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THE EXTINCTION OF OPEN FIRES WITH WATER SPRAY

PART I

THE EFFECT OF WATER SPRAY ON A KEROSINE FIRE 30 CM DIAMETER

by

D. J. Rasbash and Z. W. Rogowski

SUMMARY

A series of tests have been carried out on the effect of water sprays on a kerosine fire burning in a vessel 30 cm diameter. The sprays were produced by a battery of impinging jets which enabled a study to be made of the effect of drop size and rate of flow of spray at pressures between 5 and 85 lb/in^2, while maintaining in each test a fairly even spatial pattern of spray about the fire area.

It was found that at a given pressure there was a drop size which was most efficient in reducing the rate of burning of the fire, and at this drop size the rate of flow required to extinguish the fire was also at a minimum. At drop sizes greater than this efficient drop size there was much splashing; at smaller drop sizes a large fraction of the water spray applied to the fire did not penetrate through the flames and the kerosine, and the drops which reached the kerosine caused much sputtering. The most efficient drop size decreased with increase in pressure.

The efficiency of the spray in extinguishing the fire increased with increase in pressure. This was shown by a reduction in the minimum rate of flow required to extinguish the fire and also by a reduction in the time which was required for extinction with a given rate of flow. A reason for this result was that an increase in pressure brought about an increase in the velocity of air entrained by the spray. This helped to push the flames away and allowed the presentation of fine drops with a high capacity for heat transfer to those parts of the flame near the uprising vapour, and to the burning liquid.

At low pressures (10 and 30 lb/in^2), the fire was extinguished mainly by the kerosine being cooled to the fire point. It was estimated that the sprays which extinguished the fire in this way removed heat from the flames at a rate less than 0.2 - 0.3 cal/cm^3 of flame)(s). At a higher pressure (85 lb/in^2) the extinctions took place without cooling the liquid to the fire point and there was evidence to indicate that the flame itself was extinguished. It was estimated in most of these extinctions that the sprays removed heat from the flame at a rate greater than 0.2 - 0.3 cal/(cm^3 of flame)(s). There was no evidence that the formation of an oil in water emulsion played any part in the extinction process.

The practical implications of the results are discussed.

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INTRODUCTION

In a recent note [1] the effect of water sprays of varying drop size and rate of flow on a kerosine fire 11 cm in diameter was described. A series of tests have now been carried out on the effect of water spray on a larger kerosine fire, 30 cm in diameter. The scope of the investigation has been widened to include a study of the effect of the pressure at which the spray is produced, and the mechanism of extinction of the fire has been studied in greater detail.

APPARATUS

The two main parts of the apparatus were again a spray system which enabled sprays of varying properties to be produced in a controlled manner and a standard kerosine fire on which these sprays were tested.

The standard fire

In the tests on the 11 cm fire, the vessel in which the fire burned was situated near the bottom of a length of ducting. To minimise the effects of draughts a measured stream of air was conducted to the bottom of the ducting and flowed vertically past the fire in a manner which caused as little disturbance as possible to the flames. From experience gained in these tests it was concluded that to employ this system on the larger scale tests would have required the use of cumbersome apparatus. Moreover, the restricted view of the fire through a mica window in the ducting and the lack of accessibility of the surface of the kerosine for the purpose of taking samples were found to be further disadvantageous. The 30 cm fire was therefore burned in an open laboratory measuring 25 ft x 35 ft x 20 ft high, care being taken that draughts were excluded as far as possible.

Full details of the design, the operation and the properties of the 30 cm standard fire have been given elsewhere [8]. Some of the data relating to the fire which will be referred to in this note are given in Table 1.

TABLE 1

Properties of the standard fire and relevant data

Diameter of fire	30.0 cm
Ullage	2.0 cm
Initial boiling point of kerosine	157°C
Final " " " "	277°C
Fire point of kerosine	
(a) before burning	58°C
(b) at surface after 20 minutes burning	68°C
Temperature 3 mm below surface	
(a) 8 minutes after ignition	162°C
(b) 20 " " "	181°C
Temperature of the flame 30 cm above the surface (measured by optical pyrometer)	1270°C (approx.)
Mean temperature of the flame 30 cm above the surface (measured by Schmidt's method)	990°C
Quantity of kerosine burned in 20 minutes (mean of 38 tests)	1163 ± 39 g
Average rate of burning for period between 8-20 minutes after ignition	1 g/sec for the whole vessel = .0014 g/(cm)^2(sec)
Upward velocity of flames 60 cm above the surface (mean of 20 readings)	374 ± 62 cm/sec

The spray

In the tests on the 11 cm fire the spray was produced by a battery of hypodermic needles. The chief feature of this apparatus was that over a large range of drop sizes the sprays were of uniform drop size. This, as well as enabling the results to be interpreted more simply, considerably lessened the work in drop size measurement since only a comparatively small number of drops had to be counted to assess the drop size. There were two disadvantages in using this battery, however. Firstly, there was a non-uniform pattern of spray across the fire area. Although this was found to have little effect on the particular fire studied it was thought that it might become a serious disadvantage with other fires. Secondly, it was not possible to vary the velocity with which drops of a given size were ejected from the battery: therefore this factor, which might have had an important effect on the efficiency of the spray, could not be studied.

In the tests on the 30 cm fire it was impracticable to use a hypodermic needle battery spray since the labour in assembling and maintaining the several thousand needles required would have consumed too much time. The sprays were therefore produced by two batteries of pressure nozzles. It was found in a series of preliminary tests (2) that the use of impinging jets as pressure nozzles would give a more flexible control over the properties of the sprays produced than the use of the other types of pressure nozzles available. This type of nozzle was therefore used in the batteries. Although this system produced sprays containing a wide range of drop sizes, it was found possible to a large extent to overcome the two disadvantages of the hypodermic needle battery spray mentioned above.

The impinging jet batteries. A diagram of one of the impinging jet batteries is shown in fig.1 A was a brass tube into which water was fed through a tube B. Six pairs of brass tubes C, 6.2 mm o.d. and 3.1 i.d. were mounted on A and were used to conduct water from A to the impinging jets. The tubes were mounted on a brass bar D which was screwed on a bar E soldered on A. The tubes also passed through slots in another brass bar F which was attached to D by the bolts G. The bottom of the tubes were turned inwards at an angle of 45° as shown; the jets coming from the tubes therefore impinged at an angle of 90°. The inside of the ends of the tubes were threaded with a 6 BA tap to enable nipples H containing the required size jet holes to be inserted in the tube. The outside of the tubes were also threaded to enable caps (R) to be placed over the nipples when not in use. As a rule when nipples were inserted in a given pair of tubes, slight deviations from exact drilling of the nipples prevented the two jets hitting each other squarely. This could be overcome by slightly moving one or both of the tubes C in its slot in the cross-piece F by turning the screws M (see detail across PP). There was sufficient spring in the length of the tube to prevent any permanent distortion accompanying this operation. A photograph of the impinging jet battery is shown in fig.2.

Nipples for forming the water jets. Four sets of nipples were used to form the jets: they were all made from special brass screws which had a 6 mm length of 6 BA thread and an 8 BA head (fig.3). The whole length was bored with a 1.6 mm drill except for a length 1 which was bored with a drill of the required jet hole diameter. Table II shown the length 1 as a function of the jet hole diameter.

TABLE II

Design of nipples

Nipple No.	Diameter of jet hole in	Diameter of jet hole mm	1 mm	Velocity of water jet at 85 lb/cm² cm/sec
1	1/64	0.4	1.2	2,400
2	1/32	0.8	2.4	2,480
3	3/64	1.2	3.6	2,660
4	1/16	1.6	whole length	2,820

It was desired that for a given pressure the velocity of the water jet should be substantially independent of jet diameter. If this were accomplished it might be assumed that the initial downward velocity of the spray drops after the jets impinged would depend on the pressure[(2)]. To help obtain this 1 was varied with jet hole diameter, so as to correct as far as possible for the very different losses of pressure head which would have occurred if all the jet holes had been of the same length. The last column of Table II shows the velocity of the jets which was actually obtained at a pressure of 85 lb/sq.in. It will be seen that an equal velocity for all four jets was not quite achieved but it is doubtful whether any better performance could have been obtained without making the impinging jet battery much more complicated or designing a different battery for use with each set of nipples.

A few tests were carried out with no nipples in the tubes C; under these conditions the jets were considered as $\frac{1}{8}$ in jets, the internal diameter of tube C.

Mounting the batteries. Each battery was mounted in a pair of caps QQ (fig.1) which were rigidly connected by a bar (not shown) through which the battery was bolted to a length of angle iron above the fire. The battery was capable of rotation within the caps QQ and its position relative to the caps could be adjusted by the scale R and fixed with the screw S.

The position of the batteries relative to the fire is shown in fig.4. The angle iron struts A on which the batteries were mounted were bolted parallel to each other in a horizontal plane at a distance 65 cm apart and 175 cm above the top of the combustion vessel; the batteries were respectively North and South of the vessel. Along the central portion of the strut a slot was cut which enabled each battery to be bolted in different positions along its strut within 15 cm on either side of the centre of the strut. This arrangement was used to stagger the position of the batteries relative to the fire.

A diagram of the water system leading to the batteries is shown in fig.5. Water was supplied from a tank T through a 6 H.P. centrifugal pump. The delivery line L from the pump divided into two at point E and proceeded through two equal lengths of 1 in pressure hose K to the two spray batteries B. The pressure in the batteries was recorded on the gauge P and was controlled roughly by a valve V on a bye-pass G from the delivery line to the tank and by the stopcock S. A fine control over the pressure was obtained by the needle valve N which allowed water to flow from the delivery line to waste. A 45 B.S.S. mesh filter M was placed at the outlet of the tank and 120 B.S.S. filters were placed on the main delivery line and at points just before the entrance to the batteries. It was found after the apparatus was in use for some time that calcium carbonate was being precipitated from the water into the nipple and gradually blocked the jet holes. This was overcome by passing the water entering the tank through "Micromet" which suppressed this precipitation.

Operation of the batteries. The initial velocity of the drops was assumed to depend on the pressure at which the spray was produced. It was therefore desirable to vary the drop size, the rate of flow to the fire area and the spatial pattern of the spray while maintaining a constant pressure. This could be done by varying the following five items:-

(1) the nipple used

(2) the number of pairs of jets used

(3) the position of the jets within the batteries

(4) the position of the batteries on the supporting struts (i.e. the amount the batteries are staggered relative to each other)

(5) the angle at which each battery was rotated in its supporting caps.

The first item was the main factor controlling the drop size; the other items also affected the drop size to some extent, since they influenced the amount of coalescence of drops which occurred. For a given nipple the rate of flow to the fire area depended largely on item 2, but items 3, 4 and 5 also influenced this factor because of the variations in spray density within the spray from a single pair of jets.

In carrying out a test at a given pressure the nipple used was fixed and items 2-5 were adjusted by trial and error until a particular rate of flow of spray with the desired spatial pattern was obtained at the fire area. The drop size of the spray was then measured.

EXPERIMENTAL

Design of the experiments

The design of the experiments was very similar to that used with the 11 cm diameter fire. Sprays of different properties were allowed to fall on the standard fire and the effect on the burning of the fire was noted. A given spray was applied to the fire after the latter had been burning for eight minutes. At the end of 20 minutes or at extinction time if sooner, the spray was stopped, the fire extinguished by smothering if necessary, and the contents of the vessel removed and weighed.

The tests were carried out at four pressures 5, 10, 30 and 85 lb/in^2. At 5, 10 and 30 lb/in^2 tests were carried out at a number of rates of flow, chosen for each pressure so as to give information on the mechanism of extinction of the fire with the minimum rate of flow of water. The drop size for any given rate of flow was varied by changing the nipples by which the spray was produced, and the batteries were adjusted to give, within certain limits, an approximately even spatial pattern of spray about the fire. At 85 lb/in^2 it was difficult to obtain, within the prescribed limits for spatial pattern, rates of flow either equal to or less than, the minimum required to bring about extinction; a series of tests, therefore, was carried out at this pressure, in which the influence of the rate of flow on the time of extinction of the fire was studied. With one spray at this pressure a series of tests was carried out to find the influence of the time of preburning of the fire on the time required for extinction.

Rate of flow and spatial pattern

The rate of flow was measured before and after each test by placing over the combustion vessel a vessel of the same diameter and 10 cm deep and measuring the amount of water from the spray collected in a given time. The tolerance permitted in the mean of these two determinations of rate of flow was as follows.

Rate of flow $g/(cm^2)(min)$	Tolerance $g/(cm^2)(min)$
0.40	± .025
0.60	± .035
0.80	± .04
1.00	± .04
1.20	± .05
1.60	± .08
2.00	± .08

The spatial pattern was measured by catching the spray in a battery of 29 tubes (fig.6). This was placed over the fire area in the manner shown in plan in fig. 7, and the water collected in each tube after a given time was measured.

It was found that if the two batteries were arranged either opposite or nearly opposite each other so that the maximum density of the spray that each projected fell at or near the centre of the combustion vessel, the type of spatial pattern obtained was that shown in fig. 7 (b). the highest concentrations were within an elliptical band N to S across the vessel with the peak near the centre of the vessel. If the two batteries were either staggered, or rotated within their supporting caps so that spray was projected to two opposite edges of the vessel, there was a tendency to obtain patterns such as those shown in fig.7 (c) and (d). In this case peaks were obtained on either the E and W side when the batteries were staggered, or the N and S side when the batteries were rotated. An increase in the quantities of water projected by the batteries resulted in a greater tendency to give the spatial pattern shown in fig. 7 (b) since the larger quantities of water pulled each other into the centre of the combustion vessel. With larger rates of flow, therefore, the batteries would have to be placed further apart, or rotated further to give the type of pattern shown in fig.7 (c) and (d).

It was desired in this investigation to keep the spatial pattern about the fire area as even as possible. Owing to the limitations of the apparatus it was impossible to obtain an even pattern for all the tests, and it was necessary to introduce two arbitrary limits for the unevenness in the spray pattern. The first limit was applied to those sprays in which the peak was in the central area A (see fig. 7 (a)): it was therefore mainly relevant to the type of distribution shown in fig. 7 (b). This limit was that there should be no more than 10 tubes containing less than half the quantity of water contained in the test tube with the maximum amount and that not more than one of these should be within the central area A. An example of a distribution recorded in a test which just falls within this limit is shown in fig. 7 (e). In all tests, the batteries were if possible adjusted to give sprays of spatial pattern between complete uniformity and the above limit, i.e. these spatial patterns were characterised by a peak concentration near the centre which fell off to about half on the East and West sides of the vessel. It became difficult, however, to achieve this type of pattern with low rates of flow at the higher pressures and in about one quarter of the tests it was necessary to resort to a spatial pattern in which the peak was not within the central area: these patterns were usually of the type shown in fig.7 (c) and (d). In this case the limit was set that no more than 5 tubes should contain less than half the amount of water contained by the tube with the maximum, and none of these tubes was to be in the central area A.

Drop size

Samples of the spray were caught in slides containing castor oil at a number of points 3 cm above the top of the combustion vessel. In all tests the drop size was assessed from samples taken simultaneously in three places; above the centre of the vessel and above points 10.5 cm North and 10.5 cm South of the centre respectively. The samples were photographed in a projection apparatus and the drops counted and classified. The number of drops counted for each test varied from 2,500 to 12,000. It was estimated that for a count of 3,000 drops, the standard error in the estimation of the mass median drop size would be about 5 per cent.

Details of the apparatus used for taking the drop samples and counting the drops are given in Appendix I.

Velocity of entrained air and drop velocity

It was found during the tests that the amount of air which had been entrained by the spray while moving towards the flames, had an important influence on the effect of the spray on the flames. A method was therefore developed by which the entrained air velocity could be determined. The spray was projected downwards into a 5 in diameter asbestos tubing right angle bend, in the manner shown in fig. 8. The bulk of the spray entering the tube was thrown out at the bend and it was possible to measure the prevailing air current by placing an anemometer at the end of the long limb. The entrained air velocity was measured at points 30 cm above the centre of the vessel, and 30 cm above points 9 cm North, South, East and West of the centre of the vessel and the mean taken. Because of friction within the tubing the value so obtained was somewhat lower than that present at the points where the spray entered the short limb, but it was possible to correct for this by calibrating the tube with the short limb pointing into an air stream of known and uniform velocity produced by a wind tunnel.

A method was also developed by which the velocity of drops in a spray could be found and this determination was carried out at a point 30 cm above the centre of the vessel in a group of tests in which 3/64 in jets were used. The measurement of the mean velocity of drops of size less than 0.4 mm had a standard error of 15-20 per cent; the error was greater for drops of larger size. It was found that in any one spray the mean drop velocity increased with drop size, the velocity of the smallest drops being equal to that of the entrained air in the spray, and the largest drops to the downward component of velocity in the impinging jets forming the spray. It was also found that if allowance was made for the entrained air velocity, the mean velocity at any given drop size less than 0.4 mm was substantially independent of the rate of flow and the pressure of the spray, and followed the curve shown in fig.9. It may be expected, therefore, that in those tests in which no drop velocity measurements were carried out, a reasonable estimate of drop velocity may be obtained by adding the entrained air velocity to the velocity given by the curve shown in fig. 9.

The experimental methods for determination of drop velocity and a discussion on the above results will be given in greater detail elsewhere.

CALCULATION OF RESULTS

Quantity burned ratio,* and water loss

These were calculated in a manner similar to that used in the earlier report (1). A slight modification was made in the calculation of the quantity burned ratio. Since the reproducibility of the 30 cm fire was much better than the 11 cm fire, the quantity burned in a given test with spray was compared with the average of the quantities burned in all the blank tests (1163 g). Since the quantity burned in the first 8 minutes of the test was 434 g, the quantity burned ratio (Q) was given by the following relationship:-

$$Q = \frac{\text{Quantity burned in test with spray} - 434}{1163 - 434}$$

Mean drop size

In comparing the efficiency of sprays produced at a given pressure and with a given rate of flow to the fire, it is necessary to decide on the drop size which will represent the mean drop size of the spray. To do this it is necessary to have some preknowledge on how the processes involved in the action of the spray on the fire are likely to depend on drop size. Experience from the tests carried out on the 11 cm fire shows that three factors are likely to enter into the action of spray on a kerosine fire; the heat transfer from the flames to the spray drops, the heat transfer from the liquid to the spray drops and the kinetic energy of the drops. The first of these factors controls the amount of cooling of the flames, the amount of steam evolved in the flames and the amount of water which manages to reach the part of the flames near the burning liquid and the burning liquid itself. The second factor will control the amount of cooling of the liquid which takes place, the amount of water vapour which accompanies the combustible vapour and the sputtering. The kinetic energy of the drops which reach the liquid will control the amount of splashing which takes place and the agitation. The agitation is the main influence in the cooling of the surface layers of hot kerosine by mixing with cold layers from below; it may also be expected to play an important part in the tendency to form an emulsion at the surface.

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*The quantity burned ratio is a ratio which gives a comparison of the quantity of kerosine consumed in a test with spray to that consumed in a test without spray. In calculating the ratio, allowance is made for the time in which no spray acts on the fire.

The velocity of the drops, in the flame and the liquid, plays a very important part in determining the effect which each of the above three factors has on the fire. It is therefore necessary to know the relation between the velocity of the drops and the drop size before formulae may be deduced giving the mean drop size for these factors. This information, even for spray drops falling through air is very approximate and does not allow more than a very tentative estimation of these formulae. However, from the available information the following formulae have been deduced (see Appendix II).

D_{H_f} = Mean drop size for heat transfer in flames = $\sqrt{\dfrac{\sum n_1 D_1^3}{\sum n_1 D_1}}$

D_{H_K} = " " " " " " " liquid = $\sqrt{\dfrac{\sum n_1 D_1^3}{\sum n_1}}$

D_E " " " " kinetic energy = $\dfrac{\sum n_1 D_1^4}{\sum n_1 D_1^3}$

It will be seen that these formulae are quite different and if a given spray has a wide range of drop sizes they would give quite different values for the mean drop size of the spray. In the past the mass median drop size has been used as the representative mean drop size of fire-fighting sprays (1), (3). For the types of spray under consideration this drop size is close to the weight mean drop size $(\sum n_1 D_1^4 / \sum n_1 D_1^3)$ which it will be seen is equal to the tentative value of D_E. Owing to the uncertainty inherent in the derivation of D_{H_f}, D_{H_K} and D_E, and the fact that none of them can be used to correlate all the phenomena which may be expected to take place when a water spray is applied to a fire, it was decided to use mainly the mass median drop size. This on the whole, gave a satisfactory correlation between the drop size of the spray and most of the dependent variables measured in the tests (e.g. quantity burned ratio, liquid temperature), and inless specifically stated otherwise, all future references to drop size will refer to the mass median drop size. However, a somewhat better correlation was found between mean drop size of the spray and the water loss, if the flame heat transfer drop size was used instead of the mass median drop size.

<u>Heat transfer capacity.</u> A quantity called the heat transfer capacity was calculated for some of the sprays. This quantity is an estimate of the rate at which heat was transferred from the flame to the spray when the spray came into contact with the flame, and is expressed in cal/(cm^3 of flame)(sec). The way this quantity was calculated is shown in Appendix III. It was necessary to use information on the drop size distribution, drop velocity and rate of flow of the spray; the errors concerned with the measurement of these factors would result in a "precision error" in the estimation of the heat transfer capacity of about 20 per cent. It was also necessary to make certain assumptions about the properties of the flame and to use a heat transfer formula (4) which is only known to hold for a single evaporating drop, As there would probably have been some interference between the boundary layers of one drop and another, it is likely that the calculated heat transfer capacity would have been somewhat greater than the actual heat transfer capacity. Since, however, the mean distance between drops in the spray was of the order 5-20 times the diameter of the drops plus their boundary layer, it is unlikely that this interference would have been important and the calculated figures may be considered as being of the right order.

