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DESIGN OF SPRAYS FOR PROTECTIVE INSTALLATIONS. PART III
THE EXTINCTION OF OIL FIRES ON BANKS OF TUBES

by

D. J. Rasbash and G. W. V. Stark

SUMMARY

Tests have been made on the extinction by water sprays of fires of oil pouring over banks of vertical and horizontal tubes.

The most important factor governing extinction was the flow rate of spray to the tube bank, the ease of extinction increasing with increase in flow rate. The higher the temperature of the tube bank, and the lower the fire-point of the oil, the larger was the flow rate needed to extinguish the fire. For transformer oil, a flow rate of 1·2 gal/min of spray per square foot of superficial area of the tube bank was required under the most severe conditions tested. Although it was found that sprays with a high impact force gave qualitatively a better performance than sprays with a low force, there was a better quantitative correlation between the performance of the spray and the ratio between the drop velocity and drop size at the tube bank. An increase in pressure improved the efficiency of the sprays; the effect was more marked between 25 and 50 Lb/in^2 than between 50 and 90 Lb/in^2. While the direction of projection of the spray to the tubes did not affect extinction (except at 25 Lb/in^2) a greater cooling of the tubes was obtained when spray was projected at an angle rather than parallel to the tube axes. The results are in accord with the assumption that the mechanism of extinction is by the oil on the tubes being cooled by water spray. The practical implications of the results of this work on the design of protective installations are discussed.

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INTRODUCTION

Many industrial processes use equipment and pipe-lines containing flammable liquids, such as oils, which may be at high temperatures. The leakage of such oil could allow fires to develop on metal surfaces. This hazard is a particularly important one in the electricity generating industry, which uses oil as a medium for cooling transformers, etc. and for controlling the speed, and lubricating and dissipating heat from the bearings, of turbo-generators. Little systematic information is available on which the design of spray systems may be based to deal with this type of fire. In this report an account is given of tests on the control and extinction by water sprays of fires of oil pouring over vertical and horizontal banks of steel tubes. The object of the work has been to find how the spray properties and the fire properties influence extinction. Insofar as it was compatible with this object, however, the types of nozzles used to produce the sprays and the ways they were arranged about the tube banks were similar to those used at present for risks in electricity generating stations, so that the results might be applied directly to these risks.

EXPERIMENTAL

APPARATUS

<u>Test rig and equipment</u>. Plate 1 shows a photograph of the test rig used. The oil fire was established on a bank of 21 steel tubes each 7 ft long, 2 in. diameter and weighing 21½ lb. These tubes were braced by struts of 1½ in. steel slotted angle. In most tests the tubes were vertical, but in some tests the rig was supported on its long end so that the tubes were horizontal. In both cases an oil manifold was used to distribute a flow of oil fairly evenly over the tubes. About the rig there was a spray nozzle manifold, from which nozzles could project spray onto the rig in various directions. There was accommodation for up to 12 nozzles to spray downwards and for 12 nozzles to spray inwards at various angles. Full details are given elsewhere of the spray manifold [1] and the tube bank and its ancillary equipment [2].

<u>Nozzles</u>. Seven different designs of nozzles were used in the tests. The nozzles were chosen to give sprays with a wide range of properties; these properties are given in Table 1 and photographs of the nozzles operating at 50 Lb/sq.in. pressure are shown in Plate 2. With all the nozzles except that designated N the bulk of the spray was directed forward from the nozzles; sprays from these nozzles will be called "directional". With nozzle N, however, most of the spray was directed outward rather than forward, although a part of the spray was directed forward; the spray from this nozzle will be called "non-directional".

All values given in Table 1 were obtained directly with the exception of the drop velocity 6 ft below the nozzles, which was calculated from the other spray properties. The drop sizes of the spray at 25 and 90 Lb/in^2 were estimated from the measured drop sizes at 50 Lb/in^2. Since in the tests to be described, the parts of the directional sprays which impinged on the tube bank were reasonably representative of the whole spray, the properties in the spray listed in Table 1 were mean values for the whole spray; in particular the velocities given were mean momentum velocities for the whole spray [3]. With nozzle N, however, the bulk of the spray which impinged on the tube bank came from the central portion of the spray cone, and the listed properties in the spray refer to this portion of the spray; in particular the drop velocity given was the terminal velocity of the drops relative to the local air stream. Further details of the methods of measurement and the relation between the various properties given in Table 1 are given elsewhere [3].

Oils. In most tests transformer oil was used at a flow rate of $4\frac{1}{2}$ - $6\frac{1}{2}$ gal/min. However, other flow rates were also tested and experiments were also carried out with kerosine and gas oil.

TEST PROCEDURE AND DESIGN OF EXPERIMENTS

In order to obtain a fire which was reasonably uniform in intensity over the whole tube bank, two methods of pre-heating the tube bank were developed [2] which had as their object the development of an even fire within 10 - 15 secs after the oil was turned on, under all ambient wind conditions. Both systems relied upon the pre-heating of the tube bank by small petrol fires at the base of the tubes, and an arrangement of screens to minimise the effect of wind on the fire. Although some preliminary tests with the first system were successful, later tests (about 60) in which sprays were projected against the fire showed the system to be unreliable. Therefore, to standardise the fire in these latter tests, the preburn time, i.e. the time which was allowed to elapse between turning on the oil and turning on the water spray, was either two minutes or, if the fire had developed slowly, the longer time taken for the tube bank to become two-thirds involved in fire. Most tests, however, (about 250) were carried out with the second, improved system of pre-heating which was found very reliable in giving a rapid development of fire as soon as the oil feed was turned on. Plate 3 shows the tube bank fully involved in fire. In all tests the spray was allowed to act on the tube bank for 45 secs., while keeping the oil flowing, and the effects on the fire were observed.

It is well known that tests on fires carried out in the open air can give very scattered results because of the variation in wind and atmospheric conditions. For this reason the tests with the first pre-heating system mentioned above were carried out in four small randomised blocks. However, it was not found possible to analyse these results in the conventional way since no simple reliable parameter of performance could be found which could be applied to all the tests. Because of this and because also the site on which the tests were carried out was only available temporarily, it was decided to investigate the effect of various factors individually, rather than embark on a large, statistically arranged experiment which might have had to be left unfinished or which might have proved impossible to analyse. The following factors were investigated - preburn time, oil flow rate, water flow rate to the tube bank, type of nozzle, pressure at the nozzle, fire point of the oil, the angle of projection of sprays and the disposition of the tube bank.

