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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 HIGH BOILING-OILS

PART 2

TESTS ON TRANSFORMER OIL FIRES 3 AND 4 ft DIAMETER

by

D. J. Rasbash and Z. W. Rogowski

Summary

A series of tests have been carried out on the extinction of transformer oil fires 3 and 4 ft diameter with water sprays from a range of single nozzles. The tests were carried out in a roofless structure in the open air. Within the range of rates of flow to the fire and drop sizes tested ($0{\cdot}45 - 7{\cdot}0$ g cm^{-2} min^{-1} and $0{\cdot}4 - 3{\cdot}0$ mm respectively) the extinction time was approximately inversely proportional to the rate of flow and directly proportional to the drop size. No significant effect of the entrained air velocity of the spray was detected; this may have been due to the scatter of the results which was much wider than with small-scale tests carried out in the laboratory. In all tests but one, the liquid was cooled to below the fire point prior to extinction. In some tests however the liquid was cooled to well below the fire point without extinction; the maintenance of fire in these cases was due to the burning of oil drops splashed upwards into the flame.

[illegible], 1955.

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THE DESIGN OF WATER SPRAYS FOR [illegible] HIGH BOILING-OILS

PART 2

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Introduction

In part 1 (1), an account was given of the extinction of a transformer oil fire with sprays produced by three proprietary nozzles and three experimental nozzles. The present report gives an account of further tests with a wider range of nozzles on fires 3 and 4 ft diameter. The object of these tests has been to obtain an estimate of the performance of individual nozzles before carrying out further work with groups of nozzles on larger fires.

Experimental

Apparatus

The tests with a 1 ft fire (1) were carried out in a closed laboratory so as to eliminate the effect of external wind conditions. It would have been preferable to carry out the tests with the larger fires under similar conditions but no suitable enclosed space was available. In order to obtain some shielding from external winds, a roofless structure of scaffolding covered with light aluminium sheeting was erected to house the fire. This structure rested on the ground and formed the four walls of a box 30 ft x 30 ft x 20 ft high.

Figure 1 shows a plan of the apparatus within the structure, and the sectional elevation on the line $z - z_1$, in the plan. A concrete platform A 1 ft deep and 15 ft square was laid in the centre of the enclosure and the combustion vessel B was supported on bricks at the centre of this platform. The nozzle N was supported directly above the combustion vessel on a rigid boom C. The weight of this boom was balanced by counterweights E which were suspended outside the aluminium sheet structure. This enabled the boom to be moved up and down and thus allowed variation of the height of the nozzle above the liquid. By using the clamps F, the boom could be fixed in any given position by clamping to the vertical uprights G.

Two combustion vessels were used; they were respectively 3 and 4 ft diameter, 6 in. deep and were constructed from 16 gauge sheet steel. A steel outlet pipe 1·5 in. diameter ran from the bottom of the combustion vessel along a trough in the platform to an overflow tube L and a glass gauge tube H. There were two valves in this outlet pipe, one U, beyond H and the other, V immediately before H. A small stream of water could be introduced into the vessel through a pipe W and the overflow tube L. The height of the overflow, and this stream of water were regulated so that the liquid level in the vessel remained fairly constant during a preburn period. The glass gauge H could be used to measure the rate of flow of water spray to the vessel by measuring the increase in depth of liquid in the vessel after the application of the spray for a measured period of time.

The nozzle was attached to the end of a 20 in. vertical length of 1·5 in. diameter pipe. The inner surface of this pipe was lined with copper to prevent rusting. The pipe was attached to a "quick action" lever-operated diaphragm valve S which was in its turn attached to a horizontal length of pipe supported by the boom. A filter P was placed in the horizontal pipe as near the [illegible] as possible [illegible]
[illegible]

diameter, also operated by a pulley system, was suspended from the boom. During the preburn period of a test, this can was below the nozzle; this prevented drops of water from small leaks at the nozzle falling on the burning liquid and also helped to reduce the amount of smoke which reached the nozzle from the flames. Water was supplied to the nozzle from a 10,000 gallon storage tank through a centrifugal petrol driven pump. The throttle was sufficiently sensitive to allow the pressure at the nozzle to be controlled to 1 - 2 lb/in^2. This pressure was measured at a tapping placed immediately behind the nozzle.

Temperature and radiation measurements. The temperature of the liquid was measured with a copper-constantan couple, (Figure 2). The leads to the junction were insulated with porcelain and were sealed near the junction in a pyrex glass tube. This tube was sealed to a ground glass socket which fitted on a stainless steel cone soldered to a long length of copper tube which passed over the vessel edge and away from the fire. The thermocouple leads passed through this tube to a recording system. Radiation from the fire was also recorded by two thermopiles R, which were fixed behind a pyrex glass shield 21 ft from the centre of the combustion vessel on opposite walls of the structure, as shown in Figure 1. They pointed towards the centre of the combustion vessel, and were connected in series with each other and a recording system.

Nozzle tested. Nine nozzles were used in the tests; the properties of the sprays they produced at the different pressures at which they were used are shown in Table 1. Nozzles A, B, C and D were proprietary solid cone swirl nozzles, and nozzles E, F and G were proprietary non-directional multi-impinging jet nozzles. Nozzles H and K consisted of six pairs of impinging jets 9/64 in. diameter; the arrangement of the jets on the nozzles is shown in Figure 3. Photographs of sprays from the nine nozzles produced at a pressure of 50 lb/in^2. are given in Plates 1, 2 and 3.

The cone angle of the sprays was measured from photographs. It was difficult to measure this property for nozzles E, F and G as these sprays were non-directional and the figures given in Table 1 are therefore very approximate. The fourth and fifth column of Table 1 give the mass median and Sauter mean drop size * of the spray at a point 8 ft directly below the nozzle, and the sixth and seventh columns give these two drop sizes in the same horizontal plane but 17 in. away. (N.B. 17 in. was the radius of a circle that divided the 4 ft combustion vessel into two equal areas). With a number of the coarser sprays, it was difficult to assign a precise mass median drop size to the spray. It was found that a large proportion of the drop volume of the sample was accounted for by a few very coarse drops, and the mass median drop size fell at some point within a number of drop size groups into which no spray drops were classified. The Sauter mean drop size, which could be estimated precisely for all the sprays therefore probably gave a better indication of their relative drop sizes. The figures for the spatial pattern of the spray given in Table 1 refer to the 4 ft diameter vessel; they represent the ratio of the mean rate of flow in the central 2 ft diameter section of the vessel to the mean rate of flow at the edge of the vessel. The entrained air velocity readings are the mean of five reading in a plane 7 ft below the nozzle; one of the readings was taken on the spray axis and the other four at symmetrically placed points 17 in. from the axis. In order to make the measurements of

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*The Sauter Mean drop size is given by the formula

$$\frac{\Sigma n_i d_i^3}{\Sigma n_i d_i^2}$$

where n_i is the number of drops of diameter d_i.

entrained air velocity representative of the test conditions, the readings were taken on the site as near as possible in time to the actual fire tests. They were subject, therefore, to a variety of cross-wind conditions. The manner of measurement was such that the presence of a cross-wind almost invariably caused a decrease in the reading and this probably accounts for the negative values of the entrained air velocity obtained for nozzles F and G. The rate of flow at the fire area given in the last column is the range of mean rates of flow obtained during tests with the 4 ft diameter vessel.

Test routine. For each test, a layer of transformer oil about 5 cm deep was floated on water in the combustion vessel. During a test, a layer of about 1 cm of oil would burn away. In order to conserve oil, for the next test the oil was not changed but the depth of oil was made up with fresh oil. Samples of the oil in the vessel taken at different times during the series showed that this procedure did not have any significant effect on the distillation range or the open cup fire point of the oil although direct observation indicated that the amount of soot in the liquid increased as the tests proceeded. The position of the overflow was set to give an ullage of 5 cm. In most of the tests, the thermocouple was placed to give a reading between 3 - 5 mm below the liquid surface at a point 1 ft from the edge of the vessel. However, to give some information of the temperature distribution below the surface, a few tests were carried out in which the thermocouple depth was outside this range.

The liquid was ignited with a match after priming first with petrol; 200 and 120 cc of the priming liquid was used for the 4 and 3 ft diameter vessel respectively. The fire was allowed to burn for 5 minutes before the spray was applied; during the last half minute of this period and during the period of spray application records of the liquid temperature and the flame radiation were obtained. The behaviour of the fire when the spray was applied and the extinction time were noted. In most of the tests, the depth of the liquid remaining after the test was recorded.

