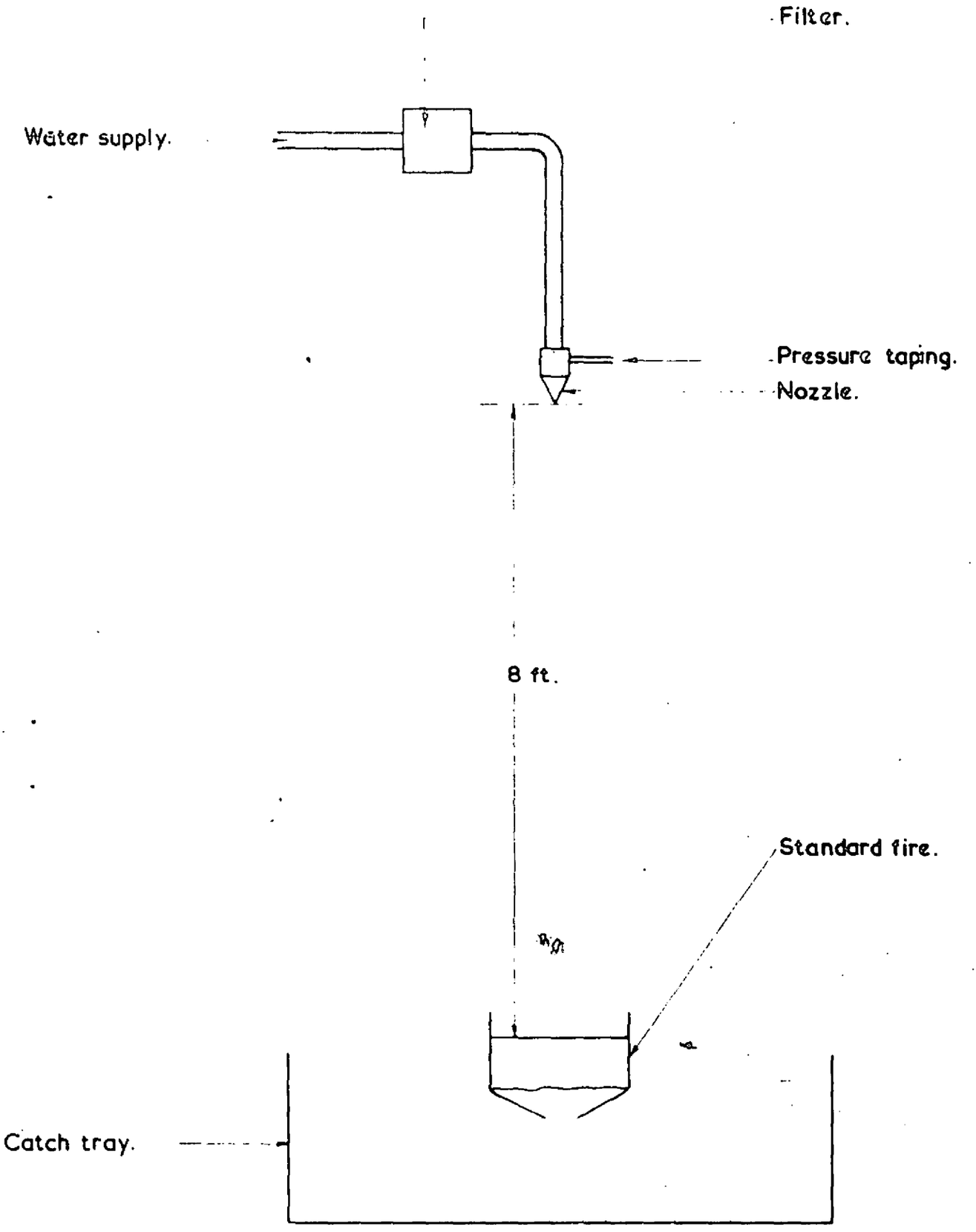


FIG. 1. DIAGRAM OF APPARATUS.