It must be emphasized that the heat transfer capacity as calculated above does not give any information on the rate at which heat was transferred to the spray after entering and passing through a finite thickness of flame, since the velocity and size of the drops was then considerably altered. For example, it will be seen in the calculation shown in Appendix III that a third of the heat transfer capacity of the spray was due to the smallest drop size group. It may be shown that the drops in this group would evaporate completely after passing through a flame 1 cm thick; the heat transfer capacity would therefore be reduced by at least a third after passing through a flame of this thickness.

RESULTS

General observations

The general effect of the spray on the fire was very similar to that observed for the fire in the 11 cm diameter vessel. The first impact of the spray on the hot kerosine caused an upsurge of flame which lasted only a few seconds. The fire then usually diminished in intensity, and if not extinguished reached a fairly steady state in three or four minutes which persisted until the end of the test. The characteristic shape of the flames for the test without spray (fig.10(a)) was lost. With sprays at pressures of 5 and 10 lb/in^2 the shape of the flame, although much more indefinite, approximated to that shown in fig.10 (b). A trapezoidal volume of flame covered the whole vessel and in places the flames reached right down to the burning liquid. As the pressure was increased there was a greater tendency for the flame to be blown about, presumably by the air accompanying the spray. The effect of this was to make the flame very unsteady; at one moment the flame height might be about 30 cm with the flame pushed to the side somewhat, and at the next the flames might reach a height of 100-150 cm. Splashing and sputtering of kerosine into the flame was noted for practically all the sprays used. When fine sprays were used a small amount of froth, probably of water vapour in kerosine, was usually formed.

Effect of spray properties on the quantity burned ratio

The effect of sprays at 5, 10 and 30 lb/sq.in pressure on the quantity burned ratio Q is shown in figs. 11-13, in which Q has been plotted against the drop size of the spray. In tests in which extinction occurred the points have been marked with an E.

The curved in these figures have in general the same shape as those obtained with the 11 cm fire; i.e. there is a drop size for a given rate of flow at which the quantity burned ratio is a minimum. For a given pressure this drop size did not vary appreciably with the rate of flow although figs. 11 and 13 show a small decrease of the efficient drop size with an increase in rate of flow. As the pressure was increased, however, this drop size was considerably reduced. At the efficient drop size the quantity burned ratio decreased as the rate of flow was increased until extinction was obtained. In the part of the curves representing drop sizes greater than the most efficient drop size, a considerable contribution to the increased consumption of kerosine was due to the amount of splashing which took place. In that part of the curves representing drop sizes less than the most efficient drop size, a high percentage of the spray failed to reach the burning liquid; that which did reach the burning liquid caused a great deal of sputtering. In Table III a summary is given of the effect of pressure on the efficient drop sizes, and these drop sizes at which appreciable splashing and sputtering took place. The last two drop sizes have been obtained by interpolating or extrapolating the curves to the 100 per cent quantity burned ratio line and are necessarily very approximate.

TABLE III

The effect of pressure on the most efficient drop size, and the splashing and sputtering drop sizes

Pressure	Most efficient drop size mm	Maximum sputtering	Minimum splashing drop size mm
5	0.7	0.5	1.1
10	0.5	0.4	0.8
30	0.35	0.28	0.52

It will be seen that not only do the splashing and the sputtering drop sizes decrease with increase in pressure but also the arithmetic difference between them decreases. Therefore the range of drop sizes at which rates of flow of spray, although less than those required to bring about extinction, may yet produce a significant decrease in the rate of consumption of kerosine, decreases with increase in pressure.

At a pressure of 85 lb/in^2 only one test was carried out under the correct conditions of spatial pattern, in which the fire was not extinguished. This was at a rate of flow of 0.4 $g/(cm^2)(min)$ with 1/32 in jets and the drop size was 0.21 mm. There was a great deal of sputtering in the test and the fire was particularly wild. The quantity burned ratio was 118 per cent. In other tests at 85 lb/in^2 in which the fire was extinguished after a few minutes of spray application it was noted that during most of the period of spray application the fire burnt wildly, with much sputtering and splashing. It would therefore appear that at a pressure of 85 lb/in^2 the tendencies of sprays with rates of flow less than those required for extinction, to create a great deal of disturbance in the fire and to cause a high rate of kerosine consumption was greater even than with sprays at lower pressures.

It is difficult to assess the statistical significance of the results shown in figs. 11-13 since the drop size of the spray was itself a dependent variable; it depended mostly on nozzle size and pressure and to some extent on the rate of flow and the spatial pattern. There were, however, three blocks of experiments with which it was possible to carry out an analysis of the variance of Q with pressure, rate of flow and nozzle size. Here nozzle size could be considered as roughly representing the drop size of the spray; for a given pressure the drop size increased as the nozzle size increased. Two of the blocks did not contain any extinctions; they were firstly a block with a rate of flow constant at 0.4 $g/(cm)^2(min)$ with the 4 nozzle sizes and the pressures 5, 10 and 30 $lb/in.^2$, and secondly a block with rates of flow of 0.4 and 0.8 $g/(cm)^2(min)$ at pressures of 5 and 10 $lb/in.^2$ and with the 4 nozzle sizes. The third block contained extinctions and had rates of flow of 0.4, 0.8 and 1.2 $g/(cm)^2(min)$, pressures of 5, 10 and 30 lb/in^2, and nozzle sizes of 1/32, 3/64 and 1/16 in.

The first and second blocks showed that nozzle size and rate of flow were significant factors in the variation of Q; pressure and the various interactions were not significant although the interaction between nozzle size and rate of flow just fell short of the 5 per cent significance level in the second block. In the third block, however, pressure and nozzle-flow interaction were the predominant factors in the variation of Q; there was also a high variance due to the nozzle size but this was made insignificant because of the high nozzle-flow interaction.

The significance of the nozzle size factor in the first two blocks was due to the occurrence of the most efficient drop size within these blocks with either the 1/32 in or the 3/64 in jet - the 1/16 in jets usually gave the coarser sprays which caused the splashing and the 1/64 in jets the finer sprays which caused the sputtering. The high nozzle-flow interaction was due to the fact that sprays which caused splashing (i.e. 1/16 in jets) did not bring about much reduction in Q as the rate of flow was increased because reduction in the rate of burning was partially or even completely balanced by the increased amount of splashing. The significance of pressure in the third block was due to the more frequent occurrence of extinction as the pressure increased; these extinctions were associated with very low values of Q.

Extinction

Table IV shows a summary of the experiments in which extinction was achieved.

Minimum rate of flow for extinction. It was not possible at 5 lb/in^2 to obtain a rate of flow at or near the efficient drop size which brought about extinction

14		·6	1/32	·21	249	116	[illegible]	[illegible]	[illegible]		
15			*3/64	·25	249	63	438	0	440	·40	·29
16						59	140	0	420		
17		1·0	1/16	·41	n.d.	130	90	0	1660	n.d.	n.d.
18		1·2	1/64	·23	319	19·5	143	0	290	·62	·45
19			1/32	·28	292	20	124	0	293	·60	·44
20			3/64	·30	310	14·2	134	0	213	·42	·31
21	85		1/16	·42	246	13·0	115	0	264	·34	·25
22		1·6	1/64	·25	310	17·5	125	0	339	1·08	·79
23			1/32	·25	337	17·5	125	0	347	1·01	·74
24			3/64	·29	355	15·0	132	0	293	·63	·46
25			1/16	·38	337	12·5	127	0	254	·50	·37
26			**3/64	·29	372	10·5–15·0	127–137	[illegible]	210–2[illegible]0	·56	·41
27		2·5	**3/64	n.d.	n.d.	6–7	n.d.	0	180–210	n.d.	n.d.
28		2·9	3/64	n.d.	463	5·2	123	0	183	n.d.	n.d.
29		[illegible]	**1/8	n.d.	n.d.	2·2–3·1	n.d.	0	240–340	n.d.	n.d.

* "0" in this co
signifies tha
reignition wa
instantaneous
far as could
judged withou
use of special
apparatus.

Table IV

Summary of tests in which extinction was achieved

1	2	3	4	5	6	7	8	9	10	11	12
Test number	Pressure lb/sq.in.	Rate of flow g/(cm²)(min)	Jet diam. in.	Mass median drop size mm	Entrained air velocity cm/sec	Time for extinction sec	Temp. 3 mm below surface at extinction °C	Time for reignition sec	Water supplied to extinguish the fire g	Heat transfer capacity flame temp. (1270°C)	Heat transfer capacity flame temp. (990°C)
1	10	1·2	1/32	·51	164	390	61	8‡	5830	·22	·16
2	30	·6	1/32	·35	134	251	61	n.d.	1930	·27	·20
3			3/64	·39	n.d.	709	67	1‡	5237	·20	·15
4			3/64	·37	167	375	62	1	2720	·20	·15
5		·8	1/32	·35	161	324	64	1‡	3000	·25	·18
6			1/32	·35	n.d.	280	62	n.d.	2630	·25	·18
7			3/64	·34	173	257	69	1·5	2590	·34	·25
8		1·2	1/32	·36	204	69	56	0*	998	·54	·39
9			3/64	·46	256	158	66	0	2350	·32	·23
10			1/16	·44	256	219	83	n.d.	3500	·31	·23
11			1/16	·52	n.d.	130	85	0	1945	n.d.	n.d.
12		·45	1/64	·19	200	247	112	0	1350	·58	·43
[illegible]		[illegible]	1/[illegible]	[illegible]	[illegible]	78	127	0	[illegible]	·38	·64

n.d. = Not determined

* Two tests carried out with this spr

** Four tests carrie out with these sprays.

‡ Lighted source applie about 10 seconds a ter

although rates of flow up to 1.2 g/(cm^2)(min) at the efficient drop size were tested. At 10 lb/in^2, extinction at the efficient drop size was obtained with 1.2 g/(cm^2)(min). No extinction was obtained at a rate of flow of 1.0 g/(cm)^2(min) at this drop size. It may therefore be accepted that at this pressure 1.2 g/(cm^2)(min) was the minimum rate of flow at which extinction could be obtained. It will be noted that at 30 lb/in^2 the fire was extinguished with sprays from both 1/32 and 3/64 in jets at a rate of flow of 0.6 g/(cm^2(min). This rate of flow, however, did not extinguish the fire when 1/64 in jets were used because the drop size was finer than the most efficient drop size at 30 lb/in^2 pressure. Since no extinction was obtained with any drop size at a rate of flow of 0.4 g/(cm)^2(min), a rate of flow of 0.6 g/(cm)^2(min) may be taken as the minimum rate of flow to extinguish the fire. The minimum rate of flow which is recorded in Table IV as having extinguished the fire when the pressure was 85 lb/in^2 is 0.45 g/(cm)^2(min). Since, however, only one test was carried out with a lower rate of flow (0.4g/(cm)^2(min), 1/32 in jets) it cannot be certain that this was the minimum rate of flow for extinction. Indeed, a test with a rate of flow of 0.4 g/(cm)^2(min) with the 3/64 in jets, did give extinction in 91 seconds but as the spatial pattern of the spray fell outside the prescribed limits mentioned previously, this test was not directly comparable to those shown in Table IV.

It follows from the above that the minimum rate of flow required to extinguish the fire decreased as pressure increased.

Time of extinction. For a given rate of flow the time required for extinction also decreased as the pressure increased (Column 7, Table IV). Thus for a rate of flow of 1.2 g/(cm^2)(min), the minimum time in which the fire was extinguished was 390, 69 and 14.2 seconds at 10, 30 and 85 lb/in^2 respectively. As the rate of flow at a given pressure was increased the time required for extinction decreased. At the pressure of 85 lb/in^2 and in the range of rates of flow of 0.45 -1.2 g/(cm^2)(min) this decrease was so large that the total quantity of water required to extinguish the fire was considerably reduced as the rate of flow increased (Column 10, Table IV). At rates of flow from 1.6 - 9.0 g/(cm^2)(min) the time of extinction continued to decrease with increase in rate of flow but there was no appreciable further reduction in the total quantity of water required for extinction. With one spray, No.26 (1.6 g/(cm^2)(min) 85 lb/in^2, 0.29 mm) four repeat tests were carried out and the time of extinction was found to vary between 10.8 and 15.0 seconds. It follows, therefore, that the differences in the times of extinction noted for tests 18-21 and 22-25 are hardly outside the range of reproducibility of a single test and no regid conclusions may be drawn from the observed variations of time of extinction with drop size. Nevertheless, it will be seen in these tests and in tests 13-16, that the sprays from the 3/64 in jets put the fire out more quickly in every test than did sprays at the same rate of flow from either the 1/32 in or the 1/64 in jets. The drop size of the 3/64 in jet sprays varied between 0.25 - 0.30 mm, and that of the 1/64 and 1/32 in jet sprays between 0.18 and 0.28 mm. From the number of tests carried out it may be deduced that the probability of these results having occurred by chance was less than 1 per cent. It will also be seen that a spray of rate of flow 0.6 g/(cm)^2(min) from 3/64 in jets was more efficient than a spray of rate of flow 1.0 g/(cm)^2(min) with 1/16 in jets (drop size 0.41 mm). It may therefore be tentatively concluded that at a pressure of 85 lb/in^2 spray of drop size 0.30 mm was more efficient than other sprays of drop size within the range 0.2 - 0.4 mm, but the difference over this range of drop size was not great, especially at high rates of flow.

The spray used in test 26 was also used to find the effect of time of preburning of the kerosine on the time required for extinction. The results are given in fig.14; which shows the range and the mean of the 4 tests carried out for each time of preburning. Although for a given time of preburning the time of extinction varied over a wide range, the mean time for extinction definitely increased as the time of preburning increased.

Temperature in the liquid at moment of extinction. The temperature at the moment of extinction as recorded by the thermocouple 3 mm from the surface is given in column 8 of Table IV; it varied from 61°C upwards. The fire point of the unburned liquid was 58°C; after burning for twenty minutes the fire point of the liquid near the surface was 68° and 4 cm below the surface 61°C. Therefore, if the temperature near the surface of the kerosine was reduced to 58 - 68°C before the extinction took place, the kerosine may be considered as having been cooled to the fire point. This happened in the extinction at 10 lb/in² and some of the extinctions at 30 lb/in², but in none of the extinctions at 85 lb/in².

Phenomena leading to extinction. In all tests extinction was preceeded by large areas of the surface being cleared momentarily of flame; an example of this is shown in fig.15. When the fire was extinguished without the liquid being cooled to the fire point, extinction took place quite suddenly, probably when one of these clearances covered the whole of the vessel at the same time. In these tests the flames were usually quite high (more than 20 - 30 cm) when clearances began to appear but the height of the flames at the moment of extinction depended on the temperature to which the liquid had been reduced. When the fire was extinguished by the liquid being cooled to the fire point the flames were usually reduced considerably in size (below 20 - 30 cm) before clearances began to appear; in these tests the flame immediately before extinction consisted of wisps of blue flame which moved about close to the liquid surface. Occasionally when sprays with a high rate of flow at 85 lb/in² were used, the clearance of the yellow flame by spray would take place quickly but would lead to the formation of a small flickering blue flame which would persist several seconds before the fire was extinguished.

Reignition. After most of the tests a lighted taper was applied to the vapour above the kerosine after the spray had been turned off. In most of these tests the lighted taper was applied within 2-3 seconds of the moment of extinction, although in some tests there was an interval of about 10 seconds. The taper was held within 2-3 cm of the surface, and the time taken before the vapour reignited was recorded. These times are shown in column 9 of Table IV. It will be noted that in practically every test where the temperature of the liquid was not reduced to the fire point the kerosine vapour reignited instantaneously; the only exceptions were in two tests in which the kerosine was cooled to within a few degrees of the fire point and in which there was an interval of about a second between the moment of application of the source of ignition and the reignition.

Condition of surface at moment of extinction. In tests 13 and 15-24 samples were taken from the kerosine surface within 2 seconds of the moment of extinction. Most of these samples were found to consist of a dilute suspension of fine water drops in kerosine; a typical photograph of one of these samples is shown in fig. 16. In some samples, however, there was also a slight turbidity present. On examination under the microscope this turbidity was found to consist of a suspension of very fine drops of a fluid (probably water) about 1-2 μ diameter, in kerosine. The fact that kerosine was the continuous medium in these samples was established by the following three tests;

(1) a drop of water when added to the suspension did not mix

(2) a drop of kerosine added to the suspension mixed

(3) crystals of methylene blue, a water soluble dye, when added to the suspension did not colour it.

The total amount of water present in the samples was obtained by a centrifuging process; in no case was it more than 1 per cent.

In tests 27 and 29 a pair of electrodes across which a potential difference of 2 volts was maintained was inserted in the kerosine 1 mm below the surface. The current which flowed between the electrodes during the actual extinction process was found to be less than $\frac{1}{500}$ of the current which flowed when the electrodes were placed in a 50-50 kerosine-water emulsion stabilized with 1 per cent Lissapol.

Entrained air velocity of sprays. It will be seen from Table IV that the entrained air velocity of the sprays which brought about extinction increased with both pressure and rate of flow; similar results were obtained with sprays which did not bring about extinction. It has been seen that the efficiency of extinction with sprays improves as the rate of flow and the pressure increases. It may therefore be concluded that the entrainment of air in the spray does more to help the extinction process by assisting fine drops to reach the base of the flames and the burning liquid, than to hinder the extinction process by feeding air to the fire. Thus it is worth noting that those sprays which extinguished the flames most rapidly had an air entrainment velocity of the same order as the upward velocity of the flames.

Heat transfer capacity. In the last two columns of Table IV the heat transfer capacity of the spray is shown for a flame temperature of 1270°C (probably the maximum temperature in the flame) and 990°C (the mean temperature across the flame in a place 30 cm above the liquid as measured by the Schmidt method). The value for the temperature of 990°C is 0.73 times the value for the temperature of 1270°C.

It will be seen that those sprays which extinguished the fire by cooling to the fire point had low values of the heat transfer capacity; on the other hand those sprays which extinguished the fire without cooling to the fire point had high values. This is shown more clearly in fig.17 in which the heat transfer capacity is plotted against the temperature of the burning liquid when extinction took place. This diagram is divided into 4 quadrants by the ordinate at 68°C and the abscissa at 0.24 cal/cm^3 of flame)(sec). Nearly all the points fall into the top right hand or the bottom left hand quadrants I and III. When the fire was extinguished by being cooled to the fire point the flame height became smaller, and in the last few minutes of the test the flame was only a few cms high. The spray would come straight at this small flame and owing to this smallness would not suffer any great reduction of heat transfer capacity as it passed through the flame. If the flame was extinguished as a result of heat transfer between spray and flame it would be expected that there would be a minimum rate of heat transfer per unit volume of flame at which extinction would be brought about. The fact that in those tests in which the fire was extinguished by cooling to the fire point the sprays had a heat transfer capacity of less than 0.24, and in most of the tests in which the extinction was achieved without cooling to the fire point the heat transfer capacity was more than 0.24 cal/$(cm)^3$(sec), indicates that in the latter tests extinction did indeed take place by a flame heat transfer process. In view of the error of the estimation of the flame heat transfer capacity, the value for extinction of the flame may be taken to be about 0.2-0.3 cal/(cm^3 of flame)(sec). The information in fig.17 will be discussed further later.

Tests without extinction.

Water lost. In figs. 18-20 the percentage of water spray which was applied to the fire but did not penetrate through to beneath the kerosine is plotted against the mass median drop size, for those tests in which the fire was not extinguished. Although the results are scattered it will be seen that for a given pressure the amount of water spray lost increased as the drop size of the spray was reduced. At all three pressures the amount of water spray lost at the efficient drop size was 50-60 per cent. It is not possible from these curves to draw any conclusions on the effect of rate of flow on the water lost.

As the bulk of the water loss was probably due to the evaporation of water drops in the flames, it may be expected that a better correlation than shown in figs. 18-20 would be obtained if the water loss were plotted against the flame heat transfer drop size (D_{Hf}). This has been done in figs. 21-23. There is some reduction in the scatter of the points in these diagrams as compared with figs. 18-20 which is reflected by an improvement in the linear correlation coefficient from -.79, -.77 and -.76 to -.80, -.86 and -.85 for the pressures 5, 10 and 30 lb/in^2 respectively. Moreover, certain relationships between the rate of flow and the water loss appear. In figs. 21 and 22 (5 and 10 lb/in^2) the best straight lines have been drawn for the points representing rates of flow of 0.4 and 0.8 g/(cm)^2(min) and in fig. 23 (30 lb/in^2) the best lines have been drawn for points representing 0.4 and 0.6 g/(cm)^2(min). On the basis of figs. 21-23 taken as a whole, it will be seen that for a given pressure the water loss decreased with increase in rate of flow at the lower drop sizes; at the higher drop sizes this effect of rate of flow was less marked and was even reversed. It may be observed in figs. 11-13 that, at a given pressure, the quantity burned ratio decreased with increase in rate of flow at small and intermediate drop sizes, but because of the splashing effect often increased with rate of flow at the coarse sizes. The effect of rate of flow on the percentage water loss was therefore probably directly related to the size of the fire when the spray was acting on it - the larger the fire the greater the percentage of water lost at a given drop size and pressure.