A measurement of the mean wind velocity over a period which included the period covered by the test, was also made. It was noted in preliminary tests, that if the wind was blowing in a certain direction, the flames would tend to veer in the opposite direction; this effect was caused by suction within the enclosure by the wind passing over the walls of the enclosure. In order to simulate conditions obtaining in the laboratory tests, it was desirable that the flames should pass vertically upwards, especially at the moment of spray application. The veering could be reduced somewhat by making an opening in the wall on the windward side of the fire. This opening was adjusted manually in the 5 minute period of preburn so as to give the greatest tendency, as judged by direct observation, for the flames to move upwards. However, because wind speed and direction tended to change so rapidly during a test, in the majority of tests, there were considerable fluctuations in the motion of the flames which were not under control.

All the nozzles were tested at a height of 8 ft on the 4 ft diameter fire. Nozzles C and D were tested against the 3 ft diameter fire from a height of 8 ft and nozzles C and K on the same fire from a height of 15 ft. With nearly all the sprays, extinction was obtained; where this occurred, at least three tests were carried out.

Results

Properties of the fires. Although few direct measurements were made of properties of the fires, a certain amount of information was obtained while carrying out the tests. When the flames moved vertically upwards, they reached heights of about 8 - 10 ft (2·5 - 3 m) with the 4 ft fire, and 6 - 8 ft (1·8 - 2·5 m) with the 3 ft fire. With both fires, a thick vapour zone formed after 1 - 2 minutes of burning. From the depth of liquid consumed during the test it was estimated that the rate of burning of the 4 ft fire was $0{\cdot}18 \pm 0{\cdot}01$* g cm^{-2} min^{-1} and the 3 ft fire $0{\cdot}14 \pm 0{\cdot}04$ g cm^{-2} min^{-1}. These values are both considerably greater than the rate of burning in the 1 ft diameter vessel in the laboratory which was $0{\cdot}067 \pm 0{\cdot}004$ g cm^{-2} min^{-1}. The temperature of the oil below the surface after 5 minutes burning was also much greater for the larger fires. In Figure 4 this temperature has been plotted against the depth of the thermocouple. For the 4 ft fire, up to a depth of 5·5 mm the temperature was approximately independent of the depth, but fell sharply at greater depths. The corresponding curve for the 1 ft diameter fire is also given in Figure 4; it is quite different in shape as well as showing much lower temperatures. With the 3 ft fire, measurements were only carried out within the range of depths 3 - 4 mm below the surface. Within this range, the temperature was independent of the depth and was $301 \pm 8{\cdot}7^{\circ}C$ as compared with $345 \pm 4{\cdot}2^{\circ}C$ for the 4 ft fire at a similar depth. The mean radiation received at the thermopiles through the pyrex shield during normal burning of the 4 ft fire was $16{\cdot}0\ (\pm 0{\cdot}48) \times 10^{-3}$ cal cm^{-2} sec^{-1} and for the 3 ft fire $8{\cdot}6\ (\pm 0{\cdot}8) \times 10^{-3}$ cal cm^{-2} sec^{-1}. The ratio between these values is not significantly different from the ratio of the surface area of the two fires.

Tests with sprays

The results of the tests with sprays are given in Tables 2 - 5. Tables 2, 3 and 4 give the results for the 4 ft fire for the swirl sprays (nozzles A, B, C, D), the multi-impinging jet non-directional sprays (nozzles E, F, G), and multi-impinging jet directional sprays (nozzles H, K) respectively; Table 5 gives all the results for the 3 ft fire. These tables show the time of extinction, the temperature in the liquid at extinction, the maximum radiation reading during the period of spray application, the mean wind speed during the test and some comments on the behaviour of the fire during the period of spray application. Figure 5 shows a typical temperature record for test (No. 6) together with photographs of the fire at various stages during the spray application. Figure 6 shows the radiation record for the same test.

Many of the sprays when applied to the fire gave an upsurge of flame. The violence of this upsurge increased as the rate of flow and the drop size of the spray increased. An estimate of the intensity of the upsurge may be obtained from the maximum reading of the radiometer after the spray was applied. However, with the more violent upsurges, such a reading was not possible as the recording pen over-shot the scale.

In all the tests except one (No. 77 Table 4), the liquid was cooled at least to the fire point (175 - 180°C) before extinction and in many tests cooling had taken place to well below the fire point before extinction was finally obtained. In most of the tests clearances were obtained before final extinction; during the last stages of spray application the bulk of the surface was usually free of flame with the fire burning at the edge of the vessel only. There was a very large scatter in the extinction times obtained with any given spray: thus with nozzle A at 50 $lb/in.^2$ a range of extinction times of 19·2 - 61·7 secs. was obtained in eleven tests. With coarse sprays with rates of flow of about 3 - 4 g cm^{-2} min^{-1} e.g. sprays from nozzles B, D and H at a pressure of 50 $lb/in.^2$, there was a tendency either for the fires to be extinguished quickly or for an edge fire to become established which took much longer to extinguish. Occasionally, as in tests 85 and 101, flashes of flame over the whole surface area took place after the establishment of this edge fire. While these edge fires were established, and when the flame flashed across the surface, the temperature of the liquid, as indicated by the thermocouple, was well below the fire point. It was observed that the edge fire was due mainly to the burning of oil drops splashed upwards by the spray.

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*Ninety-five per cent confidence limits.

Tests with no extinction with the spray

In tests 46 - 50 with nozzle K at 25 lb/in.^{2}, extinction was not obtained when the spray was acting on the fire; the flames covered the whole vessel despite the fact that after 15 seconds application the liquid was cooled to below the fire point and during most of the application time the liquid temperature was steady at 110°C. In tests 47, 48 and 50, the spray was stopped at 240, 30 and 30 seconds respectively; this resulted in the immediate clearance of flame over almost the whole surface leaving only one or two patches of liquid burning on the inside vessel edge above the liquid. These went out in a few seconds. In test No. 49, the spray was stopped at 15 seconds; this resulted in the clearance of flame over most of the surface, but a small patch of flame which remained, slowly spread again over the whole surface. No extinction was obtained in test 59 with nozzle K at 25 lb/in^2. However, in this test, the liquid was not cooled to the fire point and remained steady at about 185°C after about 15 - 20 seconds of spray application. Nevertheless, when the spray was stopped after the test, the height of the flames was considerably reduced.

Statistical analyses

A multiple regression analysis was carried out on the extinction time of the fire and the cooling* capacity of the spray. Fifty-two per cent of variance of the extinction times was accounted for by equation (1).

$$\log Y = -1{\cdot}35 \log R + 1{\cdot}08 \log D + 1{\cdot}709 \qquad \ldots\ldots (1)$$
$$\quad\ \pm 0{\cdot}30 \qquad\quad \pm 0{\cdot}52$$

where Y = extinction time (secs)
D = Sauter mean drop size (mm geometric mean between two values given in Table 1).
R = rate of flow (g cm^{-2} min^{-1} or five times gal ft^{-2} min^{-1}).

Sixty-two per cent of the variance of the cooling capacity was accounted for by equation (2).

$$K = \frac{1}{t} \log \frac{Te}{Ti - To} = 1{\cdot}44 \log R - 0{\cdot}72 \log D - 1{\cdot}94 \qquad \ldots\ldots (2)$$

t = extinction time.
Te = liquid temperature at extinction.
Ti = liquid temperature before spray application.
To = initial spray temperature (taken to be 18°C).

The following factors were tested but were not found to be significant: entrained air velocity, wind velocity, spatial pattern, nozzle height, fire diameter, entrained air velocity - wind velocity interaction, spatial pattern - wind velocity interaction.