RESULTS

GENERAL OBSERVATIONS

Most sprays considerably reduced the overall size of the flames although the amount of flame associated with the tubes themselves varied considerably between the different sprays. The bulk of the reduction of the flame when spray was applied took place within the first few seconds.

Thereafter the change in the size of the flames was relatively small; this point is illustrated in Plate 4 which shows the fire in a number of tests immediately before and during the application of the spray. Very little evidence was obtained of the sprays bringing about an increase in the flames comparable to the upsurge which occurs when sprays are applied to liquids burning in thick horizontal layers. In a few tests, however, at very low flow rates, the application of the spray hastened the spread of fire over parts of the tube bank not already involved in the fire.

In tests where a high degree of control, or extinction was achieved, the fire was generally reduced in the first few seconds of spray application to small flames 6 to 9 in. long on one or two of the tubes in the vertical bank, or on the vertical steel angle supports in the horizontal bank (Plate 5). Where the fire had been extinguished, the oil usually flowed down the tubes in the form of a creamy froth. This collected as scum on the surface of the water near the base of the tubes; this water contained a certain amount of oil and was slightly turbid. The scum, which was a mixture of water, oil and a gas, was immiscible with water which indicated that the continuous phase consisted of oil. Patches of oil formed on the scum very soon after the end of the test and grew rapidly as the scum broke down.

In the results given below, tests carried out with the first pre-heating system are regarded as preliminary tests, because there was a difference in the way the fire built up between the two systems. The flame sizes given refer to the flames 30 secs after applying the spray. The numbers given for flame size refer to the number of junctions of tubes and supporting struts involved in flame, so that a fully involved tube bank and an extinguished fire had flame sizes of 63 and 0 respectively.

Preliminary tests. Four balanced blocks of experiments were carried out using different numbers (1 to 12) of nozzles L, L', M and M' at pressures of 25, 50 and 90 Lb/in^2 and at heights of 10 ft and 5 ft above the bank. As indicated above it was not possible to analyse these results statistically but it was found that the main factor that influenced the control of the fire was the rate of flow of spray reaching the tube bank. This rate depended mainly on the number of nozzles used and the distance of the nozzles from the tube bank but it also depended on the pressure and the nozzle type. An increase in flow rate increased the percentage of extinctions that took place and also reduced the flame size ofthe fires that were not extinguished. Fig. 1 shows how the flame size in these preliminary tests diminished as the flow rate increased; the bulk of the tests fall below an "upper limit" curve. Evidence was also obtained in these tests that an increase in pressure increased slightly the ease of extinction.

MAIN TESTS

The tests to determine the effect of preburn time, oil flow rate, water flow rate and nozzle design were all carried out with downward projection of spray from nozzles operated at 90 Lb/in^2 pressure and mounted 5 ft above the vertical tube bank with transformer oil as the fuel. The effect of pressure, the angle of projection of spray, the fuel and the disposition of the tube bank were determined by varying the particular factors concerned while keeping the other factors constant. The water flow rate was affected by the wind conditions during a test; therefore a mean water flow rate for a given group of tests was calculated, making allowance for the effect of the prevailing wind [1].

Effect of preburn time and oil flow rate. Results of tests in which different oil flow rates and preburn times were varied systematically, are given in Tables 2 and 3.* The tests were carried out with groups of four of the directional spray nozzles, B, L, M, and L', and a group of twelve of the non-directional nozzles N. The temperature S reached by the centre tube immediately before the spray was switched on is included in the results; this temperature represented the temperature of the tube bank, and increased as both preburn time and oil flow rate increased (2). The ease of extinction broadly decreased with an increase in S. The results obtained showed that, with nozzles B, M and N, extinctions were obtained only at the lowest values of S($<$ 513°C), and the flame size of the unextinguished fires increased as S increased. With nozzle L the extinction time increased as S increased. With nozzle L' extinction was obtained in only one test out of four when S was higher than 600°C but in six tests out of seven when the S was lower than 600°C.

Effect of flow rate and different directional nozzles. The results for different water flow rates and different directional nozzles, operated at 90 Lb/in^2, and mounted 5 ft above a vertical tube bank, on which burned transformer oil, are given in Table 4.*

Each group of tests carried out with one spray system shows a critical value of S below which extinctions tended to take place and above which they tended not to take place. This temperature has been plotted against the flow rate in Fig. 2; the points for all nozzles fall on one line which shows that the critical temperature is proportional to the flow rate. Fig. 3 shows the mean flame size when the tube bank was at the temperature reached after two minutes preburn (mean, 500°C, range 400° - 600°C), plotted against the water flow rate. The points for the different nozzles again lie on one curve which shows a decrease in flame size with flow rate; a similar relation between flame size and flow rate was obtained as the upper limit curve in the preliminary tests (Fig. 1).

It may therefore be concluded that, for a given flow rate at the bank, differences between the various directional spray nozzles were insignificant compared with differences caused by variation of the flow rate or the temperature of the tubes.

Standard conditions. The conditions under which the above tests were carried out were adopted as standard conditions, and the effect of a change in these conditions was measured by comparing the results so obtained with those of tests under standard conditions. These comparisons were based on four factors: (a) the critical temperature for extinction at a given flow rate, (b) the flame size at 30 seconds, (c) the chance of extinction in 45 seconds, (d) the reciprocal of the extinction time. To facilitate these comparisons the results under standard conditions were grouped together to form three sets of performance curves which expressed the dependence of factors (b), (c) and (d) on the rate of flow and the temperature S. These performance curves and the methods by which they were obtained, are given in Appendix 1. The corresponding performance curve for factor (a) is the curve in Fig. 2.

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*Tables 2 - 10, in which are presented the results of individual tests under specific conditions, are not reproduced in this Note. The bulk of the information they contain is however given in the text and in relevant figures and tables of derived quantities. Copies of these tables may be obtained by interested parties on application to the Joint Fire Research Organization.