A factor which goes some way to accounting for the scatter of the results shown in figs. 21-23, is the variation in spatial pattern of the spray within the limits that had been prescribed. Some evidence to support this was obtained by studying the correlation of the distribution of points about the straight lines shown in figs. 22 and 23 and the type of spatial pattern of the sprays concerned. This evidence is summarized in the contingency table below (Table V).

TABLE V

Relation between the spray pattern and the water loss

	Sprays which gave a water loss <u>greater</u> than shown by the mean line for the respective rate of flow.	Sprays which gave a water loss <u>less</u> than shown by the mean line for the respective rate of flow.
Sprays which had a <u>central</u> type of spray pattern (as shown on fig.7b).	5	2
Sprays which had a non-central type of spray pattern (as shown in figs. 7c and d).	2	9

There is a probability of about 1 in 40 of a distribution of results as weighted as that shown in Table V having occurred by chance; it may therefore be concluded that there is a tendency for a spray with a central type of spray pattern to be associated with a high water loss and a non-central type to be associated with a low water loss. The reason for this is that with sprays having a central type of spray pattern a much larger part of the spray must pass through the middle portion of the flames than with sprays which have a non-central spray pattern.

<u>Temperature at thermocouple 3 mm below the surface.</u> In tests in which extinction did not take place, the thermocouple 3 mm below the surface usually registered a fairly steady value after 3-4 minutes following the initial application of the spray. It may be concluded that when the kerosine reached this steady temperature a stable condition had been established in

which the heat transferred from the kerosine to the water spray passing through it was equal to the heat transferred to the kerosine from the flames in excess of that required to give vaporization.

In figs. 24-26 the average temperature in the last five minutes of a test has been plotted against the drop size for the different rates of fire and pressures. It will be seen that at 5 and 10 lb/in^2 (fig.24 and 25) the temperature for sprays of a given drop size decreased as the rate of fire increased. This is to be expected as a consequence of the larger amount of water spray which reached the liquid. At a given rate of flow the first reductions of the drop size generally gave a reduction in the temperature. Presumably the reduction in the amount of water which reached the liquid was more than counterbalanced by the increased efficiency of the smaller drops in removing heat from the liquid. As the drop size was reduced below the efficient drop size, however, the equilibrium temperature increased; in this region it is probably that the greater losses of spray in the flames was not counterbalanced by the increased efficiency of the smaller quantity which reached the kerosine. At 30 lb/in^2 the temperature increased as the drop size decreased for a rate of flow of 0.4 g/(cm)^2(min). At other rates of flow insufficient information is available on the fires which reached an equilibrium temperature to allow any conclusions to be drawn.

<u>Temperature at thermocouple 60 mm below the surface.</u> The temperatures registered at a point 6 cm below the surface indicated the temperature of the water just below the kerosine-water surface. It was found to have a similar dependence on rate of flow and drop size as was found in the tests on the 11 cm diameter fire. For a given pressure, at low rates of flow and small drop sizes there was such a high percentage of water lost that the temperature at this point was hardly affected. As the drop size increased however, there was a steep increase in the temperature to about 85°C. Fig.27 shows the relationship between the temperature 6.0 cm below the surface and the spray properties for a pressure of 10 lb/in^2.

DISCUSSION

Mechanism of extinction

There are four processes by which flaming combustion of a material may be extinguished by a water spray:

(1) The cooling of the material by the spray reduces the rate at which inflammable vapour is evolved; if the fire point of the material is above the temperature of the water spray then it is possible, with a sufficiently high rate of flow of spray, for this cooling to proceed until extinction is obtained. With a burning liquid this cooling is produced not only by direct heat transfer between the water drops and the liquid, but also by the mixing of cold liquid below the surface into the hot liquid in the surface.

(2) The water vapour evolved by heat transfer between the burning material and the spray may be sufficient to inhibit combustion of the combustible vapour.

(3) The water spray may form either an emulsion, a foam or a froth on reaching the burning material which will either protect the material from heat transfer from the flames or reduce the vaporization sufficiently to prevent the evolution of enough inflammable vapour to give an inflammable atmosphere.

(4) The part of the flames nearest the burning material may be extinguished by the spray. If this happens to the extent that none of the combustible vapour rising from the material comes into contact with burning gas, the vapour would fail to ignite. There are two ways in which the flame may be extinguished by the spray; firstly, the cooling

may be sufficient to reduce the temperature to below the ignition point, secondly, the water vapour evolved may be sufficient to inhibit or smother the combustion. In both these mechanisms heat transfer between the flames and the spray is an important basic factor.

A discussion follows on the importance of these factors in the extinction of the kerosine fire.

Cooling the liquid. In practically all the tests in which extinction was obtained there was some drop in the temperature 3 mm below the surface during the application of spray. It is likely therefore that in most tests cooling the liquid played some part in reducing the intensity of the fire so as to bring about the extinction. In those tests in which the liquid was cooled to the fire point before extinction, the cooling of the liquid must have been the predominant mechanism of extinction. It is very difficult to make any estimate of the cooling action of a spray because of the complicated nature of the cooling process.

Evolution of water vapour. Burgoyne and Richardson (7) found that a mixture of pool petrol vapour and water vapour will be non-inflammable with any mixture of air if the ratio of the volume of water vapour to pool petrol vapour is greater than 4.2. If it is assumed that this figure applies also to kerosine and the composition of kerosine is assumed to be that of undecane than it may be shown that if sputtering of kerosine is neglected the vaporization of 0.5 g of water per second over the whole area of the vessel would provide sufficient water vapour to inhibit the combustion of the kerosine. Since, kerosine, however, finds its way into the flame by sputtering the above figure must be regarded as a conservative estimate.

For water vapour to be formed by heat transfer between the water drops and the burning liquid, the temperature of the liquid must be above 100°C and that of the water drops, 100°C. In some of the tests shown in Table IV extinction took place with the liquid temperature between the fire point and 100°C, and in a number of others the temperature of the liquid was not very much in excess of 100°C. It is clear that in these tests vaporization of water at the liquid could not have brought about extinction. In some of the tests at 85 lb/in^2 the fire was extinguished in a matter of seconds and the temperature of the liquid was still high at the moment of extinction. It is possible in these tests that vaporization at the liquid surface may have contributed to the extinction. The evidence available from the experiments however, does not support this. In the first place, the depth of the layer of kerosine with a temperature greater than 100°C increases with an increase in time of preburning (8); the total amount of steam formation from a water drop passing through this layer should therefore increase as the time of preburning increases. It would thus be expected that if steam formation in the hot liquid was the predominant mechanism of extinction, the fire would have been easier to extinguish with a given spray as the time of preburning increased. The relationship between time of extinction and time of preburning shown in Fig. 14 indicates that this was not so. In the second place, the chance of extinction by steam formation in the burning liquid should have been greatest in the few seconds following the application of spray since the burning liquid was then at its hottest and the rate of steam formation greatest. It was found, however, in every test that an upsurge of flame was the first consequence of putting the spray on the fire, and that in general this upsurge was more violent the greater the rate of flow and the pressure of the spray.

It may therefore be tentatively concluded that in none of the tests was steam formation at the burning kerosine the predominant extinction mechanism. It may be added, however, that more information on this method of extinction should be available after tests have been carried out on petrol, with which the mechanism cannot operate, and with the transformer oil, with which it will probably be of greater importance.

Formation of an emulsion. It has been stated [5], [9] that when oil fires are extinguished by water sprays produced by certain proprietary brands of nozzle, an oil in water emulsion is formed; the emulsion brings about extinction by preventing the vaporization of the oil droplets. In the tests described in this report no evidence was found of the formation of an oil in water emulsion. Moreover, if the fire was extinguished with the temperature of the kerosine above the fire point the fire could almost invariably be reignited immediately if a source of ignition was brought into contact with the vapour. It must therefore be concluded that the above mechanism played no part in bringing about extinction of the fires described in this report.

Extinction of the flame. By a process of elimination it would appear that the extinction of the flames in contact with the uprising vapour played an important part in bringing about many of the extinctions. If the mass of kerosine vapour burning in one second in one cm^3 of the flame is known (let this be x) then an estimate may be made of the amount of heat transfer which would have to take place to extinguish the flame by smothering and by cooling. To extinguish the flame by smothering a mass of $\frac{1}{2}x$ of water vapour would have to be formed in the same time and within the space in which the quantity x of kerosine burns. Thus the total heat transfer that would have to take place would be $\frac{\lambda x}{2}$ where λ is the heat of vaporization of water. To extinguish the flame by cooling, the water spray will have to abstract from the flame not more than the heat of combustion of the quantity x . Where x is measured in grams, therefore, about 300 x cal/(cm^3)(sec) would be required to produce enough steam to smother the flames and about 10,000 x cal/cm^3)(sec), but not more would be required to cool the flame. Since it is very unlikely that all the heat transfer from the flame to the spray will result in steam formation, it would be expected that the minimum amount of heat transfer required to extinguish the flame would lie between these two values.

There is very little information available which enables x to be calculated and it probably varies in different parts of the flame. If during the tests without spray, however, it is assumed that the kerosine burning (1 g/sec) burns uniformly throughout the whole volume of flame (about 15,000 cm^3), then x may be taken as being $\frac{1}{15,000}$ g/(cm^3)(sec). Assuming that this value will also apply when spray is falling through the flame then the amount of heat transfer which will have to take place will be .02 cal/(cm^3)(sec) for smothering and not more than 0.7 cal/cm^3)(sec) for cooling the flame.

It was found (Fig.17) that none of the sprays which extinguished the fire by cooling to the fire point had a heat transfer capacity greater than 0.24 cal/cm^3 of flame)(sec). This is about one third the estimated maximum heat transfer capacity required to put the flame out by cooling and about 12 times the estimated heat transfer capacity required to put the flame out by smothering. It is unlikely that in the last stages of extinction of a fire by cooling the liquid to the fire point, that the heat transfer capacity can be used efficiently, if at all, to produce steam since the drops have to be heated to 100°C for this to occur; therefore the figure of 0.2-0.3 cal/$(cm)^3$(sec) may be considered as a limiting value below which the flame will not be extinguished by cooling and is probably a better approximation to the actual value required to extinguish the flame by cooling than the 0.7 cal/$(cm)^3$(sec). It would therefore follow that if a heat transfer capacity of greater than 0.2-0.3 cal/(cm^3 of flame) (sec) is presented to that part of the flame near the uprising vapour the flames should be extinguished by cooling the flames. It is possible, however, that the flames could be extinguished by smothering even if the heat transfer capacity is less than 0.2-0.3 if the heat transfer results in steam production rather than merely heating the drops. For this to occur the drops should have already been heated to 100°C by the time the spray reaches the lower part of the flame, or they should be present in this part of the flame for a sufficiently long time to allow evaporation. Sprays which put the fire out in this way would when plotted in Fig. 17 give results which fall into quadrant II.

When a water spray is applied to a fire the heat transfer capacity of the spray which reaches the bottom of the flames may be much smaller than the initial heat transfer capacity since many of the drops may be evaporated or pushed away by the upper portion of the flame. However, the fire may still be extinguished if the cooling of the burning liquid is eventually sufficient to reduce the height flames to such an extent as to allow a high heat transfer capacity to be presented to the lower parts of the flame. If the spray were associated with a substantial air current which was sufficient to blow the upward rising flames away, this would also help the presentation of a spray of sufficiently high heat transfer capacity to the base of the flames.

During the course of the tests a number of phenomena were observed that lend support to the suggestion that a smaller heat transfer capacity would be required to extinguish the fire if smothering could take place than if cooling of the flames only could take place. Thus it was frequently observed that while the flames were still high the flames over nearly the whole surface area of the vessel would clear leaving a thin flame burning upwards at the edge of the vessel (see Fig. 15). It appears likely that this clearance was due to steam production; however, the heat transfer in the smaller flame afterwards could not give rise to steam production, and the heat transfer capacity at the part of the spray outside the vessel was not sufficient to extinguish the flame by cooling. It was occasionally observed too that a spray would clear the whole surface of flame quickly but leave a semi-transparent blue flame near the surface which would persist for seconds. It was probable that the heat transfer capacity of the spray within this blue flame was very low because of the low temperature of the flame, and as a result there was very little chance of steam formation.

Relation between the efficient drop size and the air entrained in the spray

At a given rate of water flow the amount of air entrained with a spray increased as the pressure increased, moreover, the velocity of the drops in the spray increased. It thus follows that as the pressure increased finer drops could be carried downwards more easily to the burning liquid. This accounts for the decrease with increase in pressure in the efficient drop size. Since with a given rate of flow of spray the rate of removel of heat from the burning liquid and the flames increases as drop size decreases it follows that the minimum rate of flow required for extinction should decrease as the pressure is increased.

It was also found, however, that at a constant pressure the amount of air entrained in a spray increased as the rate of flow of spray increased. It should therefore follow that as the rate of flow increased at a given pressure finer sprays should have been able to reach the base of the fire and that the efficient drop size should have decreased. There is some evidence of this having occurred at 5 and 30 lb/in^2 (figs. 11 and 13); at 10 lb/in^2, however, (fig. 12) the evidence points the other way, i.e. to an increase in efficient drop size with increase in rate of flow. The latter observation, however, might be due to the experimental error of the comparatively small number of experiments carried out at this pressure.

Comparison with the 11 cm diameter fire.

With the 11 cm diameter fire a most efficient drop size was found between 0.4 - 0.6 mm. Considerable amounts of splashing took place at drop sizes greater than 1.5 mm and of sputtering at drop sizes less than 0.25 mm. The minimum rate of flow of spray required to extinguish the fire was 0.4 g/(cm^2)(min) at a drop size of 0.46 mm.

These results are qualitatively similar to those obtained with the 30 cm fire. There are quantitative differences, however, which are due to the difference in the fires and the ways in which the sprays were produced.

In the earlier tests there was no control over the velocity of the drops in the spray. As the drop size of the spray decreased the air flow accompanying the spray increased since larger amounts of air were needed to tear the drops of the required size from the hypodermic needles. At drop sizes above 1 mm this air flow rate was very small and the drops could be considered as falling from rest; the air entrainment velocity and drop velocity could be considered equivalent to that produced by a very low pressure spray. These drops probably had, therefore, a smaller kinetic energy on reaching the burning liquid than drops of similar size produced at the pressure of 5 lb/in^2 in the present series of tests; this would account for the minimum drop size required for splashing on the small fire being higher than the drop size for splashing found at 5 lb/in^2 (see Table III page 15).

At the finest drop sizes tested on the small-scale apparatus, although there was a larger amount of air accompanying the drops downward, this air flow was in itself not sufficient to affect the flames appreciably or alter the rate of burning of the fire. It is unlikely, therefore, that the pressure in the present tests, which would correspond to the finest sprays used in the tests on the small-scale, would be greater than 30 lb/in^2. Nevertheless, extinction was achieved with a lower rate of flow per unit area and with a coarser drop size with the 11 cm diameter fire than was achieved with the 30 cm diameter fire at 30 lb/in^2. There are two reasons which probably account for this. Firstly the rate of burning per unit area was smaller with the smaller fire. Secondly, the difference in the conditions under which the fires burned was such that a clearance of flame over part of the surface area of the vessel may have resulted in complete extinction more easily with the smaller fire than with the larger. The reason for this is that the smaller fire was surrounded by a chimney, kept wet by the spray. Any clearance of flame similar to that shown in fig.15 would have pushed the flames outwards onto this wet chimney; moreover, the presence of the chimney would have limited any tendency for the spray itself to be pushed sideways and would have helped to confine any steam formed.

Practical implications

It has been found that within the range of pressure of 5 - 85 lb/in^2, the efficiency of a spray increases as the pressure at which the spray is produced increases. This is seen in the effect of pressure on the minimum rate of flow required to bring about extinction, and in the time required for extinction with a given rate of flow. A problem in fire-fighting is whether the use of high pressure water sprays i.e. sprays produced at a pressure of 600 - 700 lb/in^2 would result in the more efficient use of water than sprays produced at 100 lb/in^2. There is good reason to believe from the results of the tests described that there would be an increase in efficiency if the pressure were increased to 700 lb/in^2. However, it is important to check this by actual tests. It should also be pointed out that the increase in efficiency is likely to hold only for the type of fires described in this report i.e. for a fire burning openly with a free supply of air; in this case an increase in the pressure assists the spray in reaching the vicinity of the burning material where the fire may be extinguished. On the other hand if a larger fire is burning in a room where there is only limited ventilation the extinguishing capacity of the spray injected into the room would not depend primarily on the pressure since the steam formed accumulates in the room and helps to extinguish the fire.

It was also noted that as the pressure increased there was a tendency for the fire to become more disturbed if the rate of flow was not sufficient to give extinction. It would therefore follow that as the pressure of a spray is increased its use is likely yo become more dangerous in a confined space.

It may be concluded from the results of the heat transfer calculations that the most efficient use of water for extinguishing a kerosine fire is likely to occur when the water evaporates in that part of the flame near the uprising vapour. This is probably true of other fires as well although the cooling of the burning material and formation of steam at the burning material would become more important as the fire point of the material increased. This formation of steam is probably the reason why the use of an applicator allows the extinction of an oil fire at a low rate of flow compared with other methods of spray application (6). It is also interesting to note that it has been found (6) that the efficiency of a given applicator does not increase when the pressure is increased from 100 to 300 lb/in^2 in spite of an increased rate of flow of spray within the fire. It is quite likely that increasing the pressure brings about a small reduction of drop size but a large increase in velocity. The spray drops, therefore, travel through the flame too quickly to produce evaporation and the heat transfer to the drops is not efficiently used. It would therefore appear that there is an optimum pressure and jet size in an applicator with which the amount of steam formation in the flame would be a maximum.

In most fires, however, an applicator would be difficult to use since it would not be possible to approach sufficiently close to the fire. Here resort must be made to a spray which can be thrown from a safe distance; the properties of this spray must be such that a sufficient heat transfer capacity for extinguishing the flames by cooling is presented to all parts of the flames in contact with uprising vapours. The design of such a spray from fundamental principles is a difficult matter since it involves a knowledge of the dynamics of sprays and fires which is not yet available. Generally speaking, however, the spray should have a forward velocity at the point where it meets the fire of the same order as the upward velocity of the flame; with large fires this is probably of the order of 15 ft/sec. From Table IV it would appear that for a kerosine fire a spray with a rate of flow of about 2.0 g/(cm)^2(min) i.e. 0.4 gallons/(ft)^2 (min) and a mass median drop size of 0.3 - 0.4 mm would suffice to extinguish a fire within 15 seconds, when the spray at a pressure of about 100 lb/in^2 is applied vertically. With horizontal application the extinction time should be less since the resistance due to the motion of the flames is not as great. A point which must be stressed is that as the flame is extinguished by a flame heat transfer process the spray must be directed to all parts of the liquid surface simultaneously. If there is a hollow pocket within the spray, as occurs usually with swirl type nozzles, the flame will remain unextinguished within this pocket. Moreover, if a hollow pocket free from spray is formed in the wake of a solid object, and if vapour can be carried into this pocket, the vapour may continue to burn there.

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List of Symbols.

A, A', B, B', B'' - constants.

D	drop size.	cm
D_1	drop size of a particular drop size group in spray	cm
D_{H_f}	flame heat transfer drop size	cm
D_{H_k}	kerosine heat transfer drop size	cm
D_E	kinetic energy drop size	cm
H	total heat transfer to drops in the flame	$cal/(cm)^2(sec)$
H_c	heat transfer to drops in the flame by convection.	$cal/(cm)^2(sec)$
H_{c_1}	Heat transfer to a single drop in the flame by convection.	cal/sec
H_m	heat transfer to unit mass of spray falling through a given small thickness of flame.	cal/g
H_{m_1}	heat transfer to unit mass of spray of drop size D_1 falling through a given small thickness of flame.	cal/g
H_K	heat transfer to water drops in the kerosine	$cal/(cm^2)(sec)$
H_{K_1}	heat transfer to a single water drop in the kerosine.	cal/sec
$K', K'', K''', K^{IV}, K^{V}$	constants	
M	Mass of drops falling through unit area of flame per unit time	$g/(cm)^2(sec)$
n_1	number of drops in size group	
Q	quantity burned ratio	
ΔT_f	difference in temperature between the flame and the drop surface.	°C
ΔT_K	difference in temperature between the kerosine and the drop surface.	°C
V	velocity of drop in flame	cm/sec
V_K	velocity of drop in kerosine	cm/sec
X	$6\ {}^{H}/_{\rho_L}\ VD$	$cal/(cm)(g)$
c	specific heat of gases in flame	$cal/(g)(^{\circ}C)$
c_K	specific heat of kerosine	$cal/(g)(^{\circ}C)$
g	acceleration due to gravity	$cm/(sec)^2$
k	conductivity of flame gases	$cal/(cm)^2(sec)(^{\circ}C/cm)$
k_K	conductivity of kerosine	$cal/(cm)^2(sec)(^{\circ}C/cm)$

Δl	Thickness of flame	cm
t	time.	sec
x	mass of kerosine burnt per unit volume of flame in unit time	$g/(cm)^3(sec)$
λ	heat of vaporization of water	cal/g
μ	micron	10^{-4} cm
μ	viscosity of flame gases	g/(sec)(cm)
μ_K	viscosity of kerosine	g/(sec)(cm)
ρ	density of flame gases.	$g/(cm)^3$
ρ_K	density of kerosine	$g/(cm)^3$
ρ_L	density of water	$g/(cm)^3$
Nu	Nusselt number $\frac{H_c D}{k \Delta T}$	
Re	Reynolds number $\frac{VD\rho}{\mu}$	
Pr	Prandtl number $\frac{c\mu}{k}$	
Pr_K	Prandtl number for kerosine.	