Since the predominant mechanism of extinction was by cooling to the fire point, it is to be expected that the coefficients in equations (1) and (2) should be approximately equal but opposite in sign. The smaller value of the coefficient of D in equation (2) may be accounted for by the fact that the coarser sprays tended to bring about more cooling below the fire point before final extinction was achieved. It is interesting to note that the coefficients of R and D in equation (1) are not significantly different from the corresponding coefficients (-1·11 and +1·08 respectively) obtained for the 1 ft diameter fire. It is more difficult to compare absolute extinction times under the two sets of conditions because the entrained air velocity was not found to be a significant factor with the larger fires, whereas it was found to be so with the smaller ones; however, for given rates of flow and drop sizes the extinction times are approximately the same. It should also be noted that the percentage variation of the extinction time (52 per cent) which could be accounted for by equation (1) was much smaller

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*The derivation of the cooling capacity of the spray has been given in Part 1.

than was accounted for by the corresponding equation for the small-scale laboratory tests (86 per cent). This was undoubtedly due to the much larger scatter of results obtained in the present series. Thus the standard deviation of the logarithm of the extinction time in the present series was estimated to be 0·22; on the small-scale tests, this standard deviation was 0·08.

The effect of wind

It was noted in the small-scale tests that when a spray was applied sideways to a fire, a more rapid extinction with a smaller rate of flow was obtained than when the spray was applied directly downwards. The reason for this was that the spray did not have to counteract the upward motion of the flames. From this fact, it may be concluded that the wind can act in two ways. Firstly, it can blow the flames away and help access of the spray to the burning liquid and secondly it can blow the spray away and prevent the drops reaching the fire area. Some evidence of the first of these effects was obtained in tests with low winds with nozzle E (tests 30, 31, 33, 34, Table 4) in which the veering of the flames while the spray was applied seemed to promote access of the spray to the burning liquid and a comparatively rapid extinction time. Some evidence of the second effect was obtained with nozzle H at 50 lb/in^{-2} pressure acting on the 4 ft fire (tests 51 - 55 Table 4) and nozzle D acting on the 3 ft fire (tests 98 - 103 Table 5). In these groups of tests a high wind velocity tended to be associated with a long extinction time. However, as indicated in the previous section, no significant trend of the effect of wind velocity was obtained when all the results were analysed.

Comparison between nozzles

Under the conditions of the tests there were wide differences in the performance of different nozzles. There is little doubt, however, that these differences were due primarily to differences in rate of flow to the fire area and spray drop size which were found in the statistical analyses to affect the results considerably. It will be noted, that nozzles E, F and G did not bring about rapid extinction in any test, either at pressures of 50 or 100 lb/in^2. This was due to the very low rates of flow to the fire area obtained from these nozzles. It has sometimes been said that sprays of the type produced by nozzles E, F and G which shroud the fire with a comparatively fine spray, will extinguish the fire by extinguishing the flames; the drops are said to be sucked into the flames and cause the formation of steam. This was not found to be so in the present tests, since after a fairly prolonged application, the fire in every test was finally extinguished by cooling to the fire point.

Discussion

Comparison with 1 ft diameter fire

In the main the results of the present series of tests confirm the results of the laboratory tests with a 1 ft diameter fire. Extinction took place by cooling to below the fire point and the rate of flow and drop size of the spray had important and similar effects on the extinction time. The main difference between the two series was that with the smaller fire the entrained air velocity affected the extinction time, but in the present series this factor was found to be insignificant. The action of the entrained air velocity on the smaller fire was to blow the flames away and to help the fine spray to reach the burning liquid. It would be expected that with the larger fires this effect would have been more pronounced since the flames were larger. An explanation of this difference may be that the results in the present series were considerably affected firstly by variations in wind conditions, which were absent in the small-scale laboratory test, and secondly by the frequent establishment of prolonged edge fires prior to extinction. These factors caused a wide scatter of extinction times which may have masked the effects of the entrained air velocity.

Splashed oil spray fires

In many of the tests, oil splashed upwards by the spray contributed to the flames. There is little doubt that this was the main source of fuel in the edge fires and in some fires which covered the whole surface after the liquid had been cooled to the fire point. It appears that if a splash fire tends to become established, a greater amount of cooling of the oil than mere cooling to the fire point is required to bring about final extinction. It is likely also that aerodynamic conditions prevailing at the time of application of the spray have an important bearing on whether splash fires are established. Thus Spalding(2) has reported that the maintenance of a flame on a burning drop depends on the motion of the air stream past the drop; as the air stream increases the flame tends to blow off the drop, the critical air stream increasing as the drop size increases. The establishment of a splash fire under the present conditions was therefore most likely near the vessel edge where some protection was afforded from the wind, and the motion of the air associated with the water spray. It is possible that under practical conditions, where thin flowing layers of burning liquid are likely to be encountered far more frequently than thick static layers, oil splashing will be much less and therefore the development of splash fires will be of smaller importance than in the present tests.

Practical implications

The tests support the view that the most important function of a water spray in extinguishing a high-boiling liquid is to reach the burning liquid and cool it. A spray may or may not be assisted by wind conditions in performing this function. The rate of flow and drop size of the spray are important factors governing the spray efficiency. In general, for sprays of medium drop size (0.5 - 1.0 mm), a rate of flow of about 2.5 g cm^{-2} min^{-1} (0.5 gal ft^{-2} min^{-1}) was required to bring about extinction in less than five seconds whereas with coarse sprays, (drop size 1 - 3 mm) a rate of flow of about 6 g cm^{-2} min^{-1} (1.2 gal ft^{-2} min^{-1}) was required. The present tests did not indicate that these quantities would depend on the design of the nozzle which produced the spray. However, this conclusion must be accepted with reserve as it contradicts conclusions from laboratory scale tests of greater accuracy, which indicated that sprays should be designed to conserve the entrained air stream.

Note

This is an interim report on preliminary tests circulated in the first place to organizations directly involved in the discussion.

It will be noted that the tests were carried out with a comparatively simple system, i.e. spray from only one nozzle acting on a fire burning from a horizontal surface of limited size. In practice groups of nozzles have to be employed against fires, which can burn on surfaces of vertical and horizontal pipes as well as on horizontal surfaces, and which can reach intensities considerably greater than those obtained in the present tests. Under these conditions the effects of sprays of different properties may well differ from those given for the above fires. To provide information on this point, further tests are at present being carried out with a more intense fire obtained from oil flowing over a nest of hot pipes.

References

(1) D. J. Rasbash and Z. W. Rogowski. F.R. Note No. 180.
(2) D. B. Spalding. 4th Symposium on Combustion. p. 847.

Acknowledgment

Mr. G. Carter, Mr. A. Kelly and Mrs. J. Freer assisted in the experimental work and in the preparation of the report.

Table 1

Properties of the sprays tested

Nozzle designation	Pressure lb/in.^{2}	Rate of flow from nozzle gal/min	Cone angle of nozzle degrees	Mass median drop size (1) mm	Sauter mean drop size (1) mm	Mass median drop size (2) mm	Sauter mean drop size (2) mm	Spatial pattern of spray about fire area	Entrained air velocity at fire area ft/sec	Rate of flow at fire area g cm^{-2} min^{-1}*
A	50	15·4	71	0·45	0·40	0·69	0·69	1·16	9·90	0·97 - 1.2
A	100	19·3	67	0.59	0·49	0·70	0·57	1.28	10·7	2·70 - 2·70
B	50	16·0	48	1·96	1·28	0·94	0·80	2·52	12·20	3·37 - 3·72
C	50	19·3	55	3·05	2·05	1·59	1·11	2·48	12·00	6·8 - 7·0
D	50	11·1	60	1.33	1·01	0·75	0·72	1·82	9·26	2·84 - 3·05
E	50	10·4	213	0·49	0·48	0·55	0.52	1·00	4·18	0·61 - 0·79
E	100	14·2	224	0·41	0·36	0·59	0·56	1·90	6·67	1·02 - 1·56
F	50	36·1	204	0·53	0·51	0·60	0·57	1·00	-1·11	0·45 - 0·55
F	100	n.d.	203	0·58	0·55	0·58	0·57	1·06	-3·19	0·47 - 0·50
G	50	74·6	216	0·87	0·79	0·89	0·82	0·94	-3·3	0·65 - 0·78
H	25	17·2	83	1·80	1·32	1·98	1·32	1·56	4·30	1·9 - 2·1
H	50	22·2	81	4·33	2·52	1·21	0·95	2·28	10·10	3·50 - 3·60
H	100	30·4	85	3·98	2·26	0·93	0·82	2·90	16·4	6·06 - 6·60
K	25	17·0	102	0·65	0·57	0·57	0·50	0·95	2·76	0·50
K	50	23·8	115	0·49	0·43	0·58	0·57	0·90	9·70	1·00 - 1·30
K	100	32·9	103	0·51	0·41	0·60	0·57	1·10	16·5	2·5 - 2·65

*Divide by 5 to give gal ft^{-2} min^{-1}.