Effect of deviations from standard conditions. Tables 5 to 10* give the results that were obtained in tests in which some conditions were not standard. Each table refers to certain specific deviations from standard conditions. Although the number of tests carried out with each deviation from standard conditions was much less than the number carried out under standard conditions, the range of values of the variables and the number of tests were sufficient to allow a broad comparison with the results obtained under standard conditions. From the results - quantities R, called "flow rate ratios" were calculated; these were defined as (i) the flow rate required to give a certain performance under the stated conditions divided by (ii) the flow rate required to give the same performance under standard conditions.

In general, for each set of results four ratios R_a, R_b, R_c and R_d were calculated based respectively on the factors a, b, c and d enumerated above; examples of the calculation of these ratios are given in Appendix 1. It was also possible to estimate 95 per cent confidence limits for the ratios R_b, R_c and R_d which showed whether the values were significantly different from unity. A value of R greater than unity, indicated that a higher flow rate was required to obtain a given performance under the non-standard conditions than under the standard conditions, i.e. a given fire was more difficult to control. The deviations from standard conditions that were investigated, and their respective flow rate ratios are given in Table 11.

This table shows that a decrease in pressure at the nozzles increased the flow rate ratios R to values greater than unity, and therefore decreased the spray efficiency; the effect was more marked between 50 - 25 Lb/sq.in. than between 90 - 50 Lb/sq.in. The use of spray from the non-directional nozzle N instead of the directional nozzles also brought about a significant increase from unity of the values of R, which for nozzle N used at 90 Lb/in^2 pressure, were in general between the values for the other nozzles used at 50 and 25 Lb/in^2.

A very marked increase in R from unity was also obtained by decreasing the fire point of the oil (Table 8)*. Fig. 4 shows R plotted against Δ T, the difference between the fire point of the liquid and ambient temperature; this figure shows that R varied approximately as $\Delta T^{-1.5}$.

R was also greater than unity when directional nozzles were employed with angular projection (Table 9)* instead of downward projection. However, it was noted in tests with angular projection that the baffle plates used to keep the fuel within the tube bank obstructed the direct access of spray to certain parts of the tube bank. When this effect was allowed for, the values of R were smaller and not significantly different from unity. The use of a horizontal instead of a vertical tube bank (Table 10)* did not have any major effect on R. Estimates of R were not made for the results for angular projection of spray from nozzle N since there were too few results and in three of the four tests the flow rate was less than the smallest flow rate tested under standard conditions (11 gal/min.). In these tests the fire was surrounded by a shroud of fine spray of which only a small fraction impinged on the tube bank. Very little control of the fire was obtained which showed that the spray surrounding the fire did not affect the fire noticeably.

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*Not reproduced. See footnote on previous page.

Temperature of the tubes. Results for the reduction in temperature of the tubes caused by the application of the spray were very scattered. However, broadly speaking, this reduction was related to the flow rate in the manner shown in Fig. 5a, b and c. The parameter P used to express the temperature reduction made allowance for the fact that a rise in temperature equal to about 150°C would have taken place if the fire had continued to burn freely for 45 seconds and was given by

$$P = \frac{(S_i + 150) - S_f}{S_i + 150} \quad \text{......} \ (1)$$

where S_i is the temperature immediately before spray application.
S_f the temperature after 45 seconds application.

The main feature of Fig. 5 was that the temperature was reduced far more when the spray was applied to the tubes at an angle, Fig. 5b and c, than when the axes of the spray cones were parallel to the axes of the tubes, Fig. 5a. In a number of the latter tests, extinction was obtained rapidly after applying the spray, but the tubes were still hot enough several minutes after applying the spray for 45 seconds to allow a re-ignition of the oil if the oil flow was started again. An example of such a re-ignition is shown in Plate 6.

DISCUSSION

FACTORS AFFECTING EXTINCTION

The results show that the main factors affecting the extinction of the fire were the flow rate of the spray reaching the tube bank, the temperature of the tubes immediately before spray application, and the fire point of the oil. The direction of application of the spray and the disposition of the tube bank were not of major importance. There were, however, certain differences between the sprays tested.

Barclay (4) found that for flowing oil fires the best types of sprays were forceful driving sprays. The present results are qualitatively in accord with this finding but quantitatively the spray performance could not be correlated satisfactorily with the force properties in the spray, even allowing for errors in measurement. For example, Table 1 shows that the forces F and G in the spray from nozzle N were very much smaller than in those sprays from the directional nozzles produced at 25 Lb/in^2 pressure, yet the performance of nozzle N (Table 11) was between those for the directional sprays at 25 and 50 Lb/in^2. A better correlation was obtained between R and a factor I given by the ratio of the drop velocity V to the drop diameter, D. Fig. 6 shows R for standard conditions and series 1 to 6 in Table 11, plotted against the mean value of I for the same group of tests to which the particular value of R referred. Within the error of measurement of R and I the points fall on a straight line with the equation

$$R = \frac{22 \cdot 5}{I} \quad \text{......} \ (2)$$

It was also observed that at a pressure of 90 Lb/in^2 there were no substantial differences in performance between the sprays from the various directional nozzles. There were also no substantial differences in the values of I for these nozzles at this pressure. This is shown in Fig. 7 in which V is plotted against D for these nozzles at this pressure; the points fall near a straight line of slope equal to unity. However,

Table 1 shows that the force properties of the sprays at 90 Lb/in^2 were not very different either, although those for nozzles A and B were somewhat higher than the others. Thus, the observed performance of directional sprays may be accounted for whether the force properties of the spray or the factor I be regarded as the factor controlling the spray efficiency.

The above correlation between R and I implies that the efficiency of the spray increases as the velocity of the drops reaching the tube bank increases and their drop size decreases. It follows that a comparatively fine spray (drop size $\leqslant$ 1 mm) applied very close to the bank may be expected to give a better performance than obtained in the present tests since the drops will not have time to decelerate to the same extent. It also follows that an increase in pressure above 90 Lb/in^2 may have beneficial effects if the nozzles are placed closer to the bank.