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APPENDIX I

Measurement of drop size

The apparatus used to sample the sprays is shown in fig.28. It was designed to enable samples to be taken at three points simultaneously; the object of this was to give equal times of exposure to the spray to the samples taken at the three points and therefore to collect a volume of sample which was proportional to the density of spray at these points.

Three circular slides A, B and C, 5 cm diameter, rested on a trolley D at a distance 10.5 cm apart. The trolley could be moved freely on the rails E across the inside of an open-topped sheet metal box F 38 cm x 27 cm x 10 cm deep; the movement was controlled manually by the handle G. The box was covered by a removable sheet metal cover H in the centre of which were three slots S, 6.5 cm long x 2.5 cm wide. The slots were raised a distance of 2 cm from the level of H, and the sides leading up to the slots were sloped. When the cover H was in place the position which the slots occupied relative to the box F is shown as broken lines in the plan. It will be seen that when the trolley was drawn across the box the slides A, B and C passed centrally under a slot. In taking samples the apparatus rested in the required position on the combustion vessel, and the slides were moved underneath the slots through which the spray was falling.

In taking the photograph of the samples the magnification in the projector was set for a given spray so that the maximum size of drop from the spray as it appeared magnified on the photographs was about 10 - 20 mm. When this was done, about 90 - 95 per cent of the total number of drops images on the photographs were less than 5 mm diameter. The drop images on the photographs were counted and classified in intervals of 1 mm. The first five groups were counted using a graticule and a Post Office counter as shown in fig. 29. The operator crossed the drop images off with one hand and recorded them with the other. The comparatively smaller number of drops which were in the larger size groups were measured and recorded individually. On gaining experience an operator could in this way count 1,500 - 2,000 drops on 4 - 6 photographs in one hour.

APPENDIX II

Mean drop sizes

Mean drop size for heat transfer from flames

Heat transfer in the flames by convection (4) may be expressed by the equation

$$\frac{H_c D}{k\Delta T_f} = \frac{\lambda}{\lambda + 0.23\Delta T_f}\left[2 + 0.60\left(\frac{c\mu}{k}\right)^{\frac{1}{3}}\left(\frac{VD\rho}{\mu}\right)^{\frac{1}{2}}\right] \quad \ldots\ldots(1)$$

H_c = heat transfer due to convection

D = drop diameter.

V = drop velocity in the flames.

λ = heat of vaporization

ΔT_f = temperature difference between flames and drop

c, μ, k, ρ = specific heat, viscosity, conductivity and density of the gases surrounding the drop.

For a stationary drop of 0.5 mm diameter the temperature and the properties of the flame will be such that $H_c = 5$ cal/(cm)^2(sec)(see Appendix III eq.14a); for smaller drops and drops of the same size moving relatively to the flame the heat transfer will be greater. The heat transfer by radiation will be about 1.0 cal/(cm^2)(sec) since this is the reading obtained on a total radiation pyrometer sighted on the flame. As an approximation, therefore, radiation may be neglected.

The heat transfer by convection to an individual drop H_{c_1} is

$$H_{c_1} = \pi D \frac{k.\Delta T_f}{\lambda + 0.23\Delta T_f}\left(2 + 0.60\, Pr^{\frac{1}{3}}\left(\frac{\rho}{\mu}\right)^{\frac{1}{2}} (VD)^{\frac{1}{2}}\right) \quad \ldots\ldots\ldots (2)$$

$$= AD + B\,(VD)^{\frac{1}{2}}D \quad \ldots\ldots\ldots\ldots(3)$$

A and B are functions only of the properties of the flame and λ, and are considered to be constant.

Measurements on the velocity of the drops in the sprays used in these tests have shown that, according to the entrained air velocity in the spray and the jet velocity, the drop velocity will vary from being independent of drop size to being approximately proportional to drop size (see fig.9).

If the mean velocity of the drops is taken as varying as the square root of the diameter, then substitution in equation (3) gives:-

$$H_{c_1} = AD + B'\,(D^{\frac{1}{2}}D)^{\frac{1}{2}}D$$

$$= AD + B'\,(D)^{1.75} \quad \ldots\ldots\ldots (4)$$

This equation will represent the heat transfer rate to a single drop when first hitting the flame. The amount of heat transferred when the drop passes through the flame will depend on the time which it is in the flame. This is difficult to calculate since the velocity and diameter are continually changing. However, if in a small thickness of flame the velocity and diameter of the drop do not change approciably, the time taken for the drop to pass through this thickness will be inversely proportional to the velocity i.e. inversely proportional to the square root of the diameter

Therefore, on passage of the drop through a small thickness of flame the amount of heat transfer which will take place

$$H_{c_1} t = (AD + B'D^{1.75}) \frac{B''}{D^{\frac{1}{2}}} = A'D^{\frac{1}{2}} + B''' D^{1.25} \quad \text{..... (5)}$$

It would therefore appear that the amount of heat which is transferred to a drop on passing through a small thickness of flame is more nearly proportional to the first power of D than to any other integral power of D.

It is now necessary to find that mean drop size of the spray D_{H_f} such that the heat transfer from a small thickness of flame to a given mass of the spray is the same as the heat transfer to the same mass of the spray if composed entirely of drops of size D_{H_f}. For a single drop of size D_1 the heat transfer is $K'D_1$. The specific heat transfer (H_{m_1}) will be

$$H_{m_1} = \frac{1}{\frac{\pi}{6}\rho D_1^{3}} \cdot K'D_1 = \frac{K''}{D_1^{2}} \quad \text{(cal/g if c.g.s. units are used)} \quad \text{..... (6)}$$

If in a given mass of spray the number of particles of size D_1, D_2 .... are n_1, n_2 -----, then the total heat transfer to unit mass of spray (H_m) will be

$$H_m = \frac{K''}{D^2_{H_f}} = \frac{\frac{\pi}{6}\rho \sum n_1 D_1^3 H_{m_1}}{\frac{\pi}{6}\rho \sum n_1 D_1^3} = \frac{\sum n_1 D_1 K''}{\sum n_1 D_1^3}$$

$$\therefore \quad D_{H_f} = \sqrt{\frac{\sum n_1 D_1^3}{\sum n_1 D_1}} \quad \text{..... (7)}$$

Mean drop size for heat transfer in the liquid

The heat transfer by convection to a drop in the liquid is given by equation 8.

$$\frac{H_K D}{k_K \Delta T_K} = 2.0 + 0.60 \, Pr_k^{\frac{1}{3}} \left(\frac{VD\rho_K}{\mu_K}\right)^{\frac{1}{2}} \quad \text{..... (8)}$$

The velocity of the drops as they pass through the hot zone of the liquid will be at some value between the velocity at which they enter the liquid, and the terminal falling velocity in the liquid. It may be shown that the range of Reynolds' numbers which will operate for drops of the size range used in the tests will be such that the terminal velocity of the falling drops would follow Stokes' law. It if is assumed for simplicity that on reaching the liquid the drops will be immediately decelerated to their terminal falling velocities in the liquid then these velocities will be proportional to the square of the diameters. Moreover, the velocities will be so small that the second term on the right-hand side of equation 8 will be small in comparison with the first term and may be neglected. Thus, the heat transfer H_K to a drop of size D falling through a given thickness of fluid will be

$$H_{K_1} = \frac{2 k_K}{} \cdot \frac{\Delta T_k}{D} \cdot \frac{\ell}{V_k} \pi D^2 = K''' \frac{D}{V_k} \quad \text{..... (9)}$$

Where ΔT_K = difference in temperature between the kerosine and the drop

ℓ = depth of kerosine through which the drop passes.

V_k = drop velocity in the liquid.

By Stokes' law

$$V_k = \frac{g D^2(\rho_L - \rho_K)}{18 \mu_K} = K^{IV} D^2. \quad \ldots\ldots (10)$$

$$H_{K_1} = \frac{K''}{K^{IV}} \frac{D}{D^2} = \frac{K^{V}}{D} \quad \ldots\ldots (11)$$

From equation (11) it follows that the heat transfer to a water drop on falling through a given thickness of kerosine at a given temperature will be inversely proportional to the drop size. By reasoning similar to that indicated above it may be shown from this conclusion that

$$D_{H_K} = \sqrt[4]{\frac{\Sigma n_1 D_1^3}{\Sigma \frac{n_1}{D_1}}} \quad \ldots\ldots (12)$$

If on the other hand, it is assumed that the velocity of the drops when they fall through the hot kerosine is the same as that at which they enter the kerosine, then the derivation of the kerosine heat transfer drop size will be almost identical to that of the flame heat transfer drop size and D_{H_K} may be taken as

$$\sqrt{\frac{\Sigma n_1 D_1^3}{\Sigma n_1 D_1}}$$

It is probable that the best value for D_{H_K} lies somewhere between this value and that given by equation 12, and may be tentatively taken as

$$\sqrt[3]{\frac{\Sigma n_1 D_1^3}{\Sigma n_1}}$$

<u>Mean drop size for kinetic energy.</u> For a drop of size D and velocity V the kinetic energy of the drop will be porportional to $D^3 V^2$. If the velocity of the drop as it approaches the surface is taken to be proportional to the square root of the diameter (see above) then the energy of a single drop will be proportional to D^4. From this it follows that the mean kinetic energy drop size will be given by

$$D_E = \frac{\sum n_1 D_1^4}{\sum n_1 D_1^3} \quad \ldots\ldots (13)$$

The mean drop size arrived at by this equation is also known as the weight mean drop size.

APPENDIX III

Calculation of heat transfer capacity

The heat transfer coefficient by convection to the spray drops is given by

$$Hc = \frac{1}{D} \frac{\lambda k \quad \Delta T_f}{(\lambda + \quad 0.23 \Delta T_f \quad)} \left(2 + 0.60 \left(\frac{c\mu}{k}\right)^{\frac{1}{3}} \left(\frac{VD\rho}{\mu}\right)^{\frac{1}{2}}\right) \quad \ldots\ldots(14)$$

Assuming that the flames may be considered as the products of complete combustion of kerosine with the theoretical quantity of air and that the properties of the flames to be inserted in equation 14 may be taken as those at the mean temperature of the drop surface and the flames

then ΔT_f = 1170°C

k = .00016

μ = .00040 c.g.s. units - (estimated on the assumption that the gases were the products of complete combustion of the kerosine with the theoretical quantity of air).

ρ = .00038

λ = 620 cal/g

Equation 14 then becomes

$$Hc = \frac{.26}{D} + 0.070 \left(\frac{V}{D}\right)^{\frac{1}{2}} \quad \ldots\ldots 14(a)$$

The heat transfer coefficient by radiation to the spray drops is about 0.9 $cal/(cm)^2(sec)$ (based on a measurement of radiation from the flames of 1.04 $cal/(cm)^2(sec)$ and the dimensions of the flame).

∴ The total heat transfer rate is given by

$$H = \frac{.26}{D} + 0.070 \left(\frac{V}{D}\right)^{\frac{1}{2}} + 0.9 \quad cal/(cm)^2(sec) \quad \ldots\ldots(15)$$

Consider a drop of diameter D and velocity V falling through a layer of flame Δ cm thick where Δl is sufficiently small for there to be no appreciable change in drop velocity or size after a drop has passed through the layer. The time which the drop takes to fall through the layer will be $\frac{\Delta l}{V}$ seconds. Therefore the heat transfer which will take place while if falls through the layer will be

$$\pi D^2 \cdot \frac{\Delta}{V} \quad H. \quad cal$$

If there is a mass M drops of size D and velocity V falling through unit area in unit time through the flame of thickness Δ 1 then the amount of heat transferred to these drops will be

$$\frac{M}{\frac{\pi}{6} \rho_L D^3} \pi D^2 \quad \frac{\Delta l}{V} \quad H$$

$$= \frac{M}{\rho_L \quad D} \cdot \frac{6}{V} \quad H \quad \Delta 1 \qquad cal$$

This represents the rate at which heat is transferred from flame of unit area and $\Delta 1$ thickness i.e. a volume $\Delta 1$. The heat transferred from a unit volume will be

$$\frac{M}{\rho_L D} \frac{6}{V} H = MX, \text{ where } X = \frac{6H}{\rho_L VD}$$

The sum of this factor for all the various drop and velocity groups in the spray will give the total heat transferred to the spray in unit time within a unit volume of the flame.

In the calculation carried out V was taken as a function of D and the entrained air velocity in the spray. The heat transfer capacity was then calculated according to the manner shown in Table VI using the drop size distribution of the spray and the curves of $\frac{6H}{VD}$ plotted against V and D shown in fig.30

TABLE VI

Calculation of heat transfer capacity of a spray

Test No. 18 (see Table IV)

Rate of flow = 1.2 g/(cm)^2(min) = 0.02 g/(cm)^2(sec).

Jet size = 1/64 in mass median drop size = .23 mm.

Entrained air velocity = 319 cm/sec.

Drop size distribution		Mean velocity of drops in group - entrained air velocity (from fig. 9) cm/sec	Mean velocity of drops in group cm/sec	Heat transfer capacity factor (X) (from fig. 30) cal/(cm)(g)	Heat transfer capacity of drops in the group .02 $M_f X$ cal/(cm^3)(sec)
Group mm	Fraction of mass in group M_f				
.0 -.075	.0248	9	328	450	.223
.075-.125	.086	33	352	70	.121
.125-.175	.183	61	380	35	.128
.175-.225	.186	94	413	17.5	.065
.225-.275	.203	134	453	11.0	.044
.275-.325	.137	188	507	7.0	.019
.325-.375	.142	261	580	5.0	.014
.375-.425	.022	360	679	3.7	.002
.425-.475	.015	460	779	2.8	.001

Total heat transfer capacity = .617

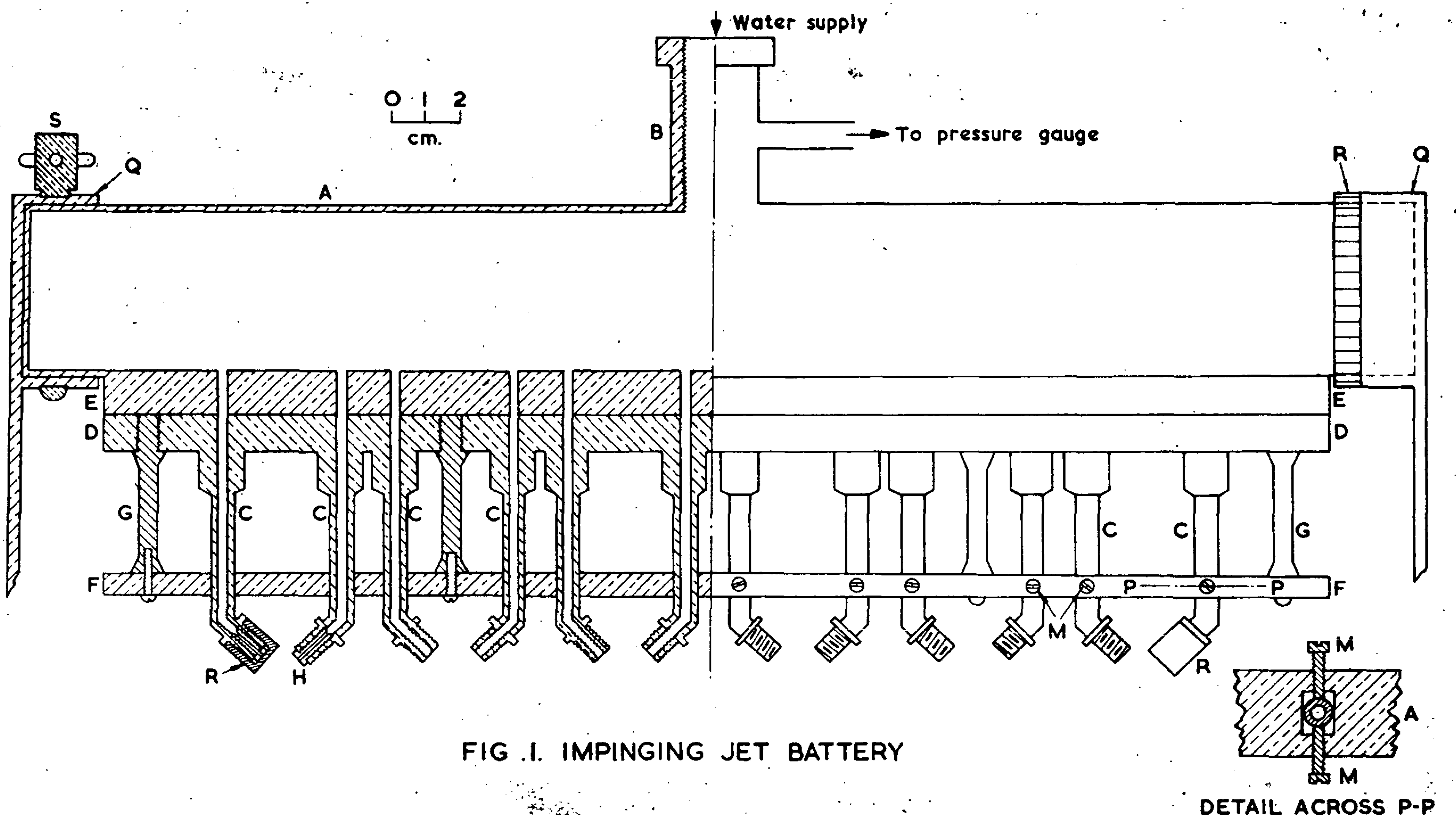


FIG .1. IMPINGING JET BATTERY

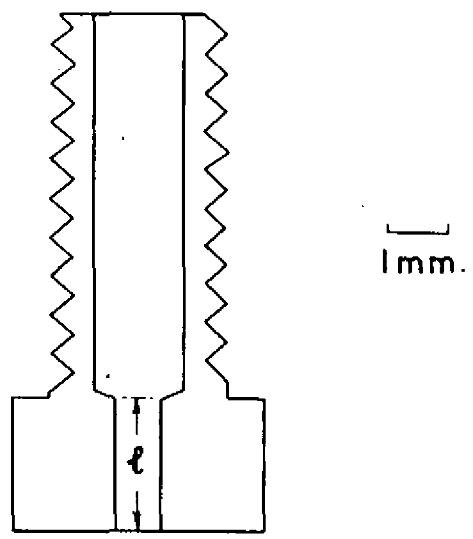


FIG. 3. SKETCH OF NIPPLE

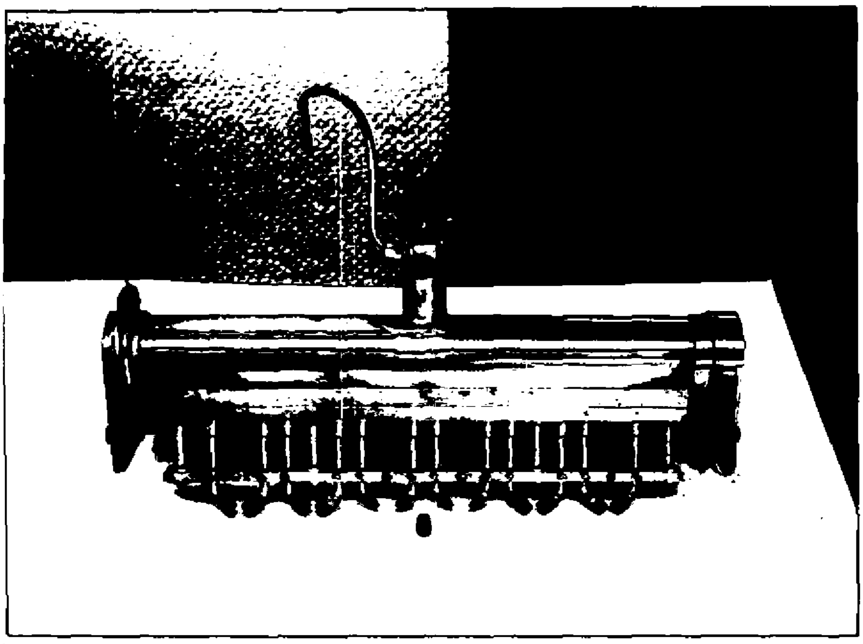
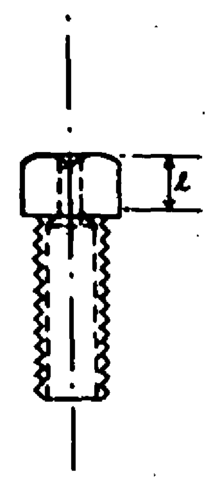