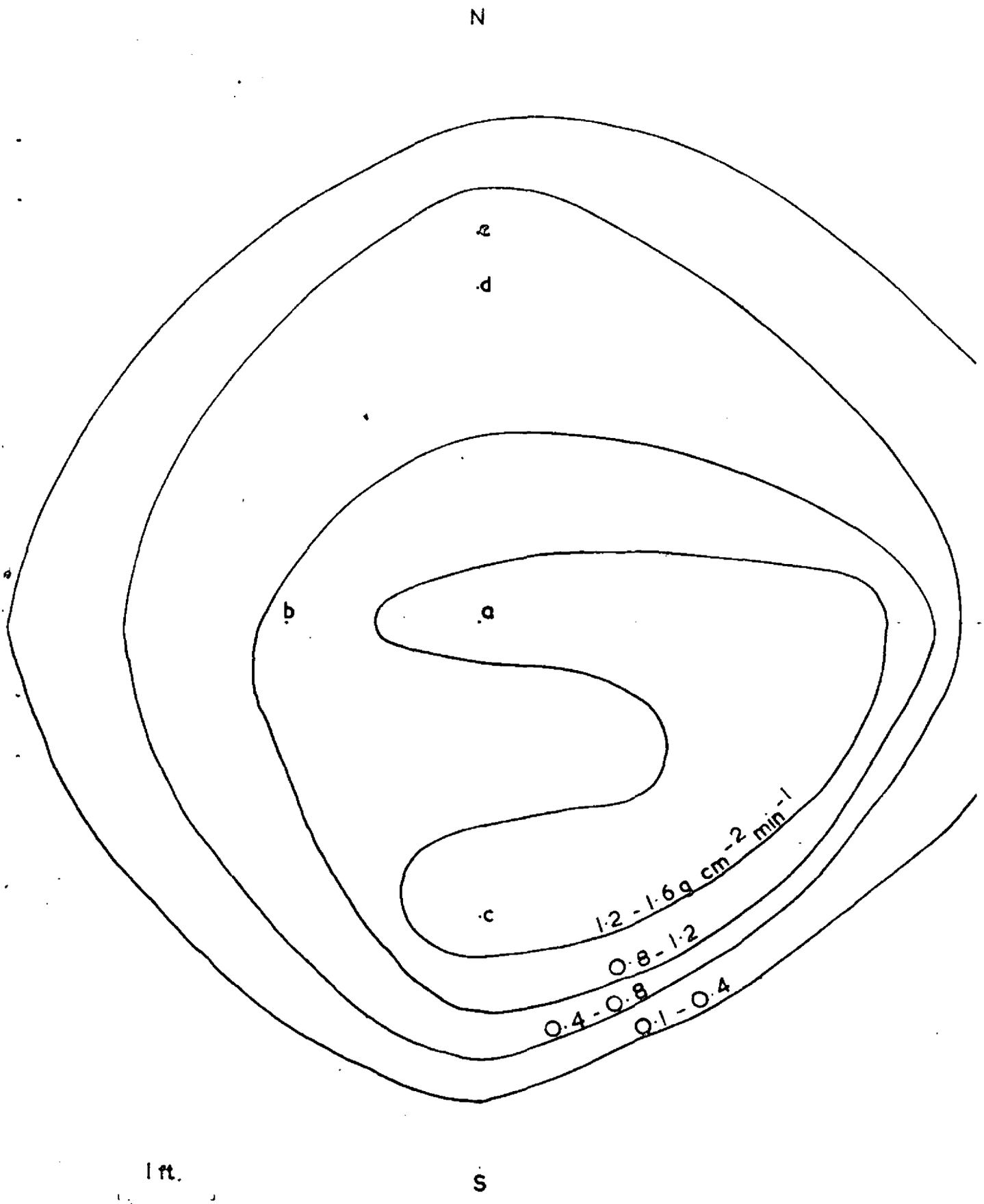


FIG. 2. PATTERN OF SPRAY A SHEWING POSITIONS AT WHICH TESTS WERE CARRIED OUT.