MECHANISM OF EXTINCTION

The relation between the performance of the spray and the flow rate of spray, the drop size of the spray and fire point of the oil is very similar to that already found for the extinction of pool fires by cooling with water spray[5]. It may, therefore, be concluded from the information in the previous section, that the fires were extinguished and controlled by a similar mechanism, the cooling of the oil which in the present tests was flowing over hot metal surfaces. The effect of preburn time with pool fires is also analogous to the effect of preburn time with the tube bank; in one case the heat content of the oil is increased and in the other the heat content of the metal; both effects lead to an increase in difficulty of extinction by cooling the oil. With pool fires, however, there was no evidence that an increase in the velocity of the drops improved the efficiency of a spray, provided that the drops could reach the burning liquid; whereas with the tube bank there was evidence that an increase in drop velocity increased the extinguishing power of the spray. A reason may be that drops do not usually break up on hitting a pool of oil, whereas they almost certainly do on hitting a metal surface even if it is thinly coated with oil, and the higher the velocity of a drop of a given size on approaching a metal surface, the smaller will be its effective drop size after impinging on the surface. Further, an increase in the velocity of the drops will increase the heat transfer coefficient between the oil and the drop; for oil flowing over tubes this effect would not be cancelled out by the effect of drop velocity on residence time in the oil, which decreases as velocity increases, as it is for drops passing through a layer of hot oil near the surface of a pool fire[6].

COMPARISON WITH OTHER WORK

The flow rate to the tube bank which can be relied upon to give extinction when transformer oil is used may be obtained by combining the curves given in Fig. 12 for zero flame size and in Fig. 13 for 100 per cent extinction. This procedure gives curve (1) in Fig. 8. This figure also shows as curve (2) a lower limit of the flow rate to the tube bank below which no appreciable control was obtained. To be sure of extinction at a preburn time of four minutes it was necessary for a flow rate of 80 gal/min. of water spray to reach the bank from nozzles giving directional sprays at 90 Lb/in^2. With sprays projected vertically downward on to the bank most of this flow would pass through the top of the bank, under these conditions the flow rate to unit area through this space was approximately 8 gal ft^{-2} min^{-1}. However, since the same flow rate was necessary for different directions of attack, as an approximation the 80 gal/min. may be considered as being distributed over that part of the outer area over which the flow rate was measured. On this basis there was an average application of 1·2 gal ft^{-2} min^{-1} to this area.

Results are given elsewhere (7) of the extinction of fires in transformer oil, burning in a layer 2 in. thick, by downward projection of water sprays from fixed nozzles. The preburn time was 5 minutes and the flow rate to unit area of the liquid surface required to give extinction within 45 seconds in every test varied from $\frac{1}{4}$ to $\frac{3}{4}$ gal ft^{-2} min^{-1} according to the drop size of the spray used. For a pool fire therefore of the same area as the top of a tube bank a flow of 2 to 6 gal/min. would have been required and for the surface area of the two long sides and the top, 16 to 48 gal/min. These flow rates are much less than those found necessary in the present work for oil burning on tubes.

Many investigators have carried out experiments on the extinction by water sprays of oil fires on mock-up transformers or other equipment found in electricity generating stations. In most cases, however, it is difficult to compare the results of the work in these tests with those obtained in the present work because of the lack of information on the oil-and spray-properties and the lack of control over the amount of oil burnt and the development of the fire. MacMahon (8) carried out a series of tests on the extinction with water sprays of transformer oil fires on a mock-up transformer. The tests were dissimilar to the present tests in that firstly, the oil was preheated and that secondly, the flow of the oil over the tubes was stopped prior to the application of sprays except for one jet of oil which affected only one tube. The heating of the oil is unlikely to have been an important difference since it was shown in the present work that the volatility of the oil pouring over the bank was unlikely to affect the development of the fire as long as the oil was ignited over the whole bank (2). However, stopping the flow of oil would have made a vital difference. In the present tests the fire would die down almost completely within a few seconds after turning off the oil and it would be expected that in the tests reported by MacMahon that the bulk of the fire involving the transformer during the application of a spray was in the pool of oil remaining on the ground. The average flow rates of water spray to unit area of risk used in these tests varied from 1 to $1\frac{1}{2}$ gal ft^{-2} min^{-1}; this is of the same order as the flow rates found necessary in the present tests to give rapid extinction. These flow rates extinguished the oil fire in all tests except one in which a boil-over of the transformer oil occurred. This boil-over was not associated with the application of the spray but with the way in which the transformer oil was preheated.

A series of tests has been carried out recently in the United States by the Factory Mutual Laboratories (9) using a large mock-up transformer. Instead of tubes or fins the simulated transformer had sheet metalwork and from this point of view presents a substantial difference to the present series of tests because the surface of the risk presented no areas sheltered from spray. No detailed results are available but a figure of 0·25 gal ft^{-2} min^{-1} has been given as the flow rate required to give control of the fire. Fig. 8 shows that this flow rate could give some control in the tests with the tube bank so long as the temperature of the tubes was not greater than 400°C.

PRACTICAL IMPLICATIONS

It follows from the above considerations that in protecting a risk similar to the tube bank used in the present experiments the most important feature must be the direct projection of water spray on to the risk. In a number of experiments in the present tests particularly with nozzles M' and N, a great deal of fine spray fell about the outside of the bank but not directly on it. This water spray had no noticeable effect on the fire burning on the risk. In practice, however, there must be a margin of overspray to allow for deflection by wind and also protection is often required for the ground area surrounding the risk. The flow rates required to protect against a ground fire are much less than those required to protect the main risk and the design of the installation should take this into account.

To conserve water it is desirable that the design of the nozzles should allow for risks of different shapes and sizes so that the bulk of the water from any nozzle may be made to fall directly on the risk rather than about it. Unless nozzles are placed very close to the risk, the cone angle should be less than 90° and the pressure at which the spray is produced should be greater than 50 Lb/in^2.