FIG. 2
IMPINGING
JET BATTERY

FIG. 3. NIPPLE FOR FORMING JETS



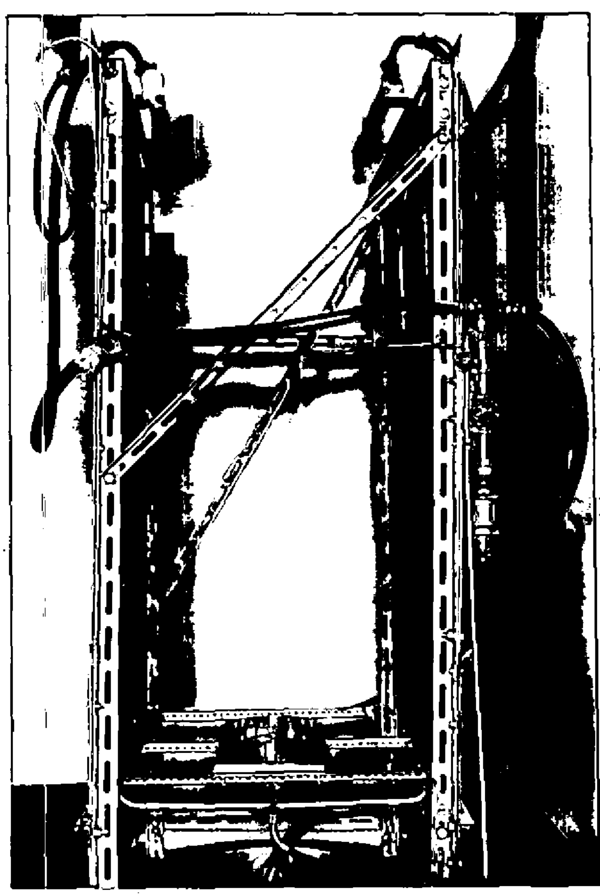


FIG. 4.
POSITION OF BATTERIES
RELATIVE TO THE FIRE VESSEL

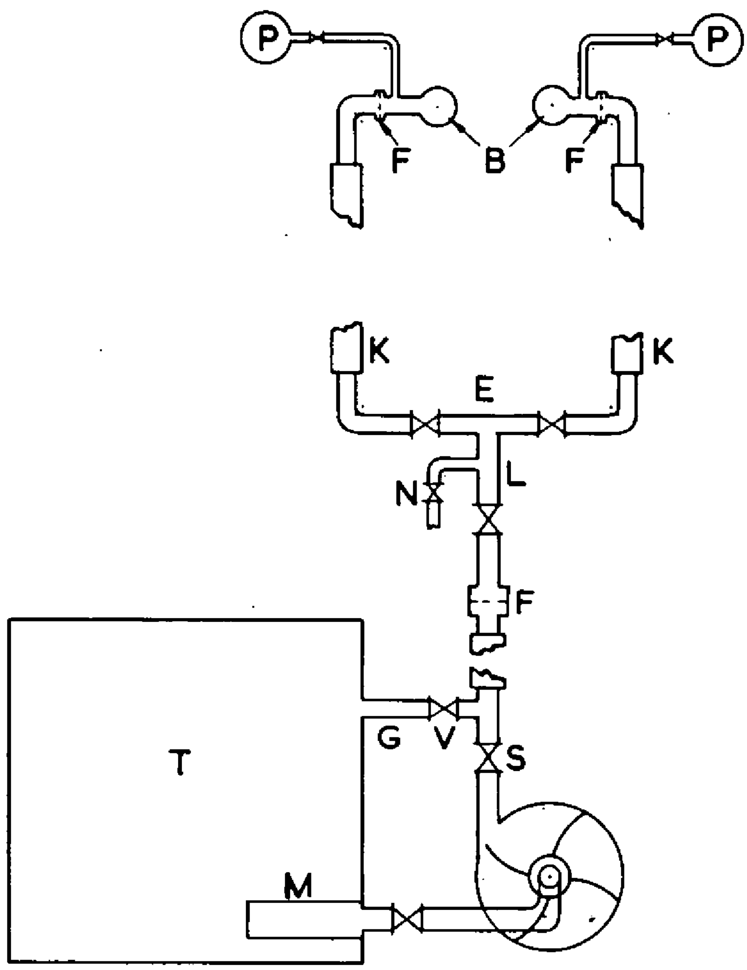


FIG. 5. WATER SYSTEM SUPPLYING THE BATTERIES

FIG.6. BATTERY OF TUBES FOR MEASURING SPATIAL PATTERN

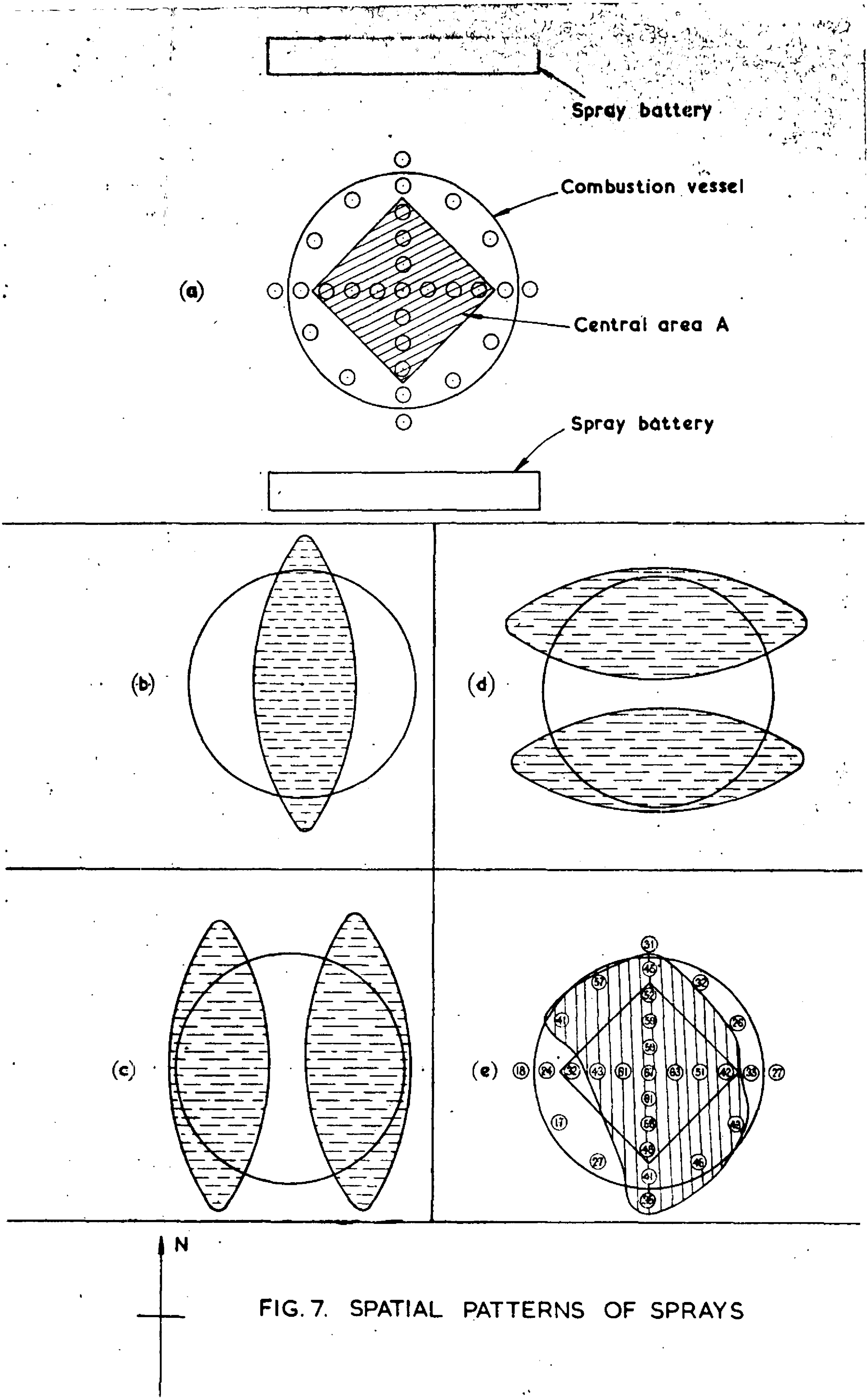


FIG. 7. SPATIAL PATTERNS OF SPRAYS

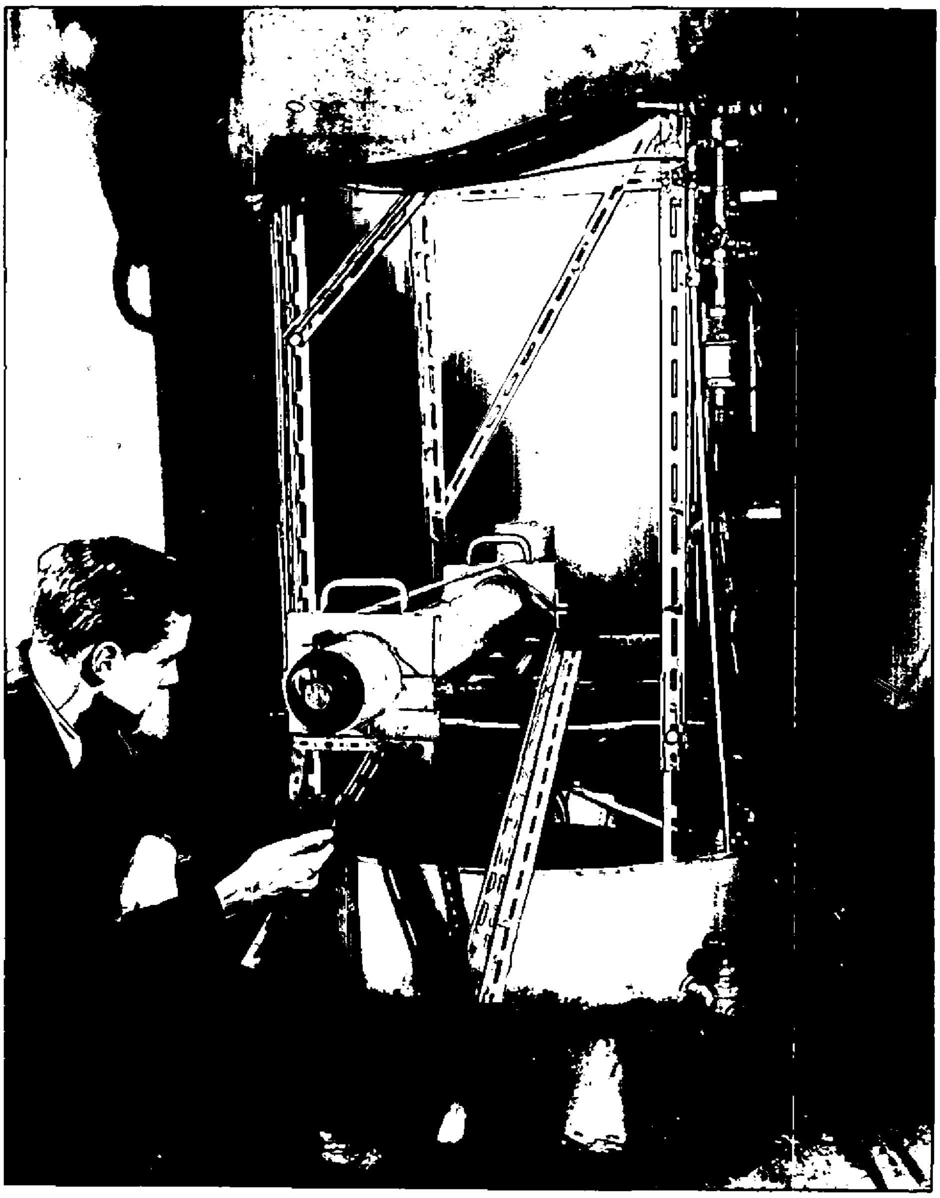


FIG. 8. MEASUREMENT OF ENTRAINED AIR VELOCITY IN WATER SPRAY

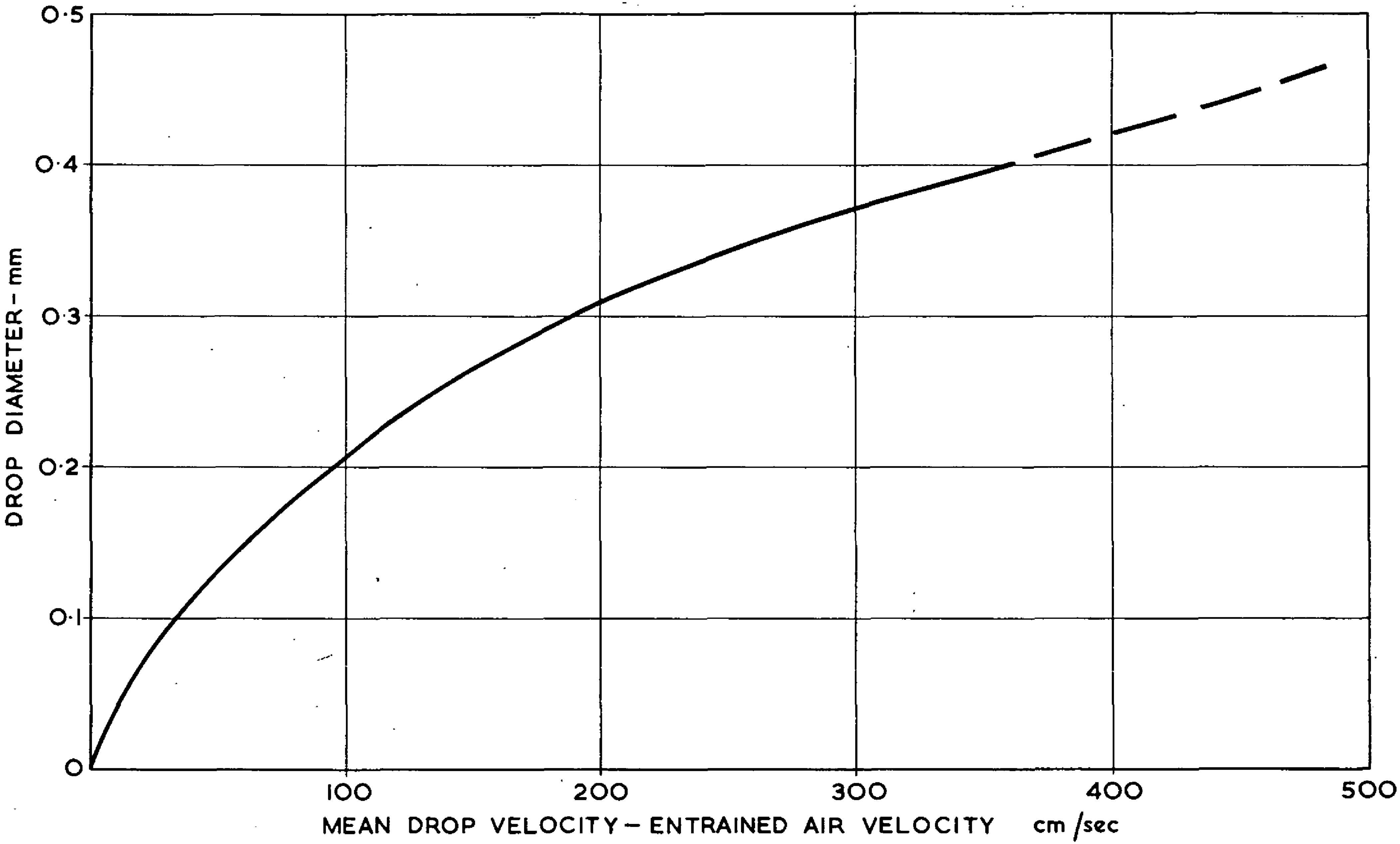


FIG. 9. VELOCITY OF DROPS IN SPRAYS

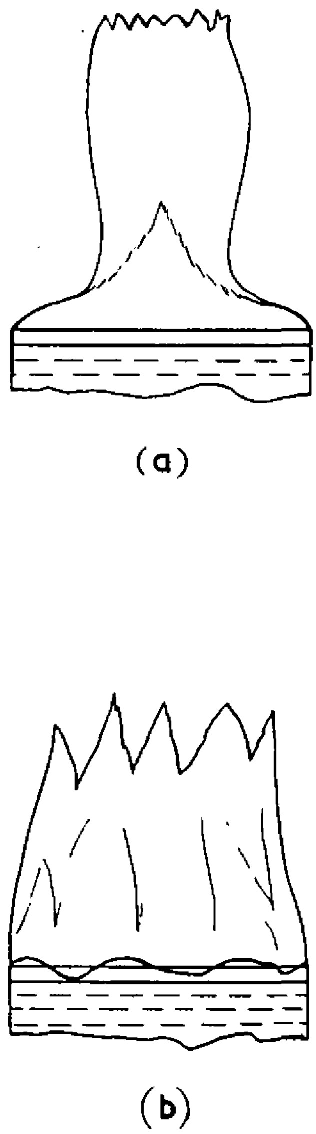


FIG. 10. SHAPE OF FLAMES

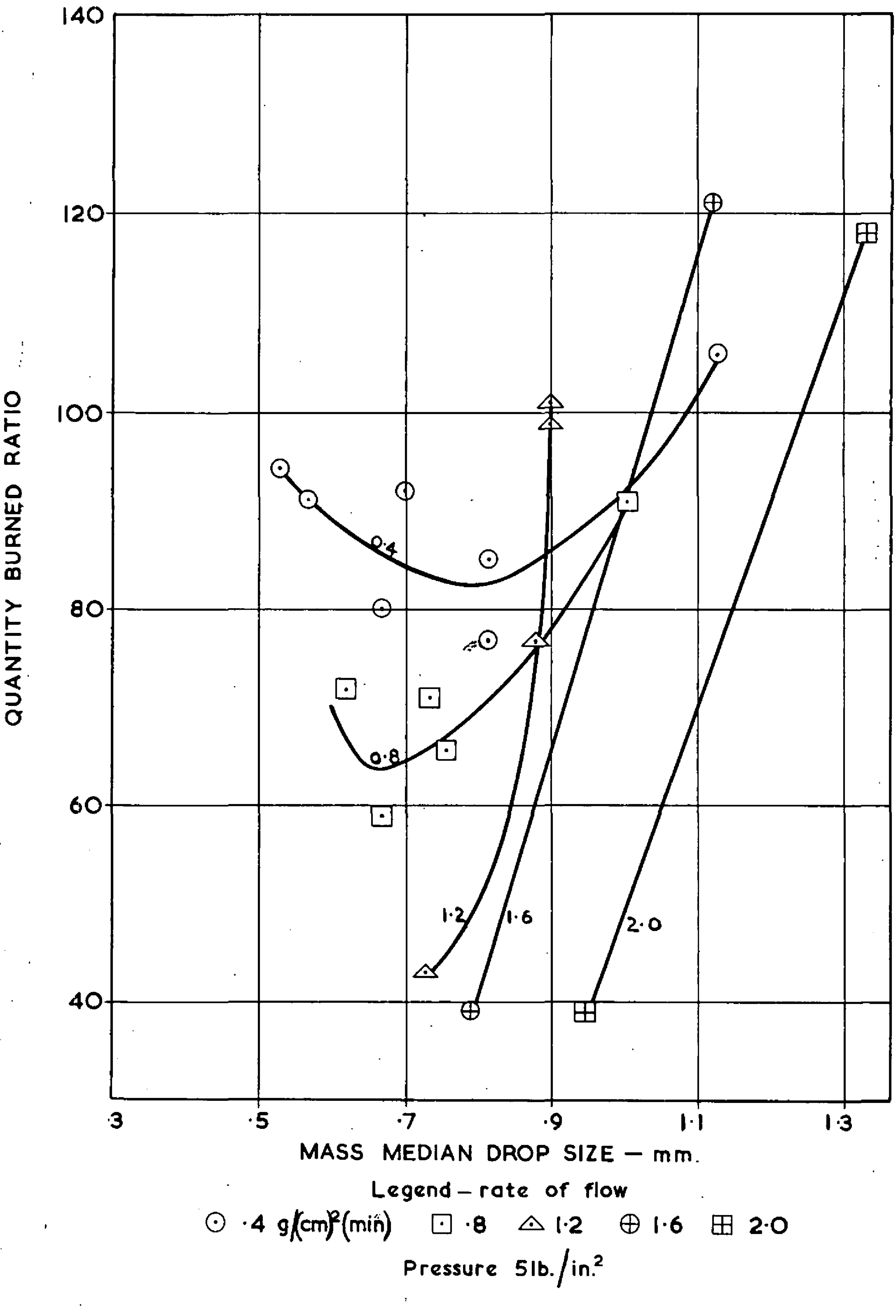


FIG. 11. THE EFFECT OF MASS MEDIAN DROP SIZE AND RATE OF FLOW OF SPRAY ON THE QUANTITY BURNED RATIO.