Table 2

Results of tests with solid cone [illegible] nozzles on 120 cm (4 ft) fire

Test desig. No.	Nozzle designation	Pressure lb/in.^{2}	Wind speed ft/sec	Extinction time sec.	Temp. in oil at extinction °C	Maximum radiation reg. after spray applied cal cm^{-2} sec^{-1}	Comments
1	A	50	7·35	44·2	117	0·0460	Upsurge; flames dying slowly. Last 5-6 sec. small flame at edge.
2	A	50	5·25	19·2	83	0·0503	Upsurge; clearance at 10^s; last 10^s small flame at edge.
3	A	50	6·50	27·8	n.d.	0·0372	Upsurge; occasional ½-clearances throughout application. Rapid clearance before extinction.
4	A	50	16·40	22·0	120	0·0350	No obvious upsurge. Gradual reduction of flame. Most of surface clear last 5-10^s.
5	A	50	14·35	42·8	118	0·0220	Most of surface clear last 10-12^s.
6	A	50	9·6	68·7	86	0·0550	Upsurge; flames decreasing to 5 ft high; clearance 30^s; spray blown off fire; clearance 55^s leaving edge flame.
7	A	50	10·2	40·1	120	0·0240	Very little upsurge; flames flattened; burnt over whole surface until 30^s; edge fire after 37^s.
8	A	50	11·4	60·2	92	0·0274	Flame flattened; clearance 35^s; further clearance 50^s; edge fire thereafter.
9	A	50	1·80	24·4	134	0·0552	Upsurge; gradual reduction of flames; 1st clearance ½ area 21^s leading to extinction.
10	A	50	1·80	12·4	147	*	Upsurge; flame flattened; clearance 10^s leaving small edge fire.
11	A	50	3·70	61·7	100	0·0380	Upsurge; flame flattened; flame close to surface at later stages; 1st clearance 35^s, whole surface 47^s leaving edge flame.

*Greater than 0·055.

Table 4 (contd.)

Test desig. No.	Nozzle designation	Pressure lb/in.^{2}	Wind speed ft/sec	Extinction time sec.	Temp. of oil at extinction °C	[illegible] radiation [illegible] cm^{2} [illegible]	[illegible]
12	A	100	12·65	3·1	89	*	Upsurge; flames diminished rapidly.
13	A	100	10·8	3·2	141	*	Upsurge; flames diminished rapidly; much steam.
14	A	100	11·05	4·1	117	*	Upsurge; flames diminished rapidly; much steam.
15	B	50	3·10	6·7	50	*	Large upsurge followed by flame 18 in. high over whole vessel; cleared in 4^s leaving edge flame only.
16	B	50	8·95	29·8	n.d.	*	Large upsurge; burning round edge only after $4\frac{1}{2}^s$.
17	B	50	10·35	4·7	109	*	Large upsurge; surface clearance in 3^s.
18	C	50	6·45	3·1	80	*	Large burst of flame; much steam.
19	C	50	7·40	4·2	56	*	Large burst of flame; main flames cleared in 3^s; small edge flame after $3\frac{1}{2}^s$.
20	C	50	6·55	4·2	62	*	Large burst of flame; flames flattened; small flame at edge at extinction.
21	C	50	9·25	4·0	57	*	Upsurge; clearance, leaving small flame at edge.
22	D	50	4·75	29·3	38	*	Large upsurge; flames burning round edge after 5-6^s.
23	D	50	4·49	29·8	n.d.	*	Large upsurge; $\frac{3}{4}$ clearance 6^s diminishing to $\frac{1}{2}$ at 10^s; last 10-15^s edge only.
24	D	50	4·60	24·2	75	*	Flames burning over part of edge only after $6\frac{1}{2}^s$.

*Greater than 0·055.

Table 3

Results of tests with multi-pair impinging jet non-directional spray on 120 cm (4 ft) fire

Test desig. No.	Nozzle desig- nation	Pressure lb/in.^{2}	Wind speed ft/sec	Extinc- tion time sec.	Temp. in oil at extinction °C	Maximum radiation rdg. after spray applied cal cm^{-2} sec^{-1}	Comments
25	E	50	4·70	63·8	130	0·0355	Few partial clearances 20-25^s; small flame at edge last 5-10^s.
26	E	50	4·70	29·8	125	0·0311	Flames burnt upwards against spray 1st 20^s; clearance 24^s; small edge flame last 3-4^s.
27	E	50	5·10	61·8	141	0·0288	Flame burnt upwards against spray most of test; ½ clearance 52^s; sudden almost complete 60^s.
28	E	100	12·15	35·0	115	n.d.	Steady reduction in flames; ½ surface clear 25^s; ¾ clear 28^s.
29	E	100	11·15	36·7	n.d.	0·0197	Flame gradually reduced; burning upright when no wind; ⅝ clear 32^s.
30	E	100	5·30	16.7	n.d.	n.d.	Flames veered gently E during whole application.
31	E	100	2·75	12·1	119	0·0332	Flame veered during application. Clearance in 10^s.
32	E	100	7·7	47·2	88	0.0187	Small upsurge; upright for 20^s; height 9 ft; burning at edge after 25^s.
33	E	100	1·60	24·6	40	0·0248	Veering S during initial stages; ¾ clearance 10^s gradually increasing
34	E	100	1·40	14·1	122	0·0445	Veering before appli- cation; flame clearing 10^s leaving small patch of flame.
35	E	100	2·25	29·1	128	0·0242	Slight upsurge; flame burnt upwards against spray. ⅓ clearance 25^s leading to extinc- tion.
36	F	50	6.20	39·6	127	n.d.	Burnt at edge after 28^s.
37	F	50	6·80	[illegible]	[illegible]	0.0278	Flame gradually decreasing for 23^s; clearances increasing in size up to 33^s; small flame left at edge till extinction.

Test desig. No.	Nozzle desig-nation	Pressure lb/in.^{2}	Wind speed ft/sec	Extinc-tion time sec.	Temp. in oil at extinction °C	Maximum radiation rdg. after spray applied cal cm^{-2} sec^{-1}	Comments
38	F	50	8·30	33·0	134	0·0317	Upsurge; flame burning vertically till 28^s then rapid diminution till small edge flame last 2 or 3^s.
39	F	50	8·45	34·2	130	0·0213	Little upsurge; first clearance 19^s; last 8-9^s small flame at edge.
40	F	100	5·45	24·1	139	0·0160	Upsurge; 1st clearance 10^s; flame covering $<\frac{1}{2}$ area after 18^s.
41	F	100	11.10	46	104	0.0198	First clearance 15^s; further after 25 increasing till small edge flame left.
42	F	100	12·15	65·1	131	0.0238	Flames burning upwards against spray; still 5 ft high at 40^s; clearance of most of surface at 60^s.
43	G	50	4·20	33·8	133	0·0177	Upsurge; flame vertical but decreasing in height; 1st clearance 25^s reducing to small flame at edge.
44	G	50	5·20	24·0	124	0·0141	Flame blown horizontal by wind; decreasing in size rapidly; 1st clearance 18^s; small flame at edge.
45	G	50	2·90	29·3	91	0·0180	Burning at edge last 5^s.