The most important factor in determining the flow rate required would be the efficiency of the detecting system. The longer the fire burns, not only the further will it spread but also the larger will be the flow rate required per unit area of fire because of the rise in temperature of the metal. Information on the times after the start of a fire at which detectors, used for protecting electrical installations, are likely to operate is very scanty. A heat sensitive detector in flame might operate within 10 - 15 secs, but wind conditions might be such that all the detectors might be outside the flames or the hot gases so that the detectors can be operated only through radiation from the flames. In some of the tests carried out by MacMahon (8) in which automatic detection was used in the outdoor tests, the time between ignition and automatic operation of the detectors varied from 1 minute to 3 minutes 38 seconds. This would suggest that the full flow rate of 1·2 gal/min. per sq. ft of risk area would be required on a risk similar to that used in the present tests, for reasonable certainty of complete extinction in a short time. A large measure of control and many extinctions would be obtained however with flow rates considerably less than this. It is possible under some conditions that a lower flow rate might be tolerated, if the fixed automatic installation were required only to control the fire and prevent it spreading and if it could be backed up by hand lines which could be relied upon to be brought quickly into action, and also if an automatic alarm could be given to a neighbouring fire station.

Another important practical point is the cooling of the tubes by water spray. Within a preburn period of one minute the tubes reach a temperature of 300°C at which oil will ignite spontaneously (10). The extinction of the oil fire is no criterion that the tubes have been cooled sufficiently to prevent re-ignition and application of water spray must be continued until it is certain that all metal work is well cooled. The cooling is much more pronounced when water sprays are projected at an angle to the tubes rather than parallel to the tubes. In this respect a water spray system will have a considerable advantage over a carbon dioxide system and also a dry powder installation, partioularly if these media are used on risks open to the atmosphere.

CONCLUSIONS

(1) The efficiency of water spray protective installations for oil fires flowing over hot metal depends mainly on the flow rate of water that reaches the surfaces on which the oil burns. Spray which passes through the space near the risk does not have an appreciable effect on the extinction of the fire. Spray performance should therefore generally be assessed in terms of flow rate per unit area of risk, rather than as a flow rate to the surrounding volume. The area of the risk may be taken as the envelope area, i.e. the area of the simple, plain surfaced, figure of the same outline as the risk.

(2) An increase in the temperature of the metal on which the oil burns increases the flow rate required for extinction. This temperature increases with an increase in the time between the start of the fire and the application of spray; this fact emphasizes the importance of rapid detection of the fire to facilitate extinction.

(3) The flow rate for extinction increases as the fire point of the oil is reduced.

(4) The present tests have indicated that the efficiency of different sprays depends on the ratio of the velocity of the drops to the drop size of the spray at the risk. For practical purposes, however, there appears to be little difference in performance between sprays from different directional nozzles produced at pressures greater than 50 Lb/in^2.

(5) The direction of application of spray did not in the present tests, have a major effect on the ease of extinction but did influence the cooling of the metal.

(6) Using directional sprays at 90 Lb/in^2 a flow rate of 1·2 gal ft^{-2} min^{-1} to the envelope area of the tube bank, was found to give extinction in 45 seconds with all metal temperatures tested, i.e. metal temperatures reached after 4 minutes preburn time.

(7) The results obtained are reasonably in accord with the assumption that extinction of the fires was obtained by cooling the oil to the fire point.

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SYMBOLS

A = Swirl Nozzle, Wide Angle, Directional.
B = " " Narrow " "
D = Drop diameter, mass median., mm.
F = Downward force of spray at an obstruction. Lb. per gal/min.
G = Downward force of air current in spray, Lb per gal/min.
H = " " of spray drops " " Lb per gal/min.
I = Ratio $\frac{V}{D}$
K = Constant
L = Impinging Jet Nozzle, narrow angle, directional, peaked pattern.
L' = " " " " " " uniform "
M = " " " wide " " peaked "
M' = " " " " " " uniform "
N = " " " " " nondirectional.

P = Parameter $\frac{(S_i + 150) - S_f}{S_i + 150}$

Q = Downward force of spray at nozzle (nozzle reaction) Lb per gal/min.
R = Flow rate ratio.
S = Temperature °C, Subscript i = at start of spray application.
f = 45 seconds after spray application.
ΔT = Temperature difference between fire point of oil and ambient.
V = Drop velocity, ft/sec.
Y = Flow rate of spray at tube bank, gal/min.

PC.

TABLE 1

PROPERTIES OF SPRAYS

NOZZLE DATA				PROPERTIES AT NOZZLE			PROPERTIES OF SPRAY			
								DOWNWARD FORCE IN SPRAY		
Code	Type	Spray pattern	Pressure Lb/in^2	Cone angle o	Total flow rate Gal/min	Nozzle reaction per unit flow rate Q $Lb/gal/min^{-1}$	Estimated mass median drop size D. mm	Measured at an obstruction F $Lb/gal/min^{-1}$(+)	Force in air current G $Lb/gal/min^{-1}$ x	Drop velocity ft/sec x
A	Swirl directional	Moderately peaked	25	65	9·9	0·261	1·2	0·29	0·183	20·4
			50		14·0	0·325	0·97	0·51	0·240	20·9
			90		18·3	0·437	0·83	0·81	0·379	14·4
B	"	Peaked	25	48	10·7	0·251	1·2	0·41	0·167	19·8
			50		15·5	0·363	0·99	0·51	0·244	26·9
			90		20·0	0·514	0·85	0·59	0·418	19·8
L	Impinging jet directional	"	25	51	19·4	0·287	3·9	0·52	0·117	36·8
			50		28·2	0·402	3·2	0·49	0·169	47·8
			90		37·2	0·537	2·8	0·60	0·298	48·4
M	"	"	25	100	19·1	0·221	1·8	0·41	0·113	26·7
			50		26·3	0·336	1·5	0·44	0·156	38·2
			90		35·4	0·421	1·3	0·53	0·267	33·0
L'	"	Uniform	25	52	18·6	0·215	1·6	0·32	0·129	22·4
			50		25·7	0·330	1·3	0·35	0·220	25·4
			90		33·4	0·449	1·1	0·67	0·344	23·6
M'	"	"	25	98	17·7	0·157	0·84	0·18	0·102	18·4
			50		24·1	0·224	0·68	0·49	0·175	15·9
			90		31·1	0·318	0·59	0·49	0·278	12·8
N	Impinging jet non-directional	Hollow	25	140	17·1	0·071	0·91	N.M.	0·0201Ø	12·[illegible]
			50		22·4	0·105	0·7[illegible]	N.M.	- 0·007[illegible]Ø	9·[illegible]
			90		30·6	0·164	0·64	N.M.	- 0·0227Ø	8·1

N.M. = Too small to measure.