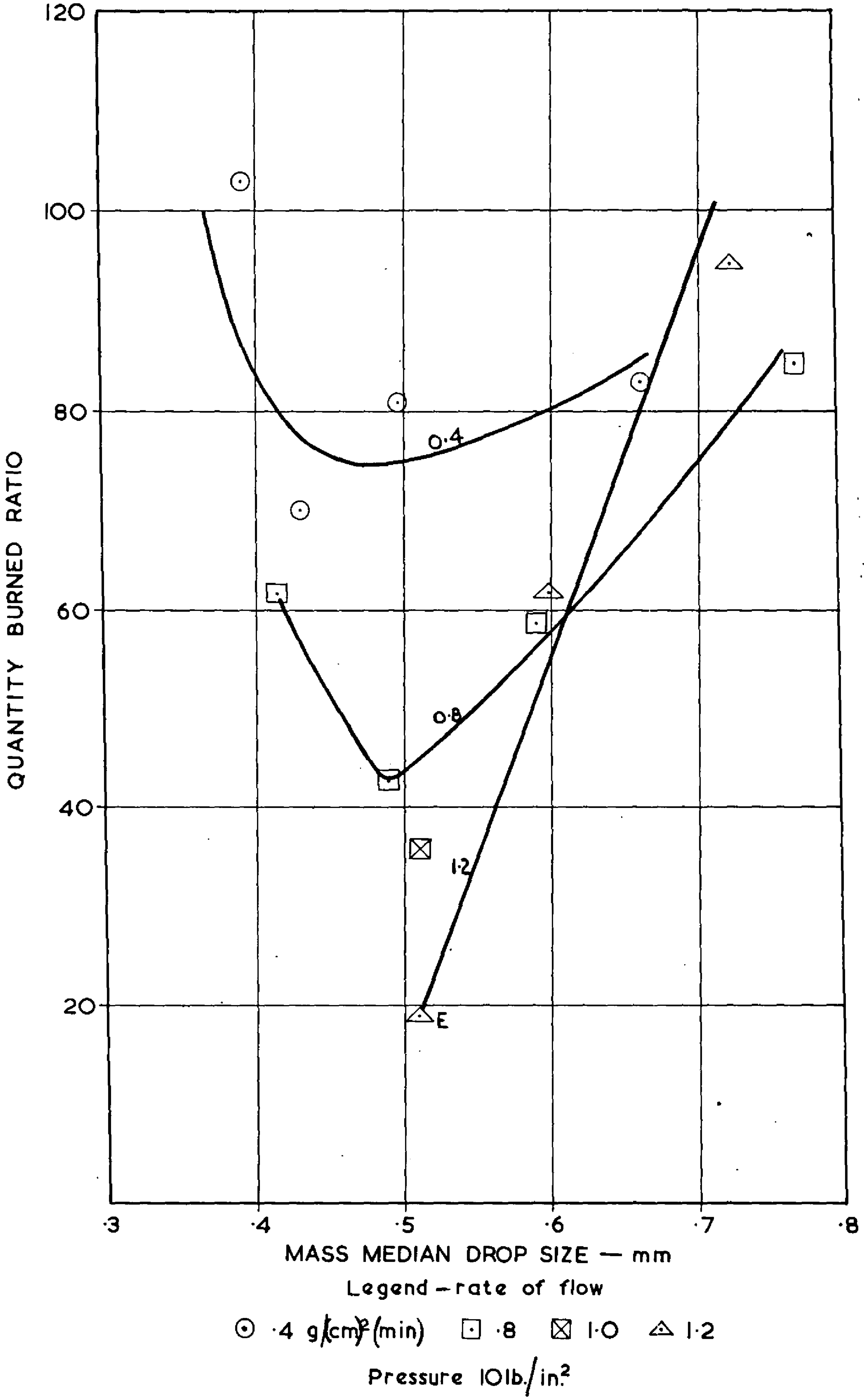


FIG. 12. THE EFFECT OF MASS MEDIAN DROP SIZE AND RATE OF FLOW OF SPRAY ON THE QUANTITY BURNED RATIO.

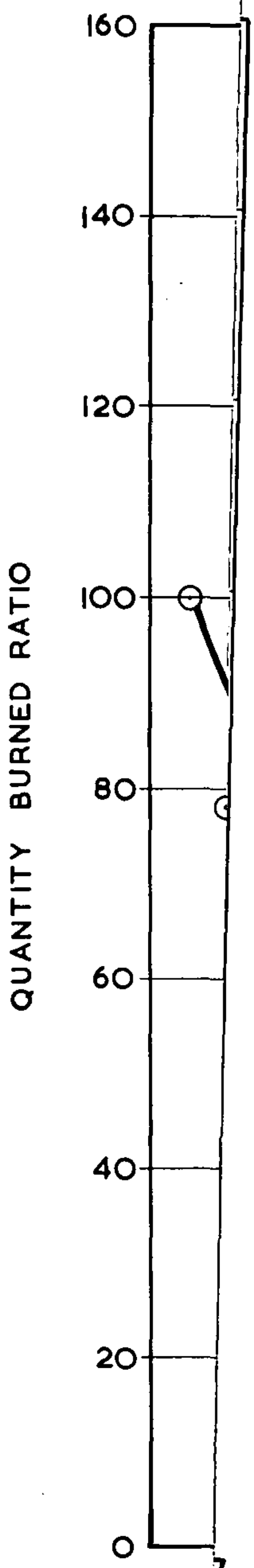
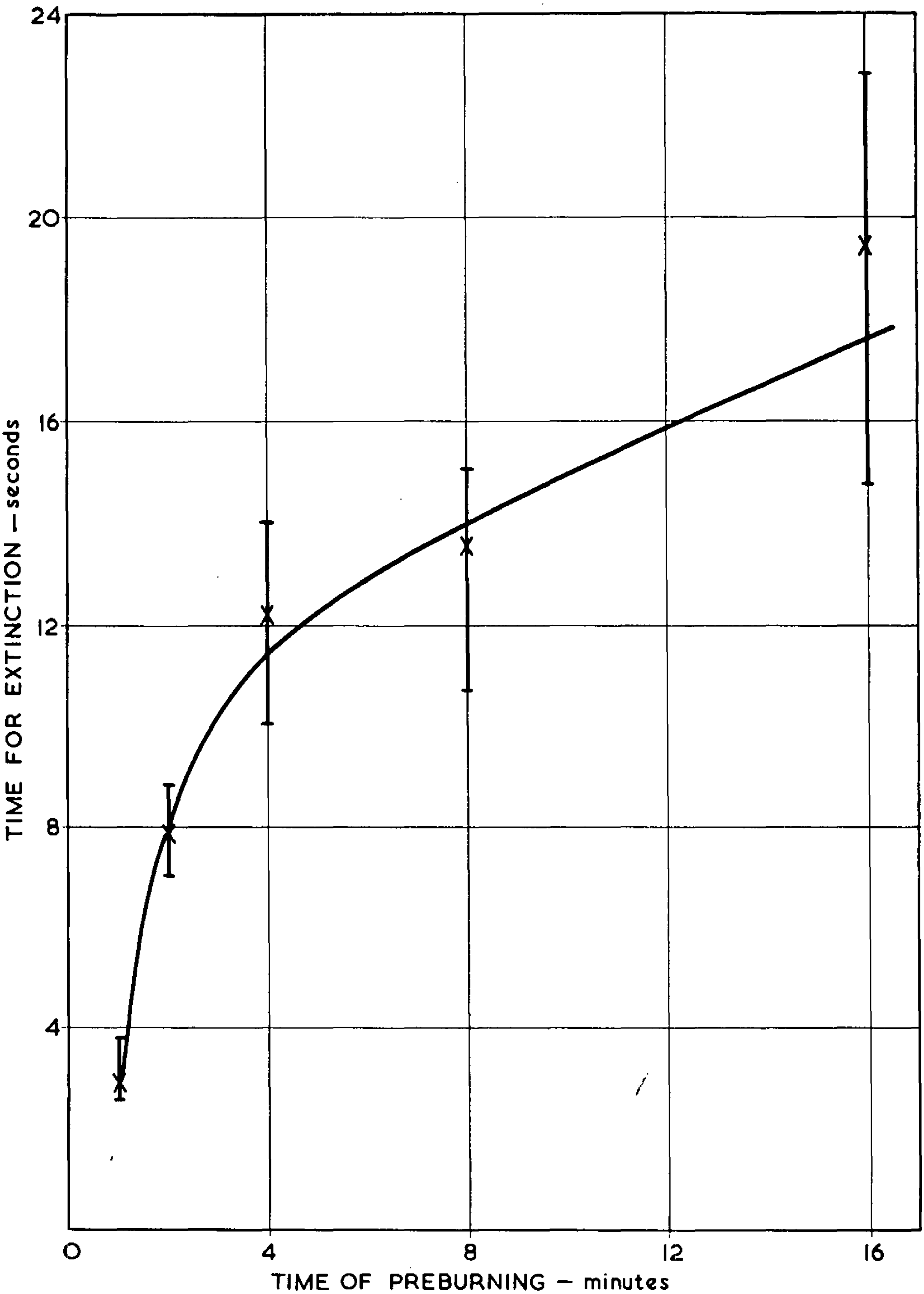


FIG. 13. THE LOW
OF



Spray — 1·6 g/(cm)^2 (min), 85 lb./in.^{2}

I — Range of 4 tests

X — Mean point of 4 tests

FIG. 14. EFFECT OF TIME OF PREBURNING OF KEROSINE FIRE ON TIME FOR EXTINCTION

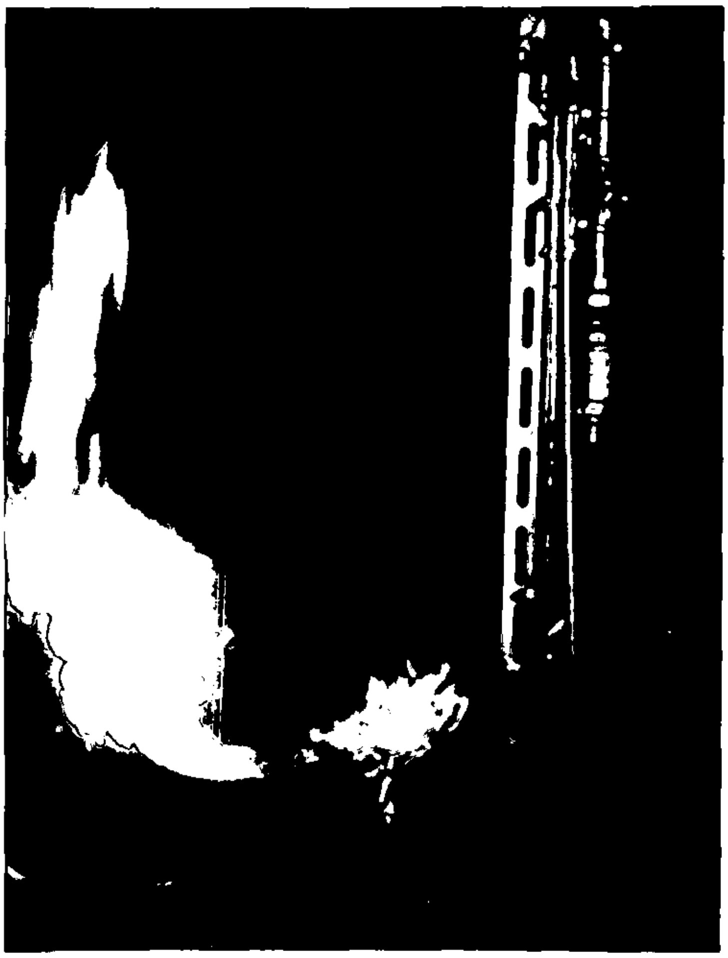


FIG. 15. EFFECT OF WATER SPRAY ON A KEROSINE FIRE SHOWING CLEARANCE OF FLAME (TEST NO. 24)

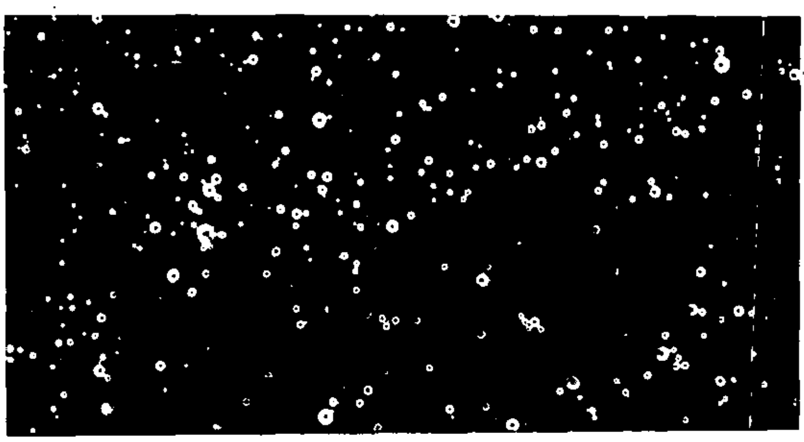


FIG. 16. SAMPLE OF KEROSINE TAKEN FROM SURFACE $1\frac{1}{2}$ SEC AFTER EXTINCTION (TEST NO. 18) MAGNIFICATION - X 19.6

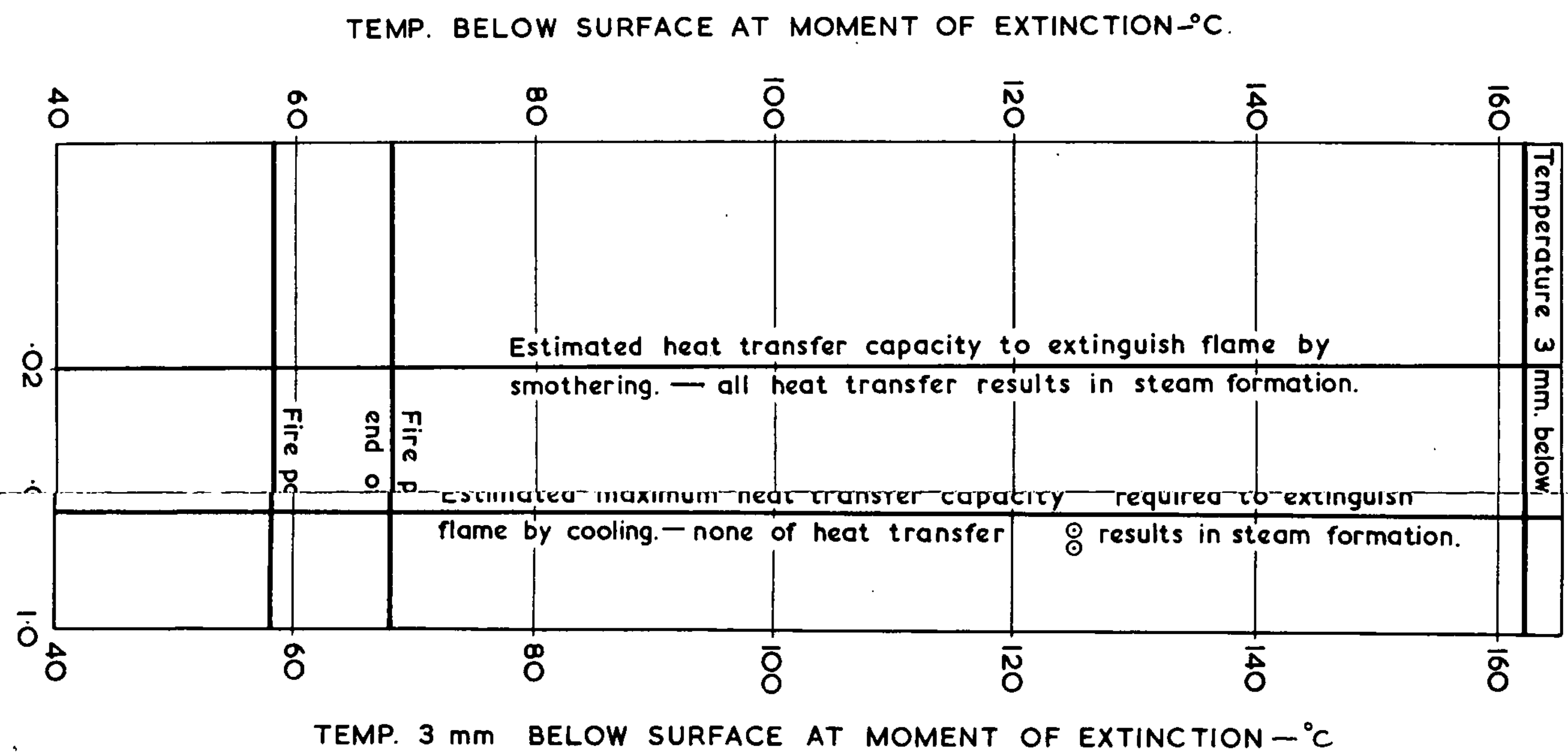
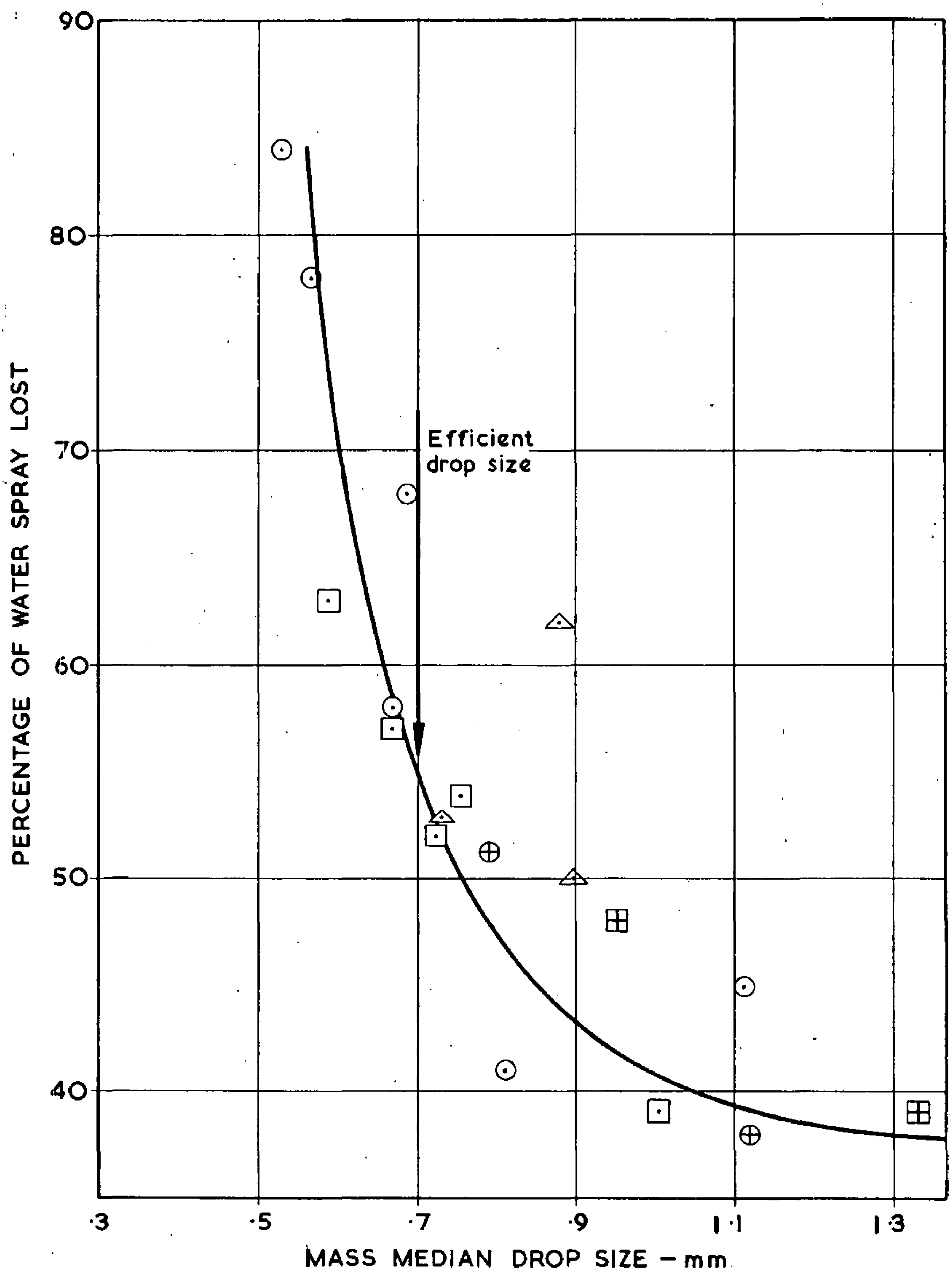


FIG. 17. RELATIONSHIP BETWEEN KEROSINE AT THE MOMENT OF EXTINCTION.



Legend – rate of flow

⊙ ·4 g/(cm)^2(min) ⊡ ·8 △ 1·2 ⊕ 1·6 ⊞ 2·0

Pressure 5lb./in^2

FIG. 18. THE EFFECT OF MASS MEDIAN DROP SIZE AND RATE OF FLOW OF SPRAY ON THE LOSS OF SPRAY.