Table 4

Results of tests with multi-impinging jets directional sprays on 120 cm (4 ft) fire

Test desig. No.	Nozzle designation	Pressure lb/in.^{2}	Wind speed ft/sec	Extinction time sec.	Temp. in oil at extinction °C	Maximum radiation rdg. after spray applied cal cm^{-2} sec^{-1}	Comments
46	H	25	6·00	>240		0·0313	Flame height about 7 ft during test.
47	H	25	6.00	248·9	103	‡	Flames reaching 5 ft height; spray stopped at 240^s; small*.
48	H	25	6.50	42·3	116	0.0475	Spray switched off 30^s.*
49	H	25	6·00			0.0515	Spray switched off at 15^s. No extinction.
50	H	25	5·70	46.2	124	0·0515	Spray off 30^s.*
51	H	50	9·25	4·4	102	‡	Flame blown sideways when spray applied; flame flattened and went out.
52	H	50	7·75	6·0	143	‡	Upsurge of flame; flattened; stayed flat; flame clearance 5^s.
53	H	50	7.5	4·8	152	0.0353	Upsurge; flattened; extinction.
54	H	50	11·15	44·6	52	0·0464	Upsurge; clearances at 20 and 35^s; burnt round edge in last 10^s.
55	H	50	9.2	26·8	66	0·0410	Clearance 15^s; burnt at E edge till extinction.
56	H	100	8·55	3.3	87	‡	Large upsurge; flame blown flat; clearance at 2½^s leaving small flame at edge.
57	H	100	4·15	4·2	124	‡	Large upsurge; flame blown flat; small flame at edge.
58	H	100	9·15	2·4	102	‡	Large upsurge; flame blown flat; small flame at edge.
59	K	25	11·4	>240		0·0222	Flame maintained height of 8 ft during application.
60	K	50	6·20	13·0	143	0.0384	Pronounced upsurge; flame blown flat; 1st clearance 10^s increasing in size.
61	K	50	6.30	15·6	154	0·0310	Flame flattened when spray applied. Normal upsurge; clearance at 3^s further clearance at 12^s.

*Small flame at edge till extinction.
‡Greater than 0·055.

Test desig. No.	Nozzle desig-nation	Pressure lb/in.^{2}	Wind speed ft/sec	Extinc-tion time sec.	Temp. in oil at extinction °C	Max Radiation after spray applied cal cm^{-2} sec	Comments
62	K	50	7·30	15.6	143	0.0132	Flame blown flat. 1st clearance 10^s; flame diminished thereafter.
63	K	50	2.75	14.1	122	0.0253	Upsurge; burnt upwards against spray to height of 10 ft; flattened 10^s; clearance 13^s.
64	K	50	1.0	9.9	177	0.0211	Flattened 5^s; clearance 9^s.
65	K	50	2.0	28.4	114	0.0133	Flattened 20^s; clearance 23^s.
66	K	50	2.80	20.7	126	0.0318	Flattened 10^s; clearance 16^s.
67	K	50	2.80	22.3	151	0.0275	Flattened and burnt upwards twice; flattened 16^s; clearance beginning 18^s.
68	K	50	6.0	15.5	130	0.0191	Flame flattened 15^s with clearance.
69	K	50	5.1	16.0	155	0.0181	Flattened 7^s; burnt upwards 10^s; flattened 14^s.
70	K	50	5.0	31.7	149	0.0270	Flattened 20^s; clearance 30^s.
71	K	50	5.9			0.0263	---
72	K	50	6.8	30.1	135	0.0193	Flame upwards into spray, decreasing in size; clearance 26^s leaving edge flame.
73	K	100	11.6	2.3	158	0.0363	Upsurge; flame appeared to be blown off vessel, leaving small flame at edge.
74	K	100	9.6	2.6	148	0.0552	Upsurge; flame appeared to be blown off vessel, leaving small flame at edge; much steam.
75	K	100	9.6	2.8	165	0.0360	Upsurge; flame burning to height of 6 ft at edge before extinction.
76	K	100	10.9	3.5	162	0.0175	No upsurge; flame flattened; cleared, leaving edge fire.
77	K	100	10.0	3.5	197	0.0274	Large upsurge; much steam; flame disappeared.
73	K	100	8.4	5.5	138	0.0115	Large upsurge; much steam; flame disappeared; last flame at edge.

Table 5

Results of tests on 90 cm (3 ft) fire

Test desig. No.	Nozzle designation	Pressure lb/in.^{2}	Spatial pattern	Rate of flow g cm^{-2} min^{-1}	Height above nozzle ft	Wind speed ft/sec	Extinction time sec.	Temp. in oil at extinction °C	Maximum radiation after spray applied cal cm^{-2} sec^{-1}	Comments
90	B	50			8	8·8	5·6	54	*	Upsurge; clearance 3^s, edge flame 2 ft high.
91	B	50			8	6·0	4·3	65	*	Large upsurge; clearance; much steam.
92	B	50	1·76	4·66	8	6·3	5·8	64	*	Large upsurge; centre clearance almost immediately; flame at edge.
93	B	50			8	6·8	5	58	*	Large upsurge; centre clearance almost immediately; flame at edge.
94	B	50			8	4·1	6·5	n.d.	*	Clearance 2^s leaving small patch of non-luminous flame.
95	B	50			15	4·7	28·2	32	0·030	Upsurge; flattened; clearance 5^s; thereafter flame round edge.
96	B	50	1·60	2·99	15	4·0	32·3	46	0·415	Upsurge; flames flattened burning close to surface; clearance 10^s, flashed round edge and over whole surface several times between 15 and 25^s. Edge fire after 25^s.
97	B	50			15	5·4	29·4	50	0·0385	Upsurge; flames flattened; 1st clearance 9^s, flash round edges 9–17^s; edge fire getting smaller.

* Greater than 0·055.

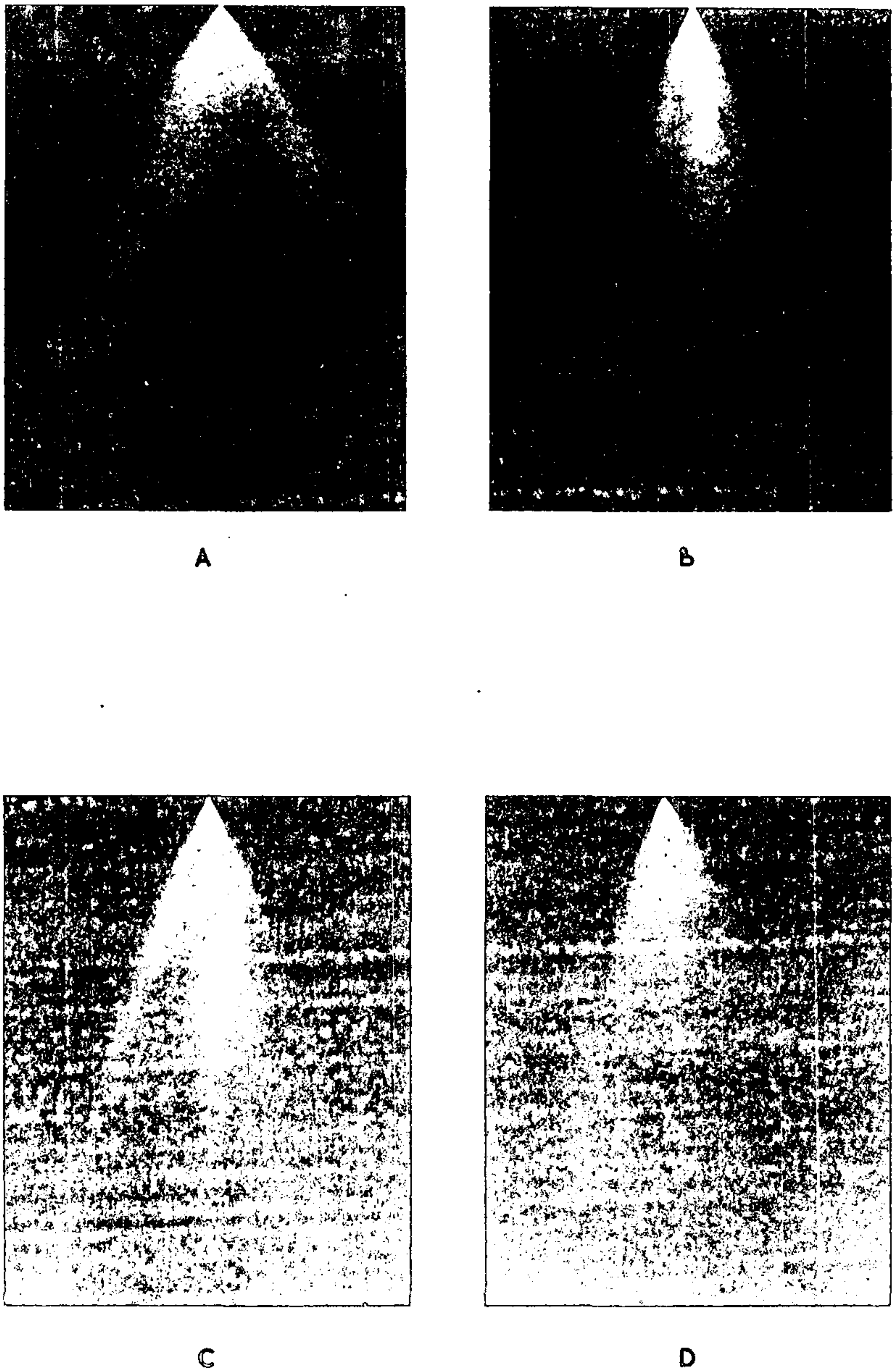
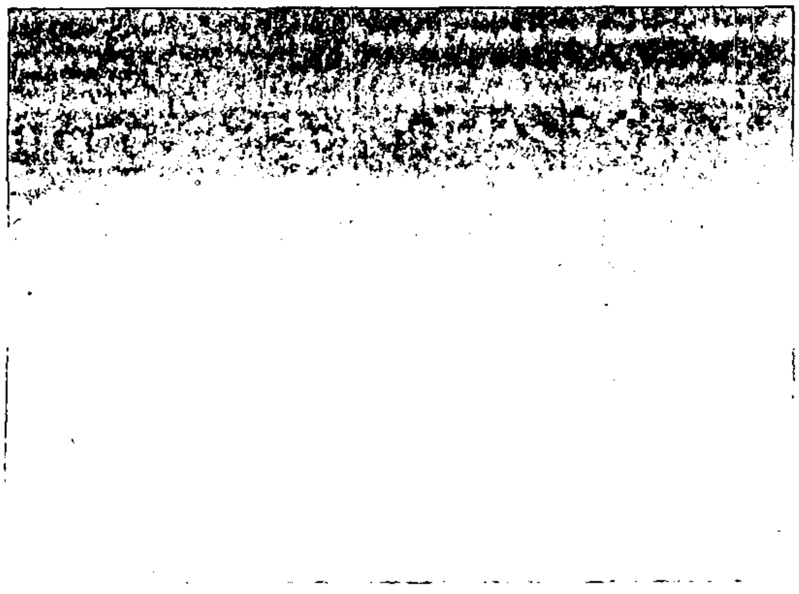