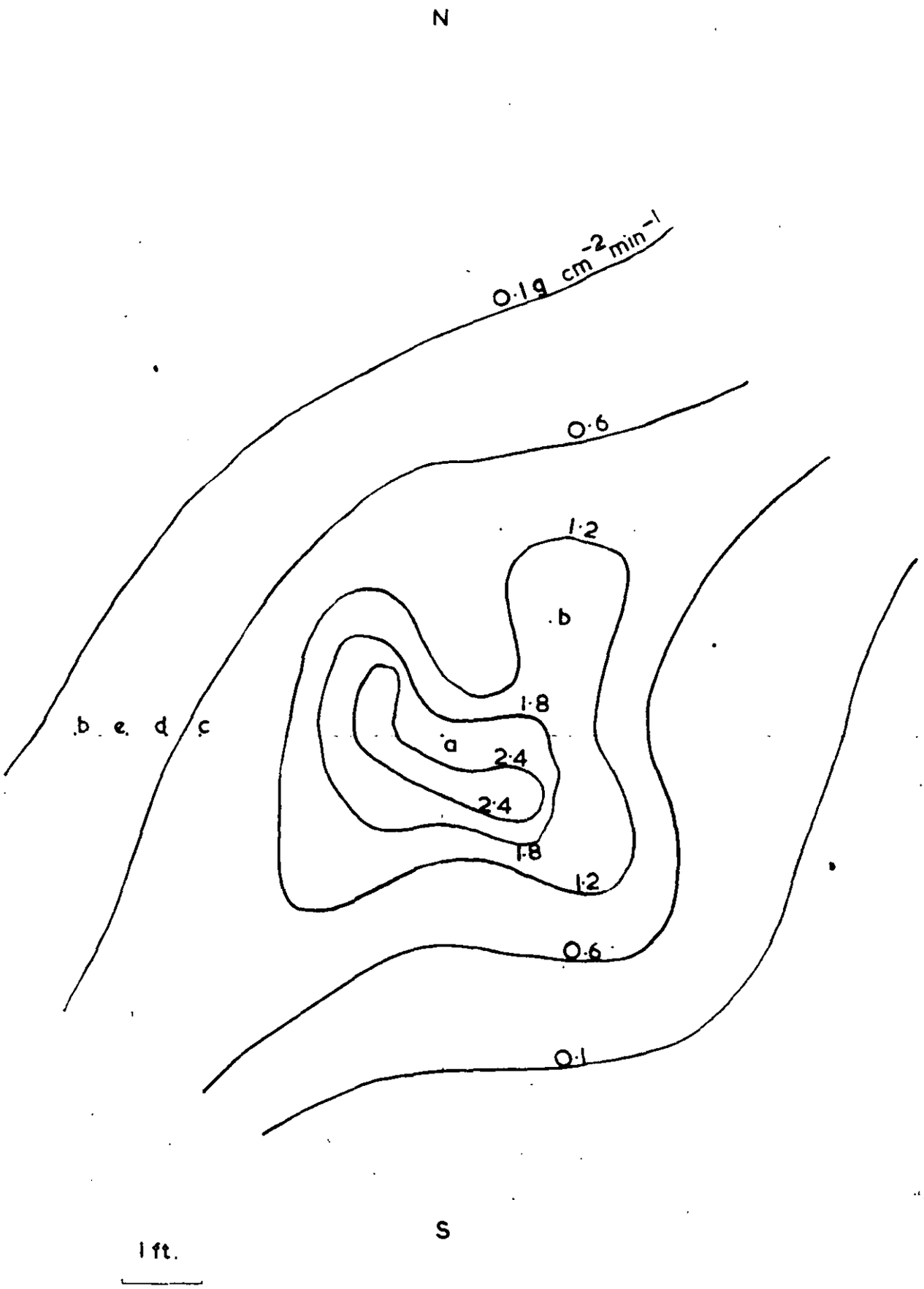