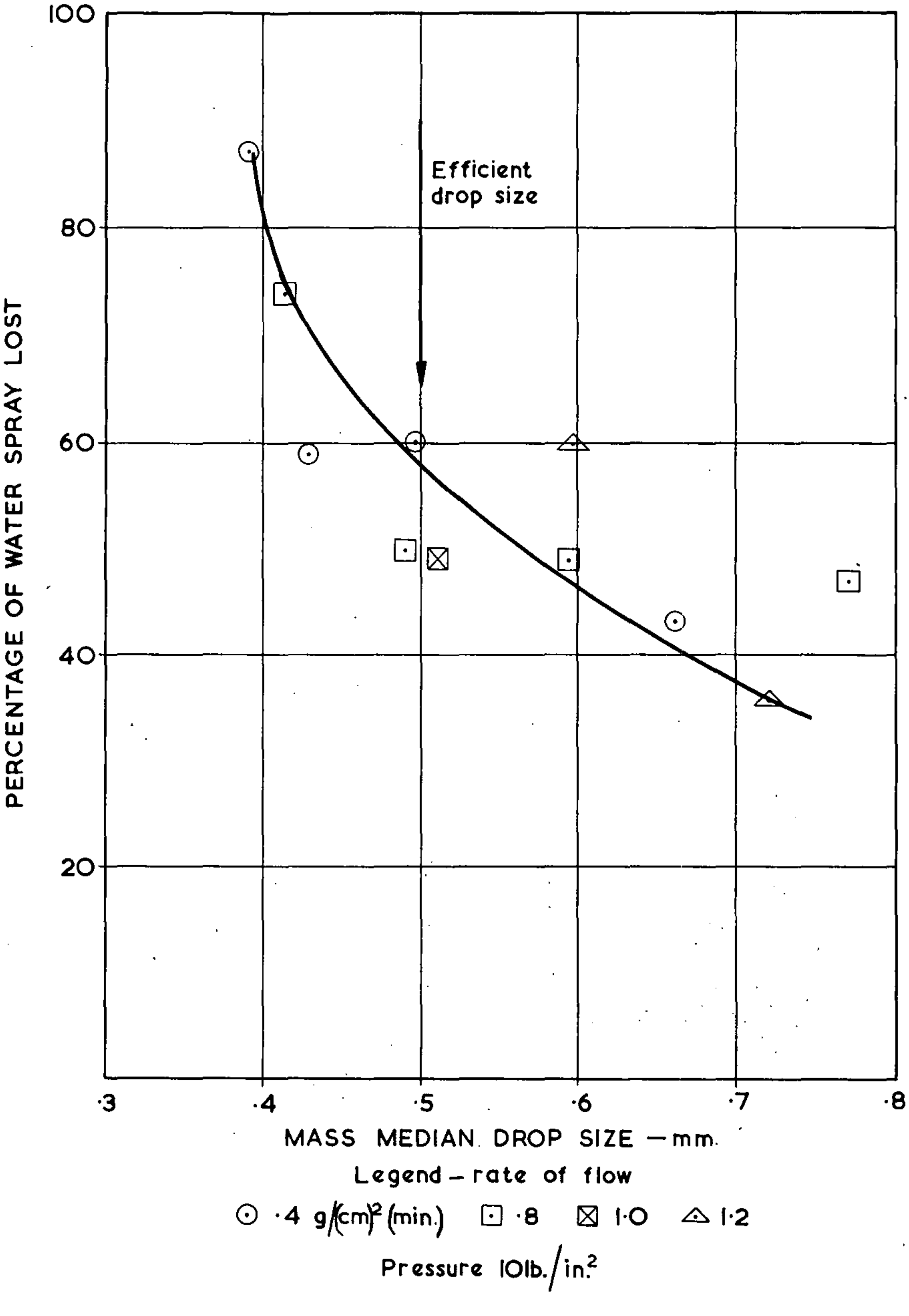


FIG. 19. THE EFFECT OF MASS MEDIAN DROP SIZE AND RATE OF FLOW OF SPRAY ON THE LOSS OF SPRAY.

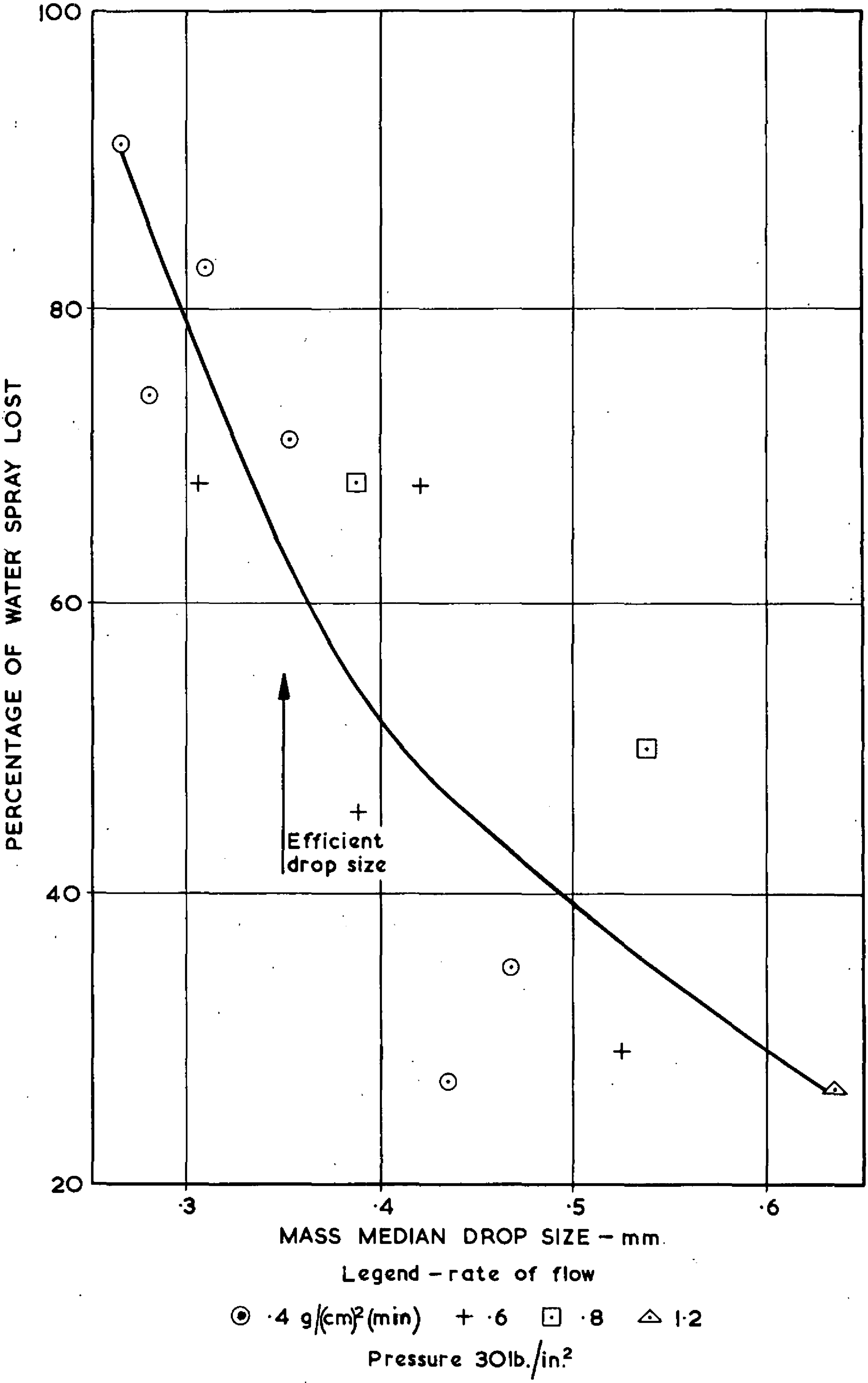


FIG. 20. THE EFFECT OF MASS MEDIAN DROP SIZE AND RATE OF FLOW OF SPRAY ON THE LOSS OF SPRAY.

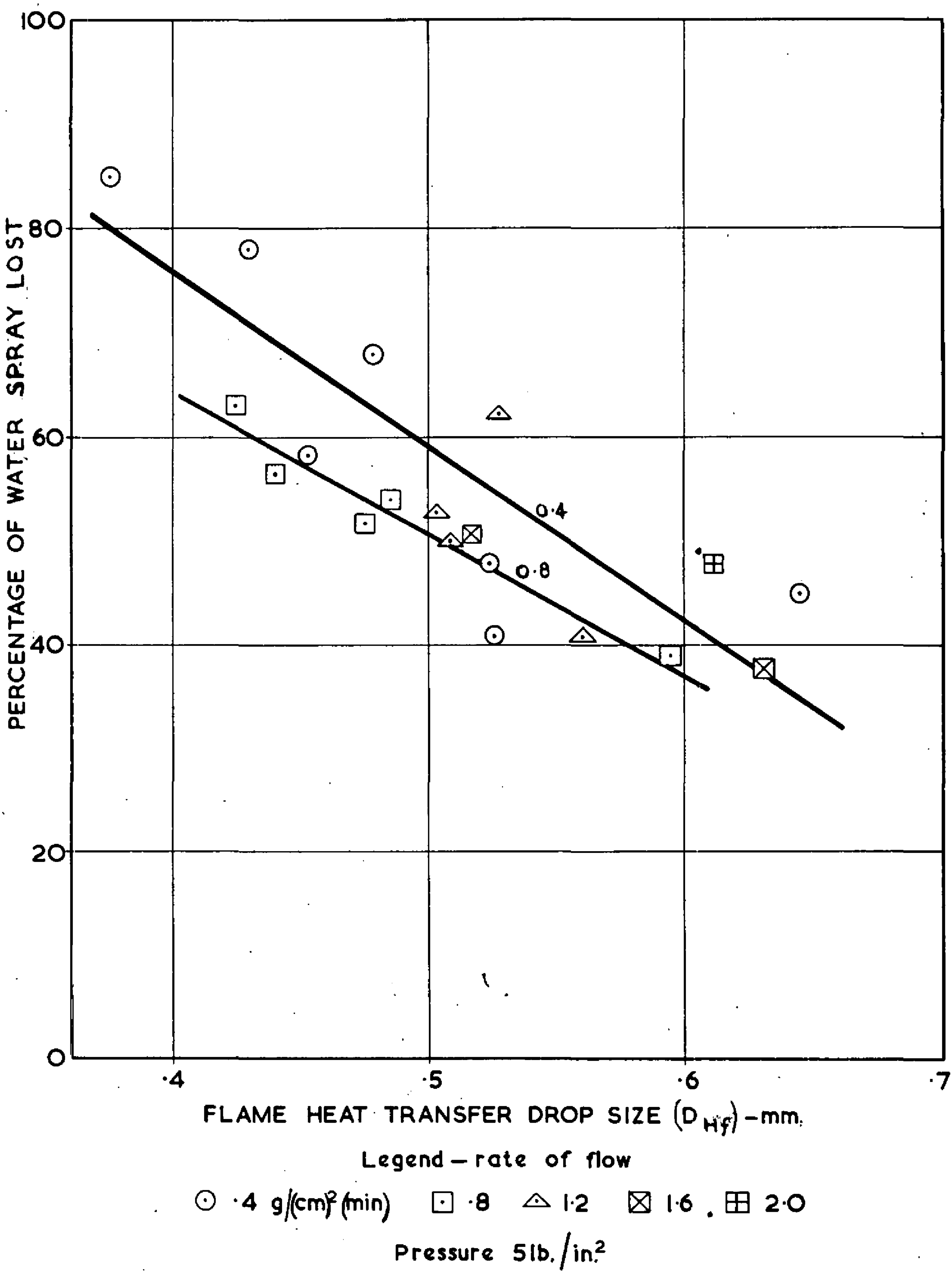


FIG. 21. THE EFFECT OF FLAME, HEAT TRANSFER, DROP SIZE AND RATE OF FLOW OF SPRAY ON THE LOSS OF SPRAY.

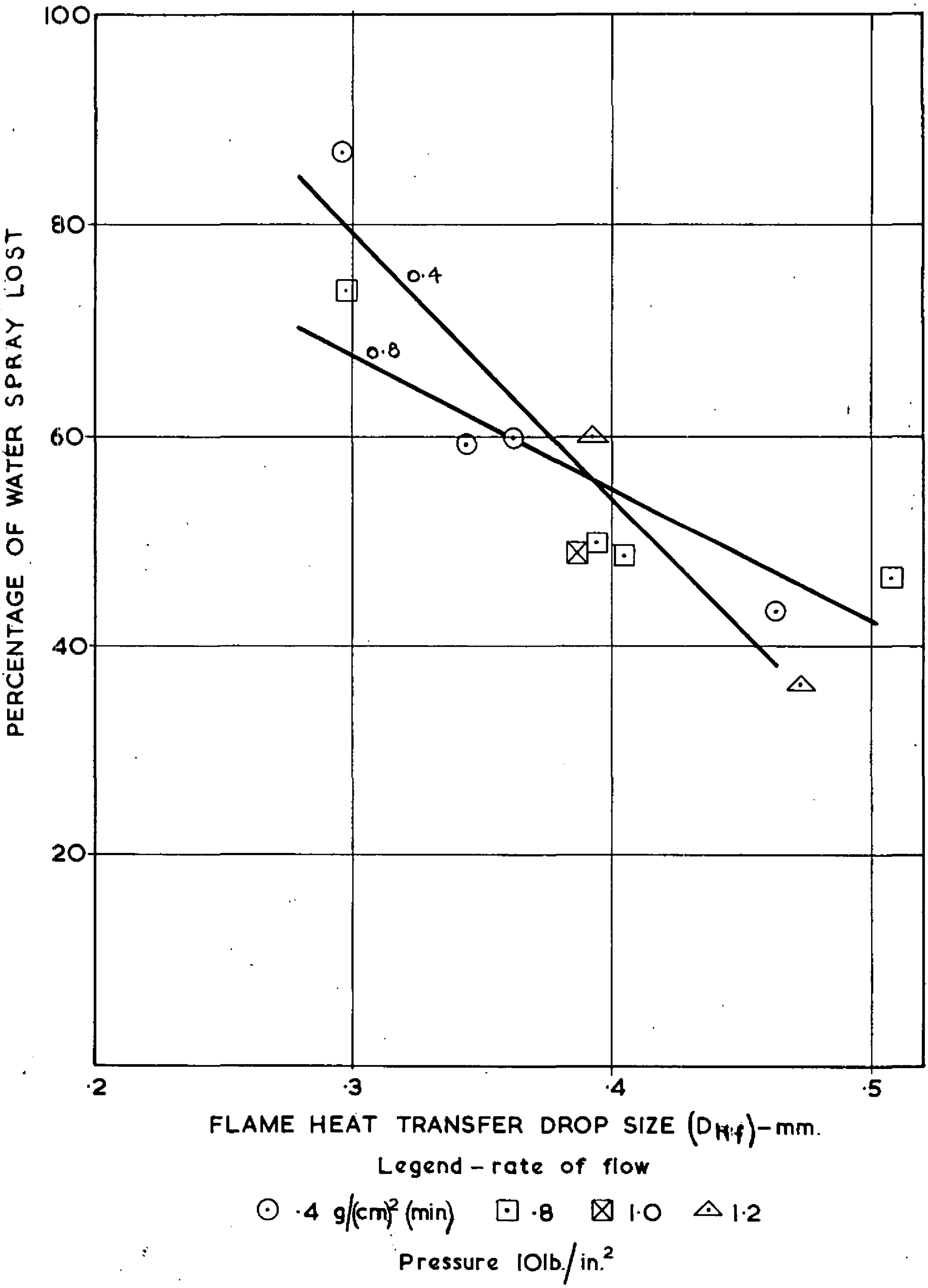


FIG. 22. THE EFFECT OF FLAME, HEAT TRANSFER, DROP SIZE AND RATE OF FLOW OF SPRAY ON THE LOSS OF SPRAY.

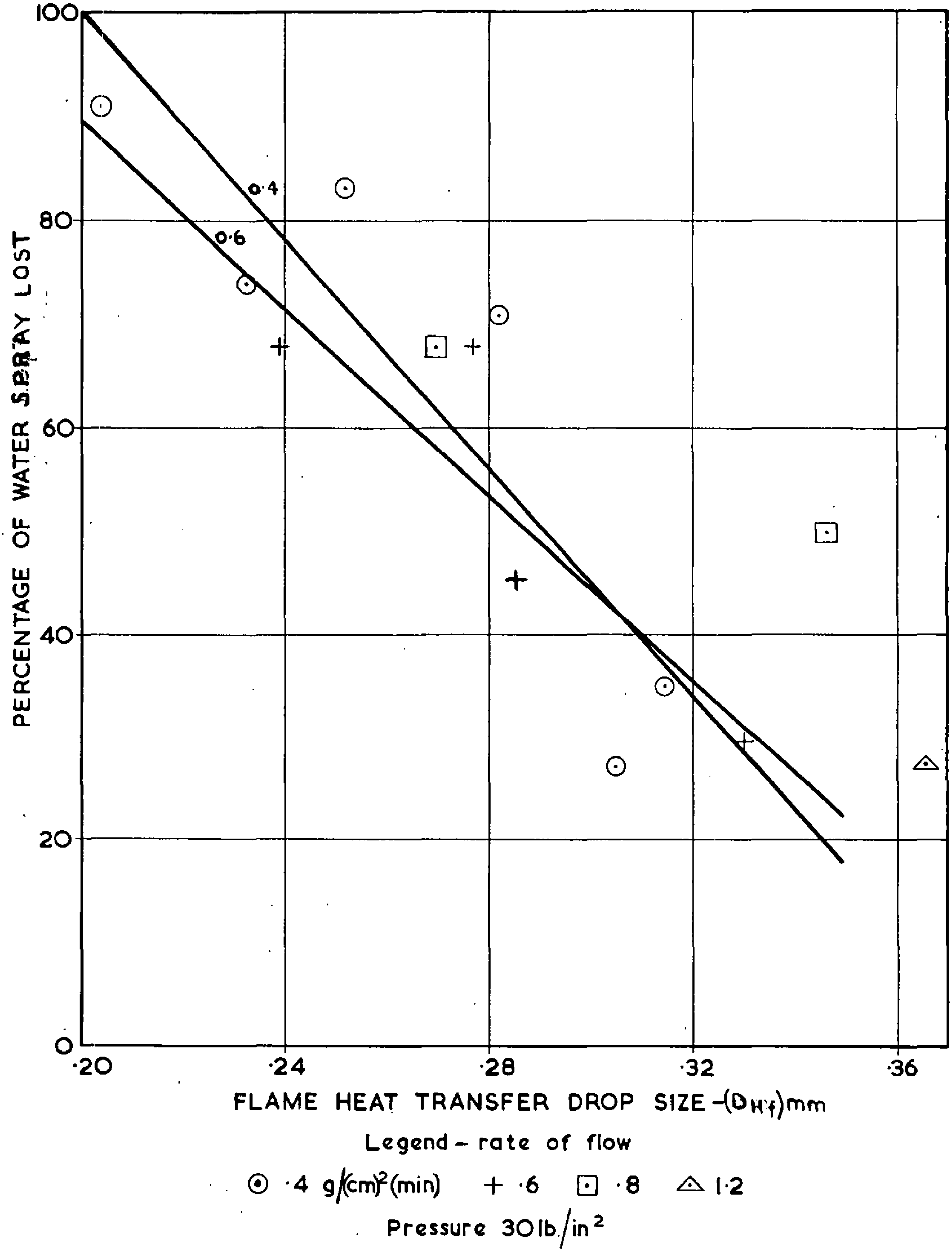
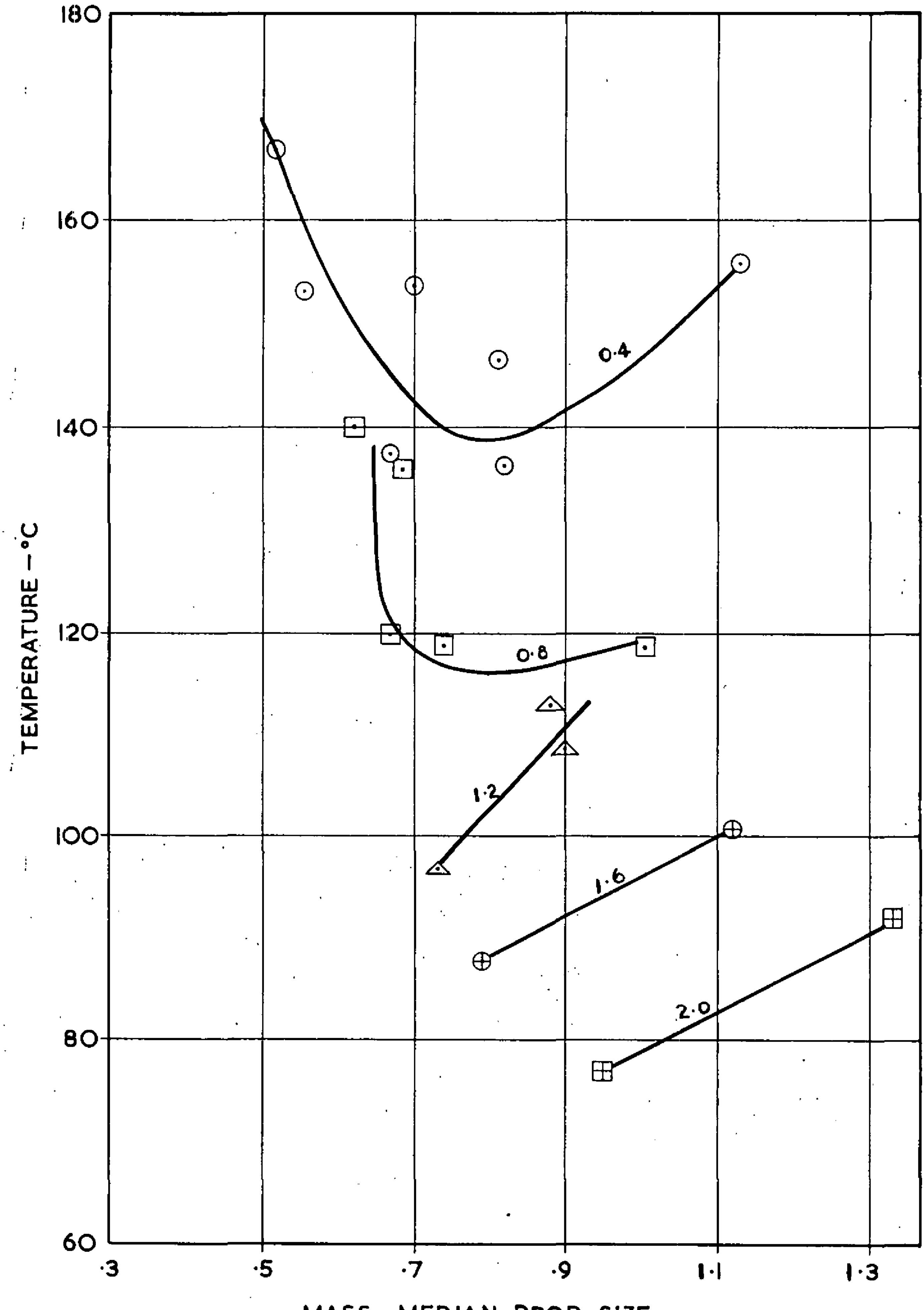


FIG. 23. THE EFFECT OF FLAME, HEAT TRANSFER, DROP SIZE AND RATE OF FLOW OF SPRAY ON THE LOSS OF SPRAY.