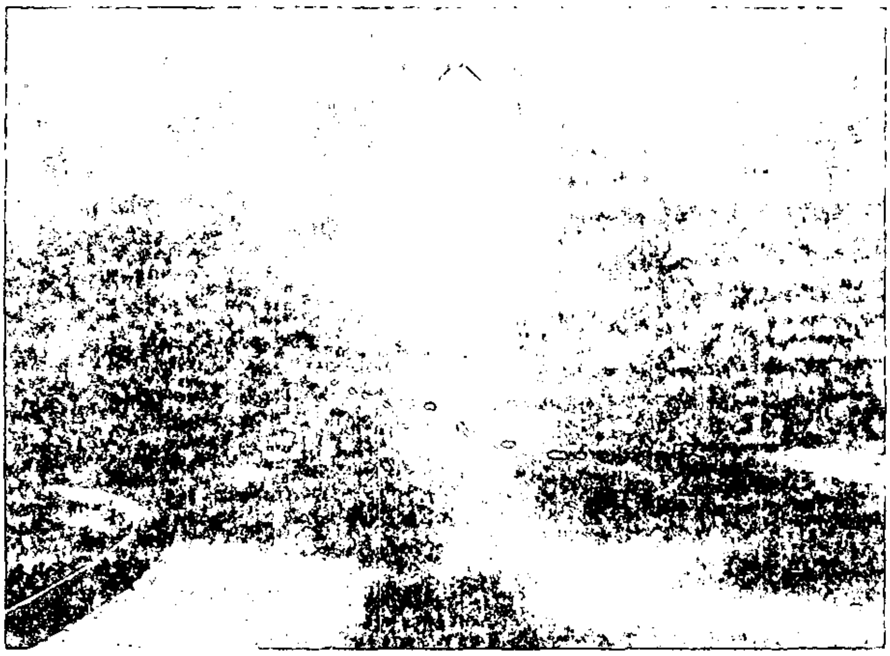
PLATE [illegible] SWIRL NOZZLE SPRAYS

E

F



G

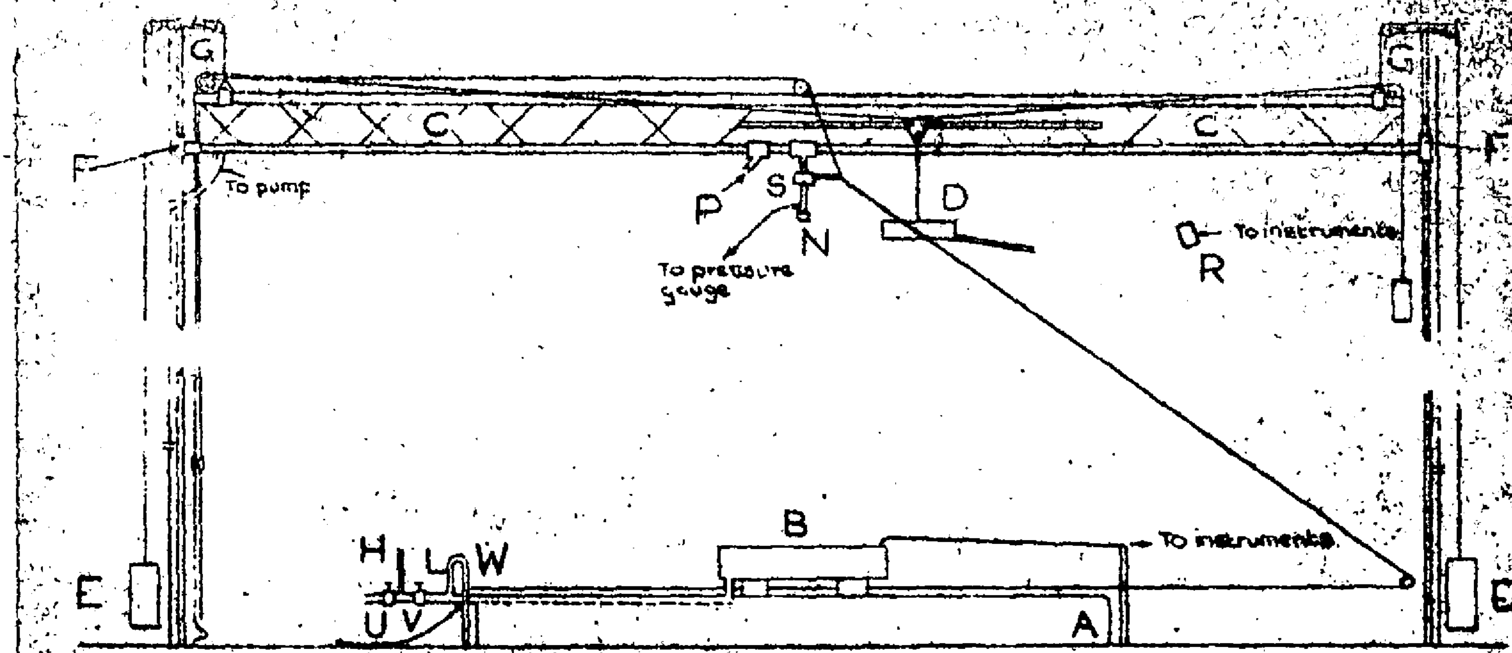


H

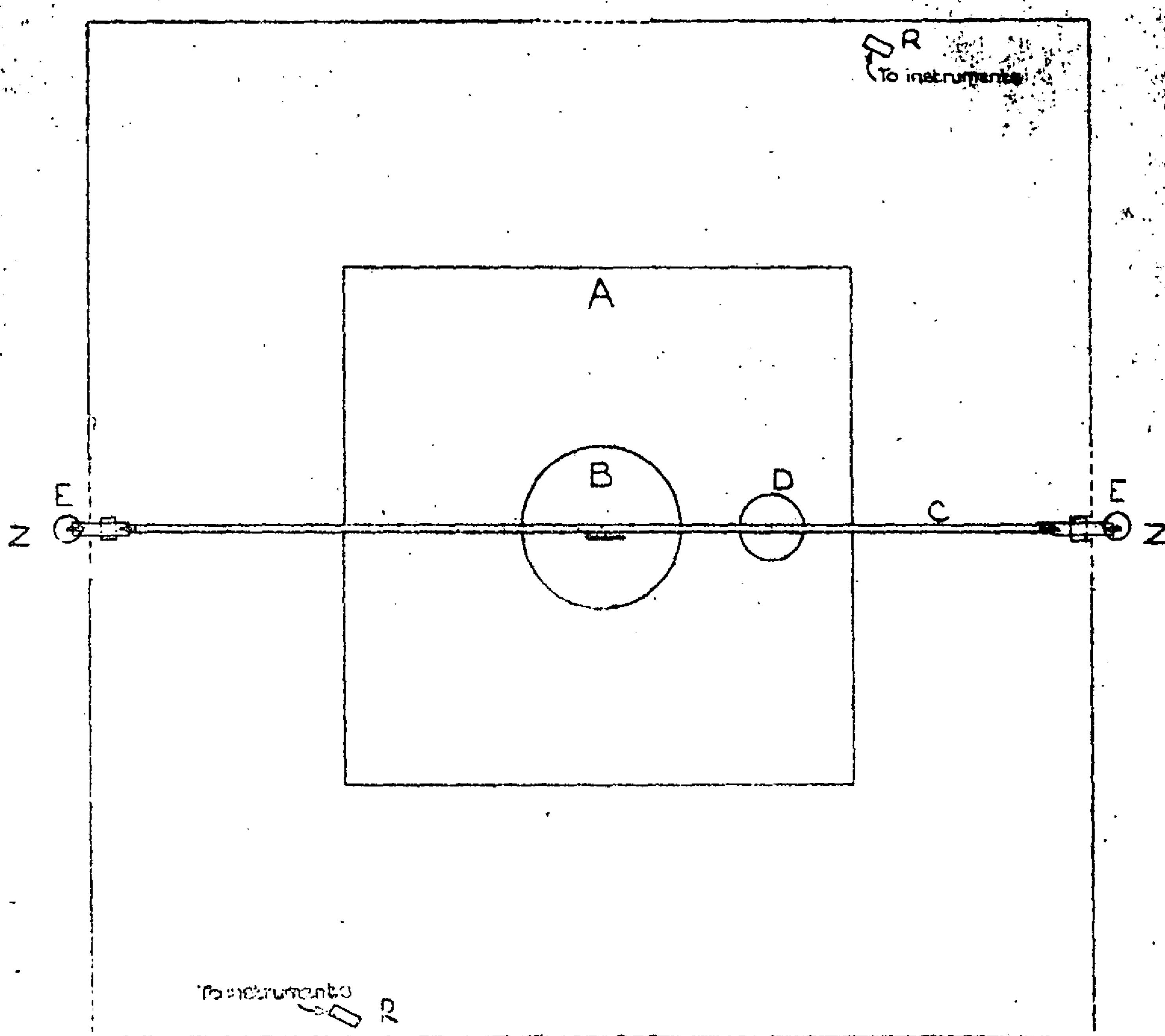
K

PLATE.3. DIRE[illegible] MULTI-IMPINGING JET SPRAYS