(+) = Force measured 7 ft 6 in. below nozzle.

x = Measured 6 ft below nozzle.

Ø = Force over central 9 ft diameter.

Ø = Sum of terminal velocity and velocity due to the current.

TABLE 11

EFFICIENCY OF SPRAYS: FLOW RATE RATIOS, R.
COMPARISON OF FLOW RATE WITH THAT OF STANDARD CONDITION.

SERIES	PARAMETER		R_a - CRITICAL TEMPERATURE FOR EXTINCTION			R_b - FLAME SIZE				R_c - PROPORTION OF EXTINCTIONS				R_d - RECIPROCAL EXTINCTION TIME			
	Conditions of test	Pressure Lb/in^2	Mean temperature S_i °C	Mean flow rate Y Gal/min	Flow rate ratio	Mean temperature S_i °C	Mean flow rate Y Gal/min	Flow rate ratio	95% confidence limits	Mean temperature S_i °C	Mean flow rate Y Gal/min	Flow rate ratio	95% confidence limits	Mean temperature S_i °C	Mean flow rate Y Gal/min	Flow rate ratio	95% confidence limits
1	Directional nozzles 5 ft above vertical tube bank.	50	300	39	1·28	610	45	1.10 (22)	0·90-1·35	496	48	0.87 (14)	0.74-1.04	492	57	1·51 (21)	1·12-2·01
2	Transformer oil fires.	25	300	75	2·48	416	41	1·47 (21)	1·21-1·78	310	53	>3·03 (13)	1·67-N.D.	308	54	>3·20 (14)	2·27-4·78
3	Non-directional nozzles 5 ft above vertical tube bank. Transformer oil fires.	90	400	68	1·70	615	57	1·89 (14)	1·38-2·58	622	68	1·55 (13)	1·31-1·64	590	68	1·69 (15)	1·52-1·88
4	Directional nozzles 5 ft above horizontal tube bank.	90	400	40	1·00	495	43	1·00 (7)	0·69-1·46	496	50	0·90 (8)	0·73-1·07	444	50	1·32 (11)	0·87-2·01
5	Transformer oil fires.	50	400	50	1·03	447	54	1·18 (8)	0·89-1·56	280	33	1·65 (6)	0·99-2·96	326	51	1·84 (9)	1·14-2·98
6		25	400	>62	>1·55	339	32	1·33 (8)	1·06-1·65	390	51	1·63 (6)	1·06-1·99	384	56	2·10 (8)	1·32-3·33
7	Directional nozzles 5 ft above vertical tube bank. Kerosine fires.	90	100	140	11·7	213	80	3·18 (13)	2·17-4·67	240	75	>3·59 (11)	2·00-N.D.	239	87	5·04 (12)	3·05-8·36
8	Directional nozzles 5 ft above vertical tube bank. Gas oil fires.	90	300	137	4·5	252	99	2·35 (4)	1·25-4·41	259	61	>4·38 (2)	1·00-N.D.	252	99	4·72 (4)	2·94-7·62

NOTE: Figures in parenthesis = No. of tests.
N.D. = upper confidence limit not determinable.

YR Note 303.

APPENDIX

THE CALCULATION OF FLOW RATE RATIOS

Three factors, the mean flame size, the proportion of extinctions, and the mean reciprocal extinction time in a group of tests were used to relate the efficiency of control or extinction of a fire with the flow rate Y to the tube bank and the temperature S_i of the tube bank. The results given for standard conditions of test, Table 4,[*] were grouped with respect to Y and S_i; this allowed the data in the table to be represented by a number of mean values, each based upon a reasonable number of tests in which the conditions of flow-rate and tube bank temperature were similar. By plotting each of the three factors against flow rate, groups of curves for different temperatures of the tube bank were obtained for the three factors, these are shown in Figs. 9, 10 and 11. In deriving Fig. 11 any extinction time greater than 45 seconds was considered as giving zero reciprocal time. From these curves, sets of curves were derived in which different levels of the factors flame size, proportions of extinctions and reciprocal extinction time were plotted for the variables flow rate and temperature. (Figs. 12, 13 and 14 respectively).

Flow rate ratio. Figs. 12, 13 and 14 were used to estimate the flow rate ratios of systems of spray and tube bank fire differing from the standard conditions.

For example, for any test carried out under non-standard conditions, where there was a flow-rate Y_t and a tube bank temperature S_t, and for which a certain flame size was recorded, an equivalent flow rate Y_s was read off, from Fig. 12, which would have given the same flame size at the same temperature S_t under standard conditions; a flow rate ratio Y_t/Y_s could be assigned to that particular test. The mean flow rate for a group of tests was obtained by taking the geometric mean of the individual values of Y_t/Y_s; and was the flow rate ratio R_b of that group of tests. The flow rate ratio R_d was obtained in the same way from Fig. 14, and examples of the calculation of R_b and R_d are given in Tables 12 and 13 respectively.

A different method was used to obtain the flow rate ratio R_c from the curves for the proportion of extinctions, Fig. 13 as follows. For a given group of tests the proportion of extinctions P_t, and the mean temperature S_t was calculated. For each test in the group, the expectation of extinction P under standard conditions at the same temperature S and flow rate Y was obtained from Fig. 13. The mean of the expectations for all tests in the given group was an estimate of the proportion of extinctions P_s which would have been obtained if the tests had been made under standard conditions. The flow rates Y_s and Y_t required to give P_s and P_t expectations of extinctions at temperature S_t were obtained from Fig. 13. Y_s is the estimated flow rate for standard conditions equivalent in performance to the mean performance of the group of tests, and Y_t is the estimated flow rate for tests under standard conditions giving the same expectation of extinction as the group of tests under non-standard conditions. The flow rate ratio for the group of tests is thus given by $\frac{Y_s}{Y_t}$.

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[*]See footnote, page 4.

It will be noted from Tables 12, 13 and 14 that certain tests were omitted from the summations. These were tests in which both the test result and the estimated quantity for the standard condition were beyond the minimum or maximum limits of the curves, (Figs. 12, 13 and 14), so that no accurate estimate could be made of equivalent flow rate, (or expectation of extinction).