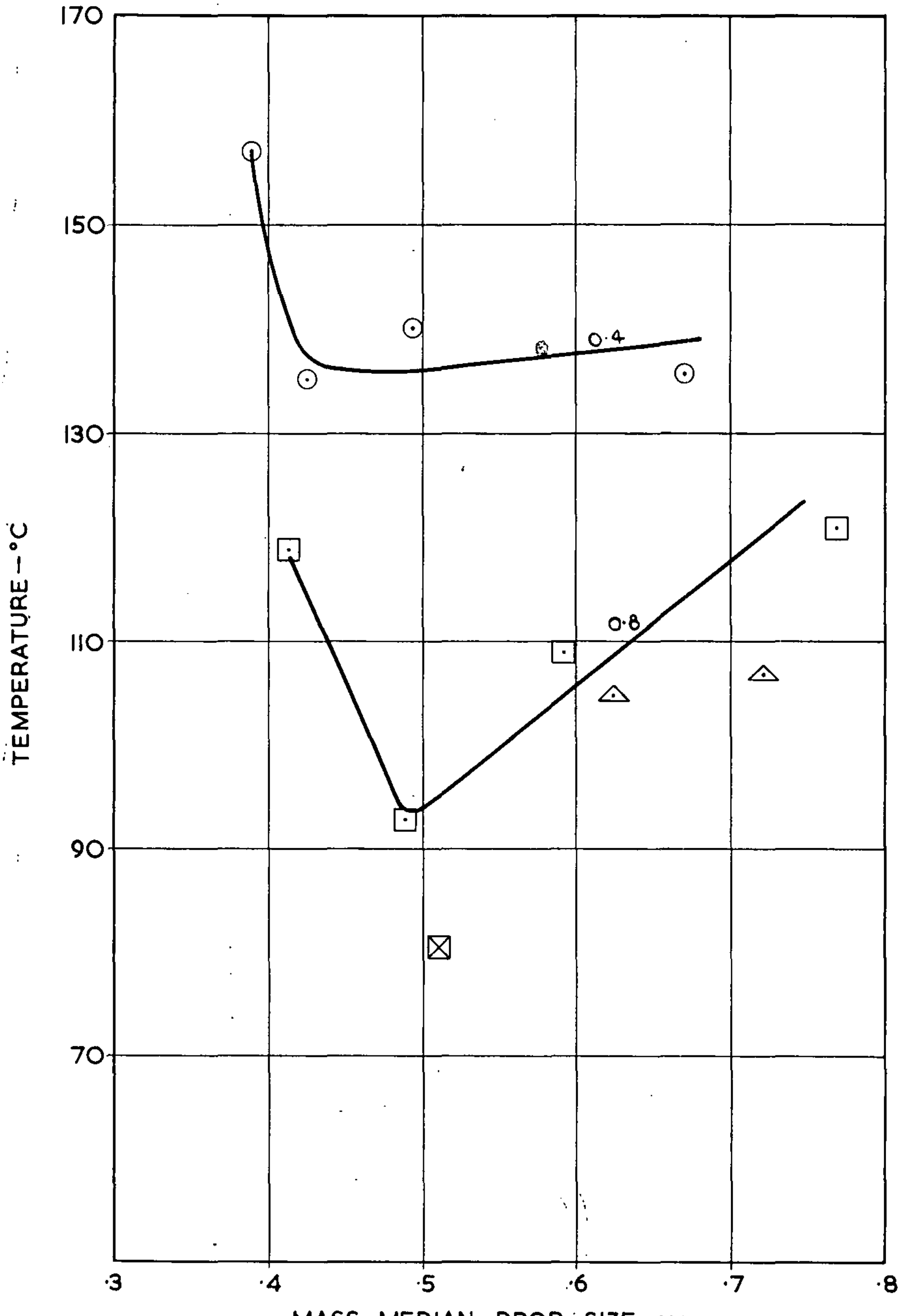


Legend – rate of flow

⊙ ·4 g/(cm)²(min.) ⊡ ·8 △ 1·2 ⊕ 1·6 ⊞ 2·0

Pressure 5 lb./in²

FIG. 24. THE EFFECT OF MASS MEDIAN DROP SIZE AND RATE OF FLOW OF SPRAY ON THE TEMPERATURE 3 MM. BELOW THE SURFACE



Legend — rate of flow

⊙ ·4 g/(cm)²(min) ⊡ ·8 ⊠ 1·0 △ 1·2

Pressure 10 lb./in.²

FIG. 25. THE EFFECT OF MASS MEDIAN DROP SIZE AND RATE OF FLOW OF SPRAY ON THE TEMPERATURE 3 MM. BELOW THE SURFACE

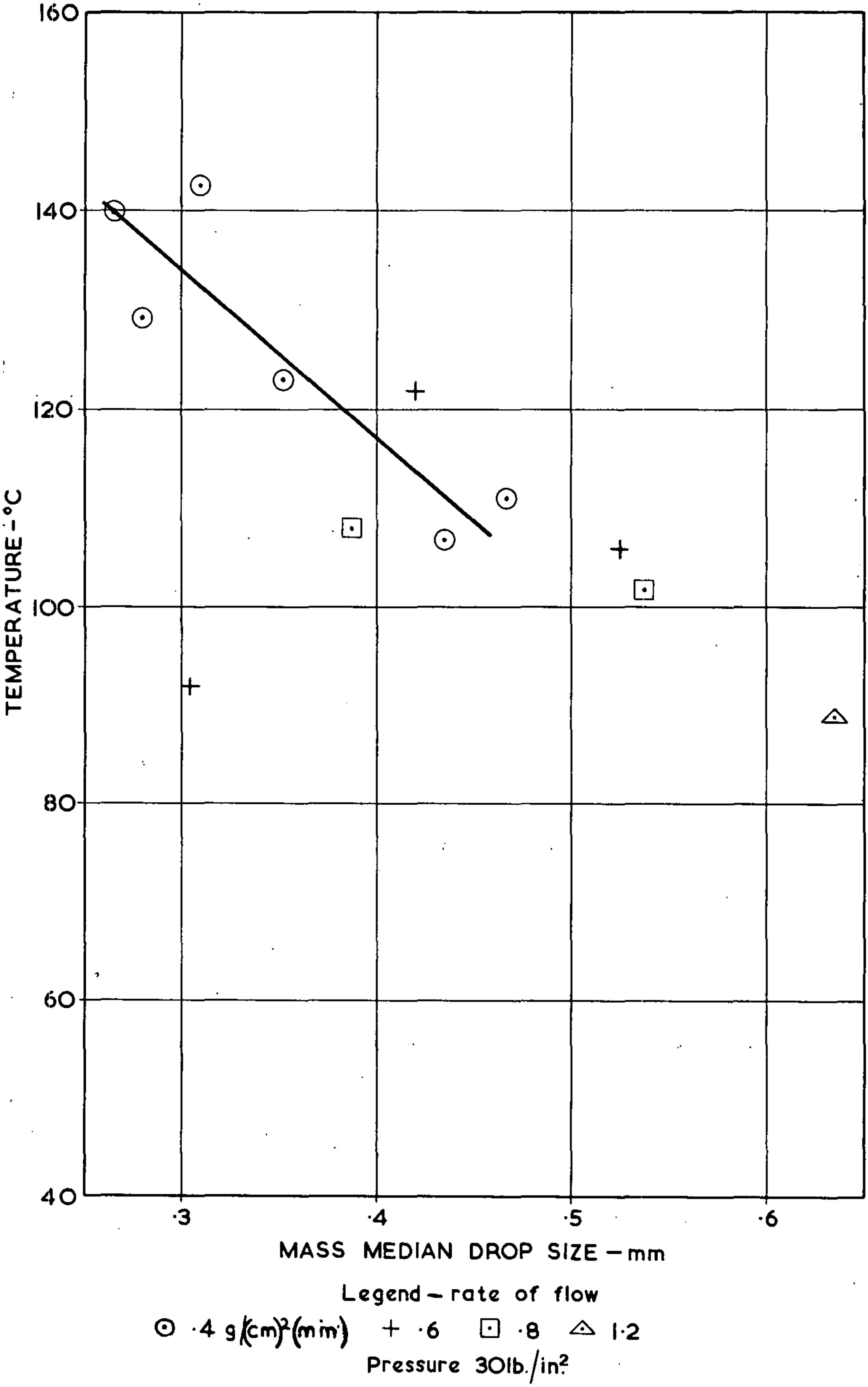


FIG. 26. THE EFFECT OF MASS MEDIAN DROP SIZE AND RATE OF FLOW OF SPRAY ON THE TEMPERATURE 3MM. BELOW THE SURFACE.

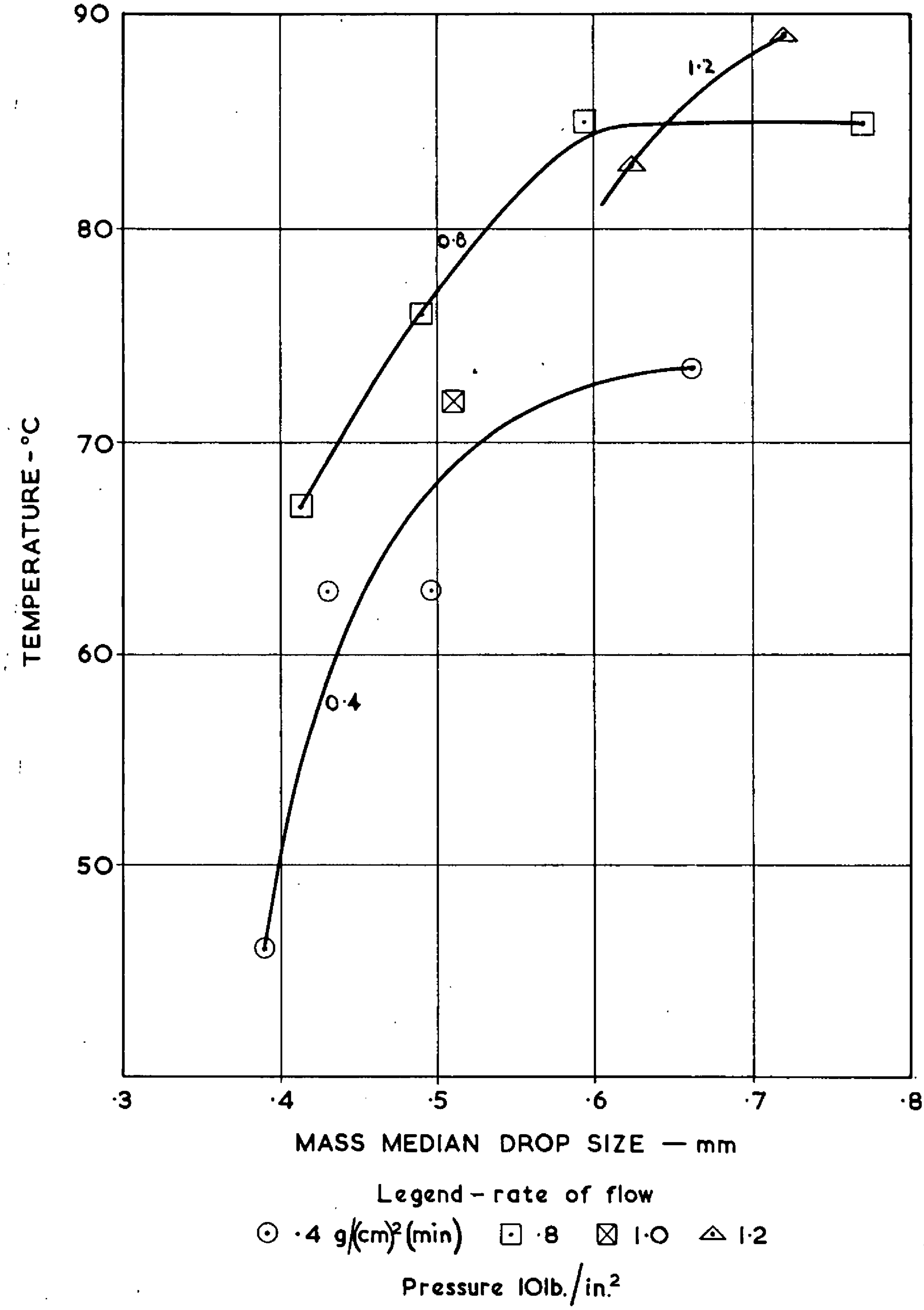


FIG. 27. EFFECT OF MASS MEDIAN DROP SIZE AND RATE OF FLOW OF SPRAY TEMPERATURE 6·0 CM. BELOW THE KEROSINE SURFACE.

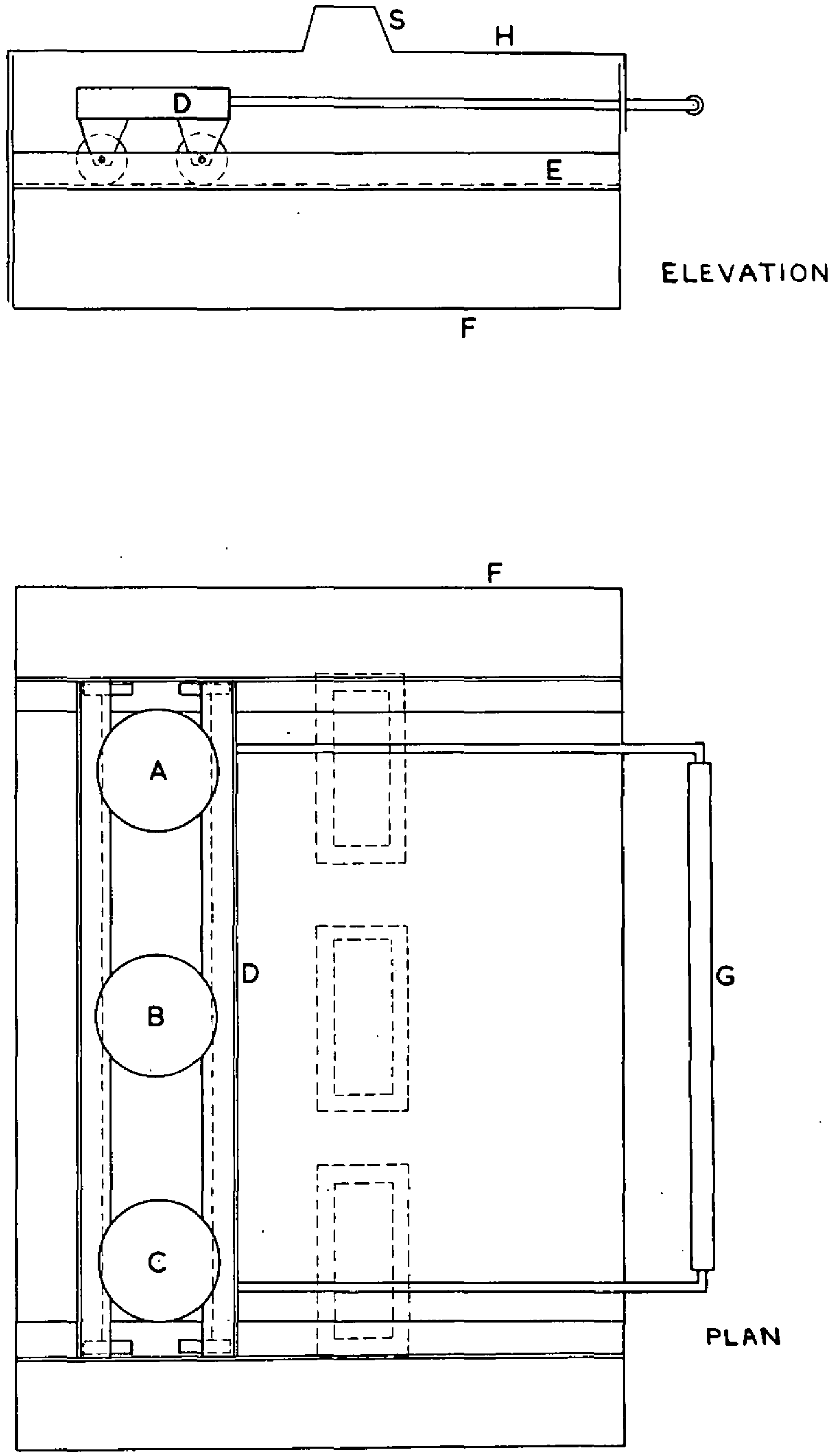
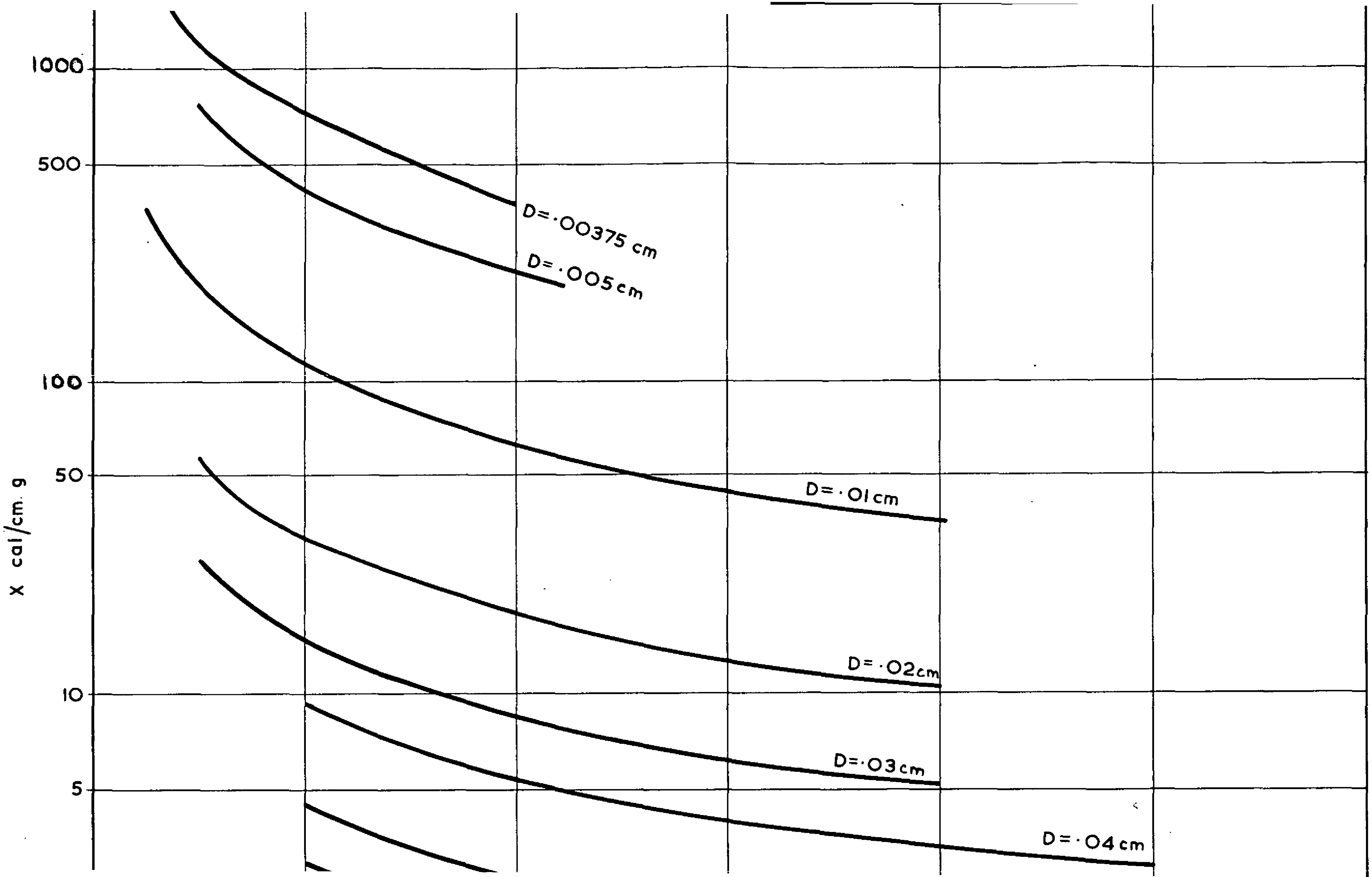


FIG. 28. APPARATUS FOR MEASURING DROP SIZE

FIG. 29. COUNTING AND CLASSIFICATION OF DROPS



1000
500
100
50
10
5
X cal/cm. g
D=·00375 cm
D=·005cm
D=·01cm
D=·02cm
D=·03cm
D=·04cm