DS98126/1/191 60 11/55CL



ELEVATION OF APPARATUS.



PLAN VIEW OF APPARATUS.

FIG. [illegible] OF APPARATUS

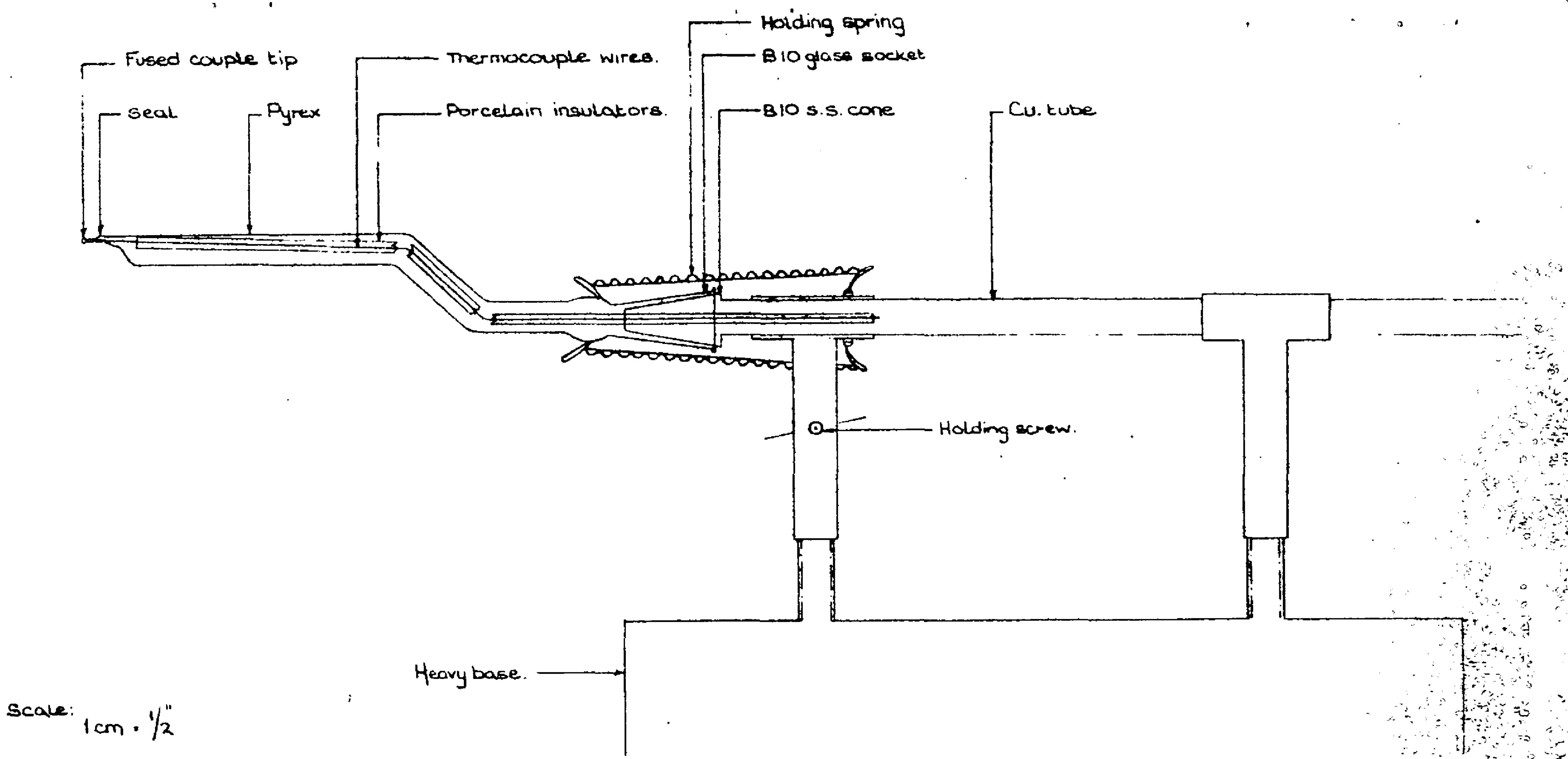
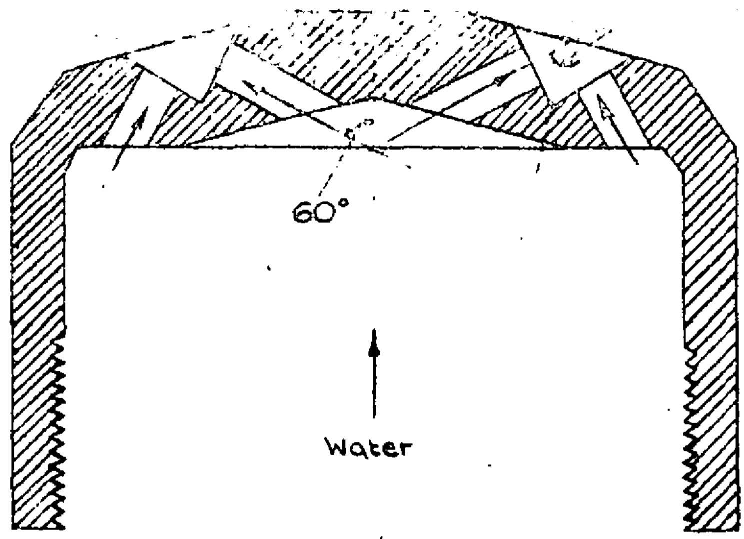
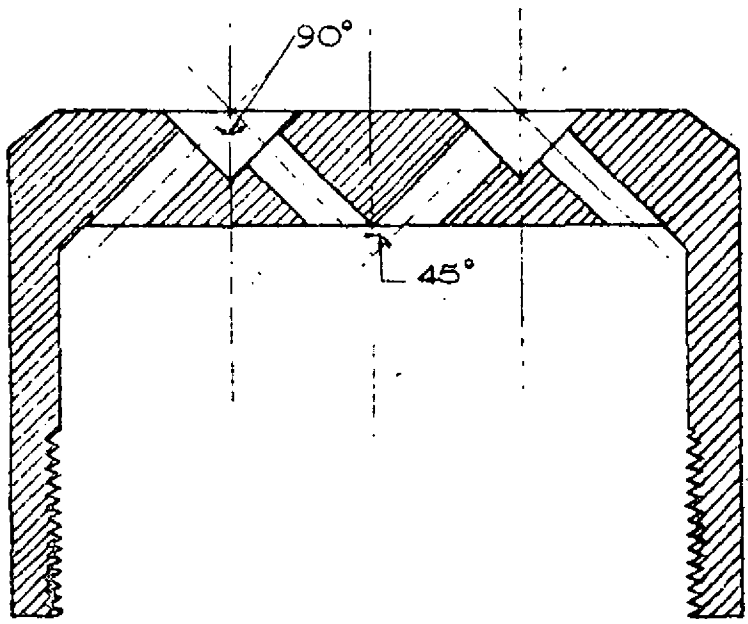