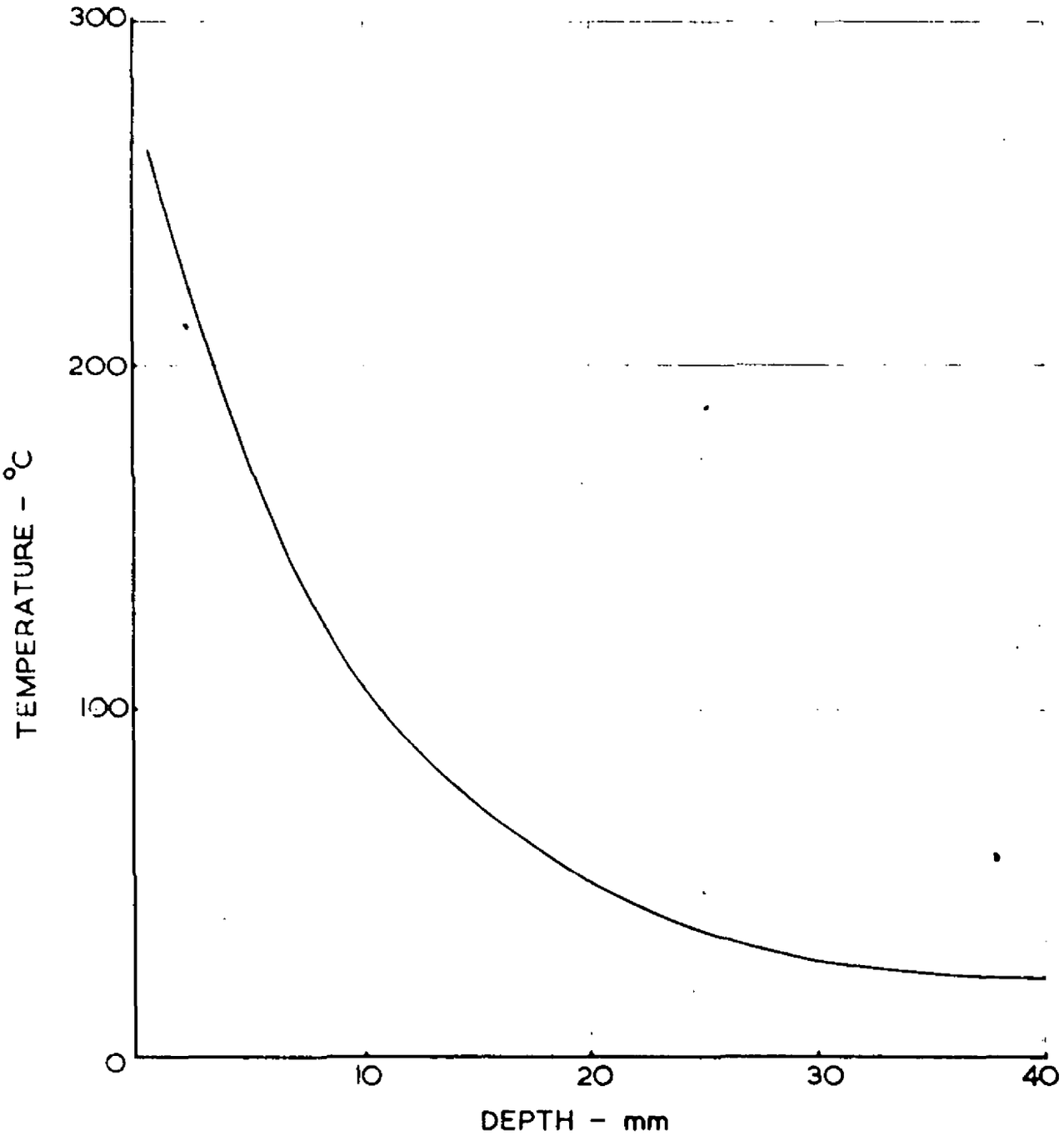