For each flow rate ratio, except R_a, 95 per cent confidence limits could be calculated and these are given in Table 11. Those for R_b and R_d were obtained from the variance of the logarithms of the individual results from which the mean value was obtained, and that for R_c from the data in Table VIII, 1, Fisher and Yates. "Statistical Tables for Biological, Agricultural and Medical Research". (Oliver and Boyd, 1948).

TABLE 12

CALCULATION OF FLOW RATE RATIO, Rb FROM FLAME SIZE
STANDARD CONDITIONS, EXCEPT PRESSURE, 25 Lb/in^2, TABLE 6

TEST RESULTS			Equivalent flow rate Gal/min	FLOW RATE RATIO		COMMENT
Flow rate Y Gal/min	Temperature S_i °C	Flame size		Value	Log	
12	630	63	-	-	-	Beyond limits, Fig. 12, see Appendix
13	685	56	10·0	1·30	0·114	
24	670	21	27·2	0·88	- 0·055	
18	600	42	15·0	1·20	0·079	
23	644	55	10·2	2·25	0·353	
32	610	21	29·5	1·08	0·035	
40	77	1	19·5	2·05	0·312	
40	106	1	22·2	1·80	0·255	
40	118	4	20·2	1·98	0·296	
40	266	27	18·2	2·20	0·342	
40	320	2	49·2	0·81	- 0·090	
40	560	24	25·5	1·57	0·195	
40	560	12	41·0	0·98	- 0·010	
75	285	0	-	-	-	Beyond limits, Fig. 12, see Appendix
75	585	1	64·5	1·16	0·065	
31	450	7	46·2	0·67	- 0·173	
31	600	45	13·7	2·26	0·354	
68	200	3	33·0	2·06	0·314	
68	300	16	27·5	2·47	0·392	
68	460	12	37·8	1·80	0·255	
10	464	50	11·3	0·89	- 0·053	
64	190	3	31·7	2·02	0·305	
64	280	6	39·0	1·64	0·214	
3	604	63	-	-	-	Beyond limits, Fig. 12, see Appendix
41	416				0·1666	Mean value

Geometric mean flow rate ratio R_b = 1·47.
95 per cent confidence limits = 1·21 - 1·81.

TABLE 13

CALCULATION OF FLOW RATE RATIO FROM RECIPROCAL EXTINCTION TIME STANDARD CONDITION, EXCEPT PRESSURE 25 Lb/in^2. TABLE 6 (Fig. 64)

Flow rate Y Gal/min	Temperature S_i °C	Reciprocal extinction time sec^{-1}	Equivalent flow rate standard condition Gal/min	FLOW RATE RATIO		COMMENT
				Value	Log	
3	604	0	-	-	-	Beyond limits of curve. Fig. 14. See Appendix.
10	464	0	-	-	-	" " "
12	630	0	-	-	-	" " "
13	685	0	-	-	-	" " "
18	800	0	-	-	-	" " "
23	644	0	-	-	-	" " "
24	670	0	-	-	-	" " "
31	450	0	-	-	-	" " "
31	600	0	-	-	-	" " "
32	610	0	-	-	-	" " "
40	118	0	10·0	>4·0	0·602	
40	77	0	10·0	>4·0	0·602	
40	106	0	10·0	>4·0	0·602	
40	320	0	10·4	>3·84	0·584	
40	266	0	10·0	>4·0	0·602	
40	560	0	36·5	>1·09	0·037	
40	560	0	36·5	>1·09	0·037	
64	190	0	10·0	>6·4	0·806	
64	280	0	10·0	>6·4	0·806	
68	200	0	10·0	>6·8	0·833	
68	300	0	10·0	>6·8	0·833	
68	460	0	26·4	>2·58	0·412	
75	285	0·067	48·0	1·56	0·193	
75	585	0	37·8	>1·98	0·297	
54	308				>0·518	Mean values

Geometric mean flow rate ratio = >3·29.
95 per cent confidence limits 2·27 - 4·78.

TABLE 14

CALCULATION OF FLOW RATE RATIO R_c FROM PROPORTION OF EXTINCTIONS
STANDARD CONDITIONS EXCEPT HORIZONTAL TUBE BANK. TABLE 10
NOS. 1 - 12

TEST DATA		EXTINCTION PROPORTION		
Flow rate Y Gal/min	Temperature S_i °C	Found	Estimated for standard condition	
27	266	0	0·40	
27	401	0	0·01	
27	617	0	0.00	Omitted. Beyond limit of curve. Fig. 13.
40	434	1	0·27	
40	457	1	0·22	
55	170	1	1.00	Omitted. Beyond limit of curve. Fig. 13.
55	264	0	1·00	" " "
55	446	1	0.66	
64	379	1	0·92	
64	600	1	0·71	
64	713	1	0.66	
64	767	0	0·66	
50 Y	496 S_t	0·667 P_t	0·501 P_s	

From Fig. 13. Flow rate Y_t (at S_t = 496°C, P_t = 0·667) = 58·5

" " Y_s (at S_t = 496°C, P_s = 0·501) = 53·0

$$\text{Flow rate ratio } R_c = \frac{Y_s}{Y_t} = 0{\cdot}90$$

95 per cent confidence limits = 0·73 - 1·07.