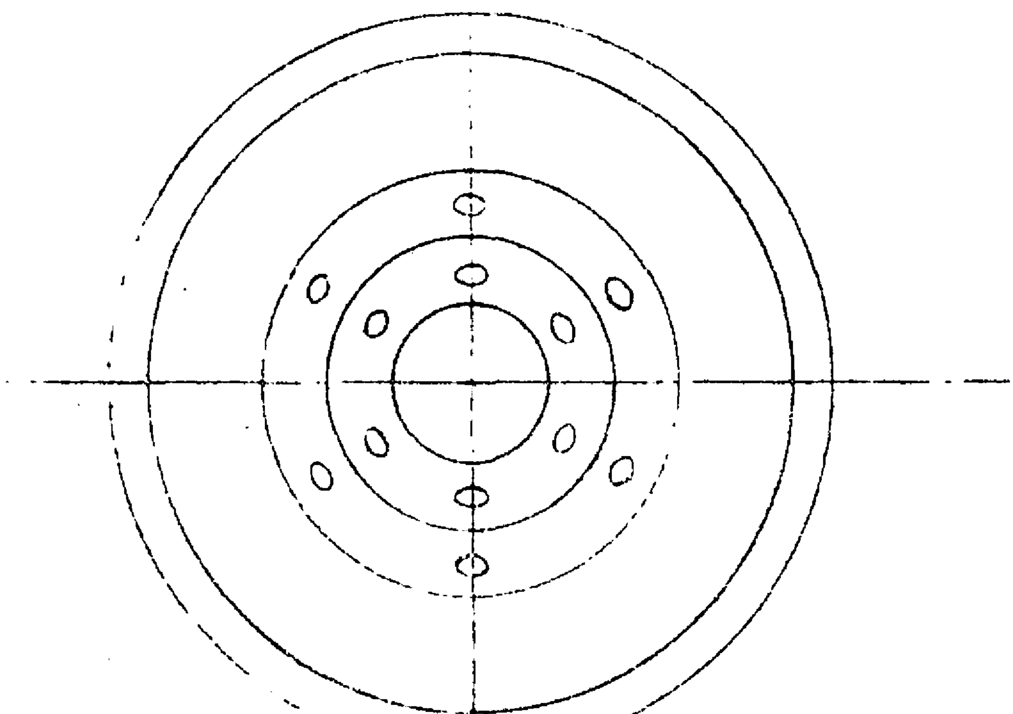
FIG. 2. DESIGN OF THERMOCOUPLE.



NOZZLE K. IMPINGING JET : WIDE CONE (Sectional Elevation.)



NOZZLE H. IMPINGING JET : NARROW CONE (Sectional Elevation).



NOZZLE H. Plan

SKETCH OF NOZZLES 'H' AND 'K'.

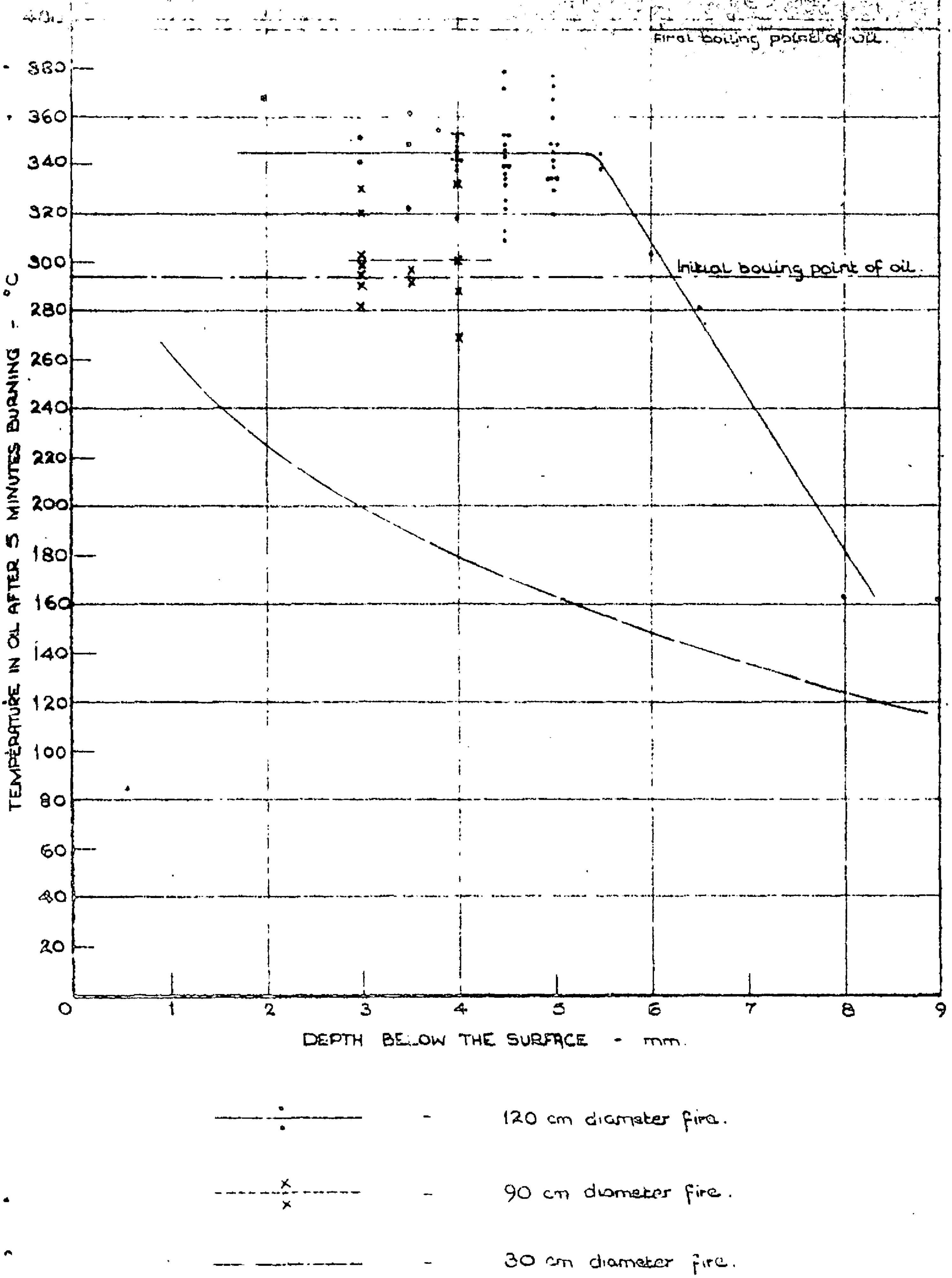


FIG. 4. TEMPERATURE DISTRIBUTION BELOW THE SURFACE OF BURNING TRANSFORMER OIL.