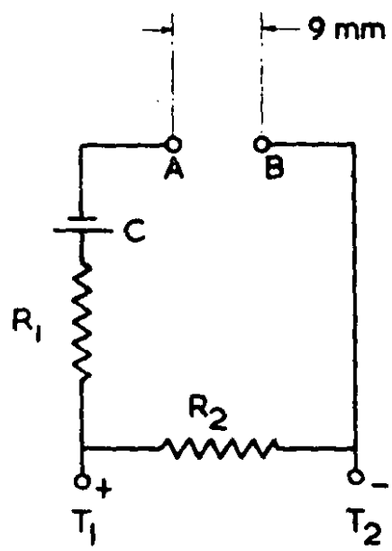
FIG. 3. PATTERN OF SPRAY B SHEWING POSITIONS AT WHICH TESTS WERE CARRIED OUT.



Time of burning 5 min.

Diameter of fire 30 cm.

FIG. 4. TEMPERATURE DISTRIBUTION BELOW THE SURFACE OF BURNING TRANSFORMER OIL.



A and B electrodes 1·5 mm diameter spheres.

R_1	10,000 Ω
R_2	100 Ω
C	12 v. cell.
T_1 and T_2	D.C. Amplifier terminals.

FIG. 5. CONDUCTIVITY MEASUREMENT CIRCUIT.

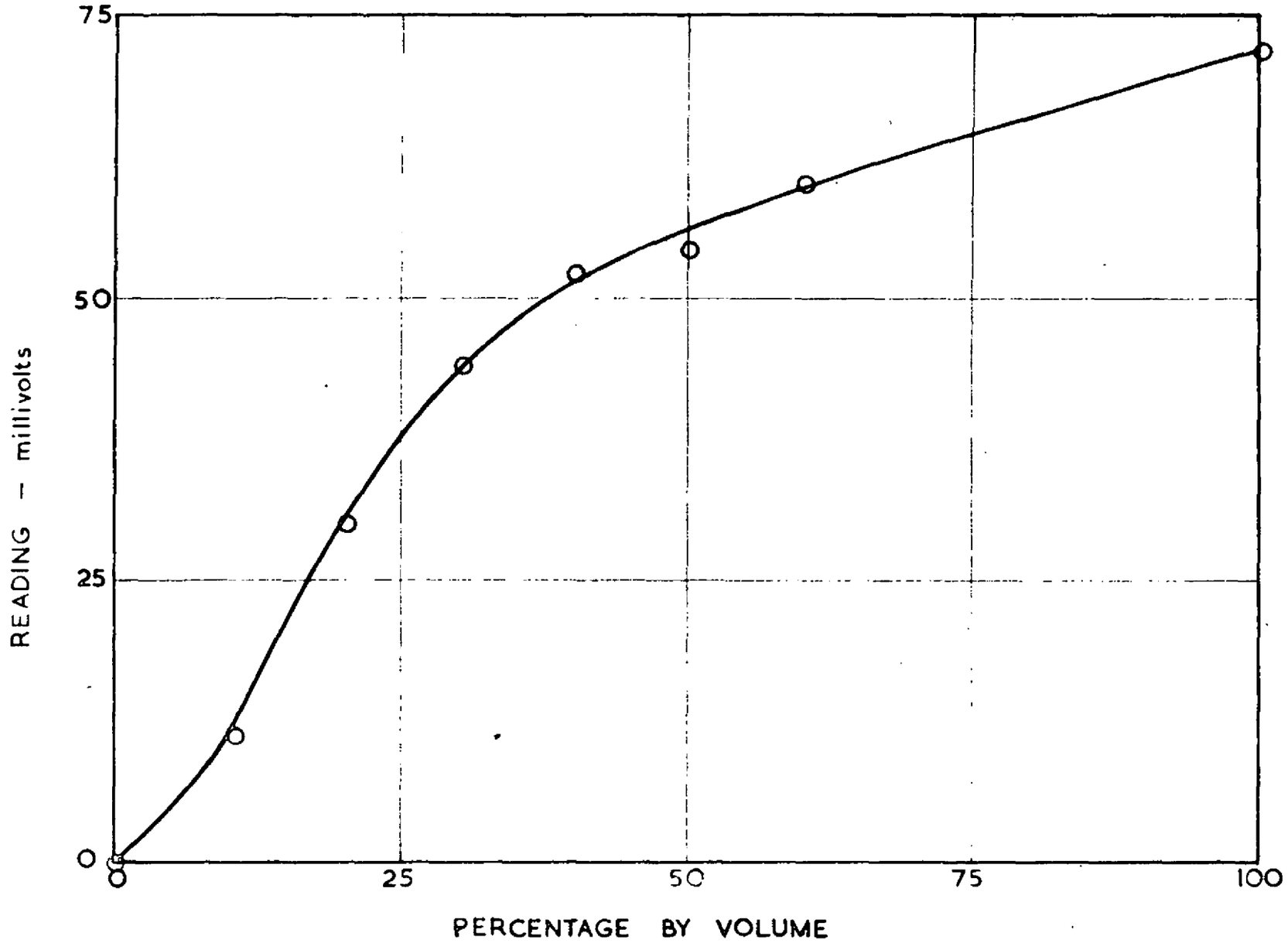
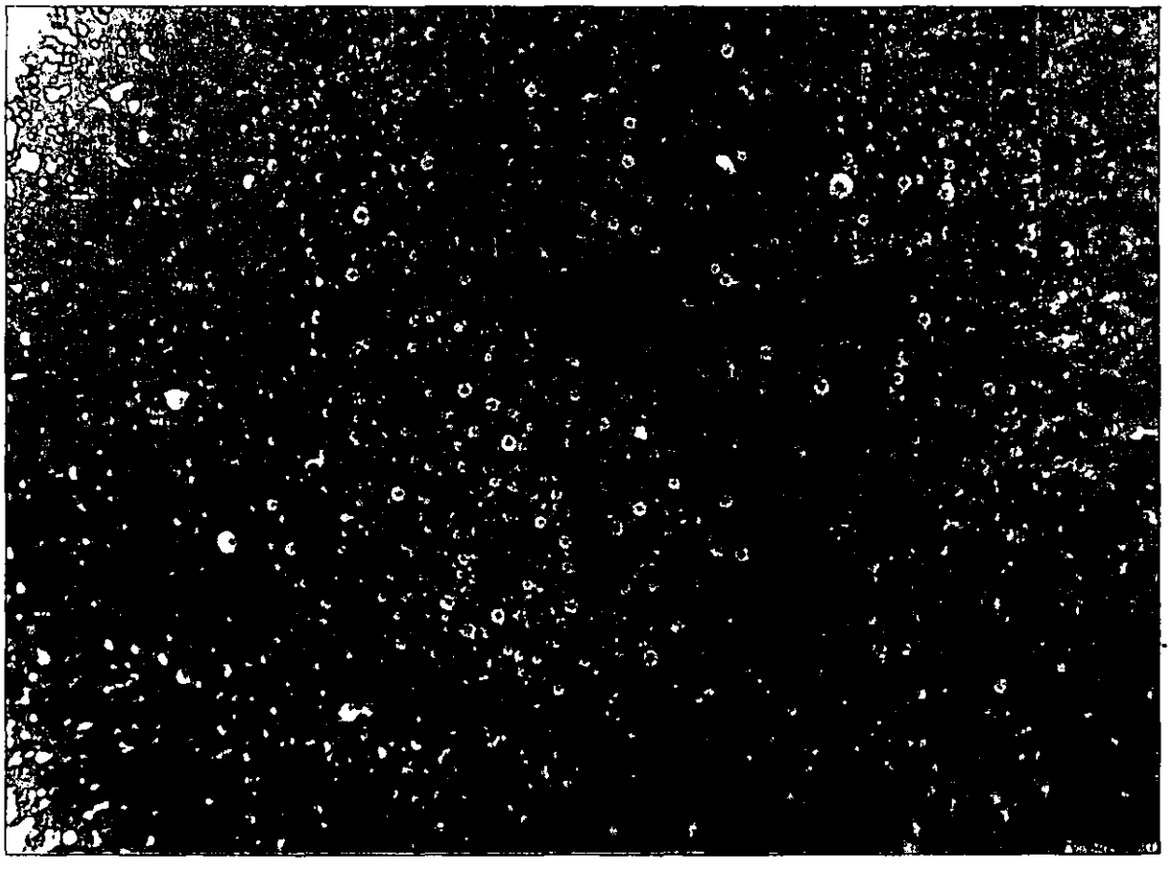


FIG. 6. CONDUCTIVITY MEASUREMENTS ON STABILIZED EMULSIONS



Sample of suspension of water drops in oil. Taken from near surface of sprayed liquid.

Spray C.

Time of application	—	30 s
Time between sampling and photographing.	—	40 s

FIG. 7.

$\frac{1}{2}$ s 1s 3s 5s 7s 9s 11s 13s

Test no. 10 Flames burning upwards against the spray because of low entrained air velocity (7·5 ft/s)

EXTINCTION 15·5 s

1s 2s 4s 6s 8s

[illegible] blowed away by the spray because of high entrained air velocity (15·4 ft/s)

EXTINCTION 8·8 s

Be[illegible]

ON A TRANSFORMER OIL FIRE

[illegible]