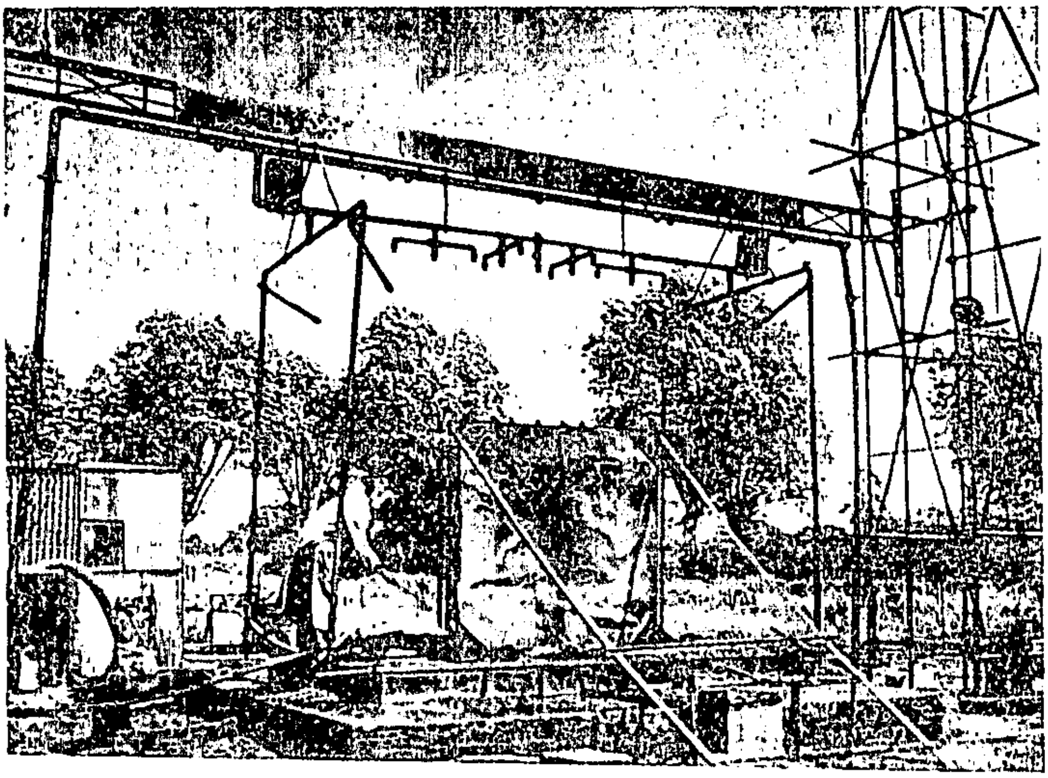
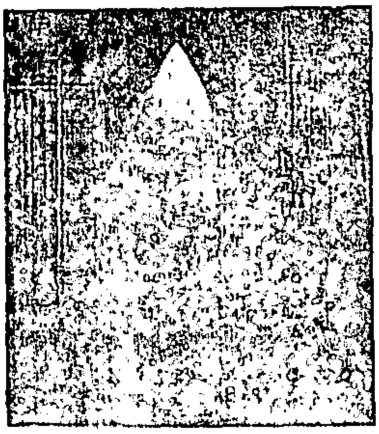
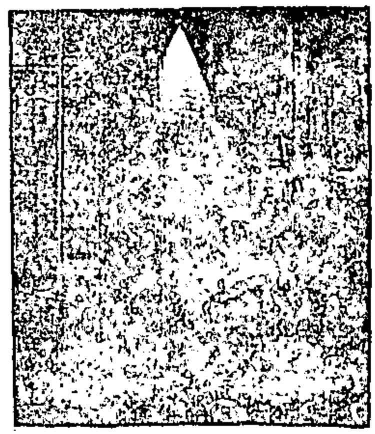


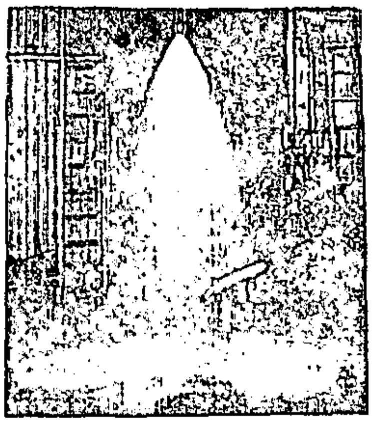
PLATE. I. TEST RIG



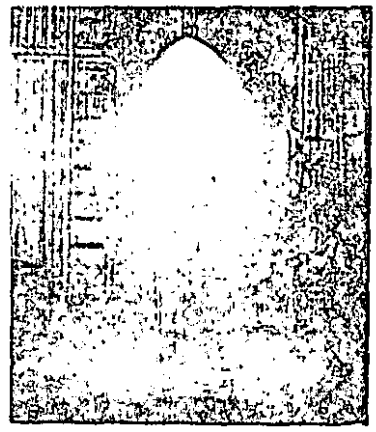
Nozzle A



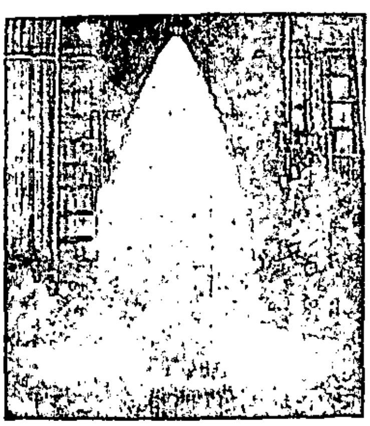
Nozzle B



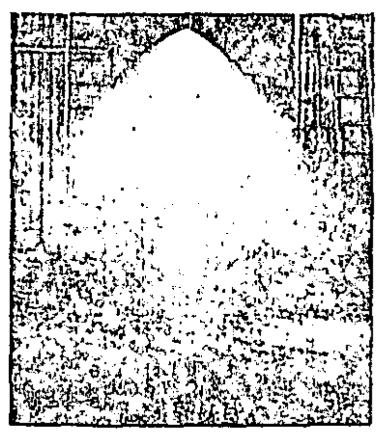
Nozzle L



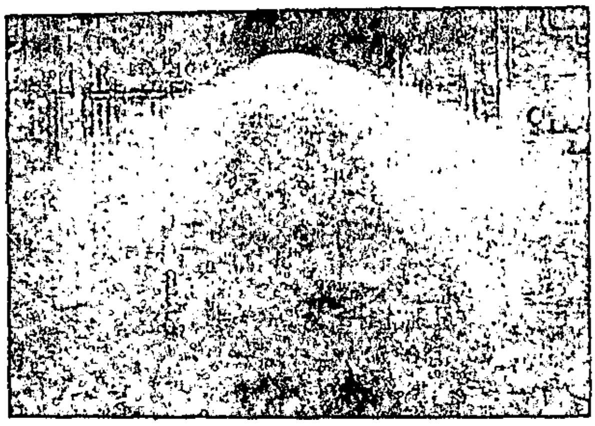
Nozzle M



Nozzle L'



Nozzle M'



Nozzle N

PLATE. 2. SPRAYS PRODUCED BY NOZZLES OPERATING AT 50 lb/in^2

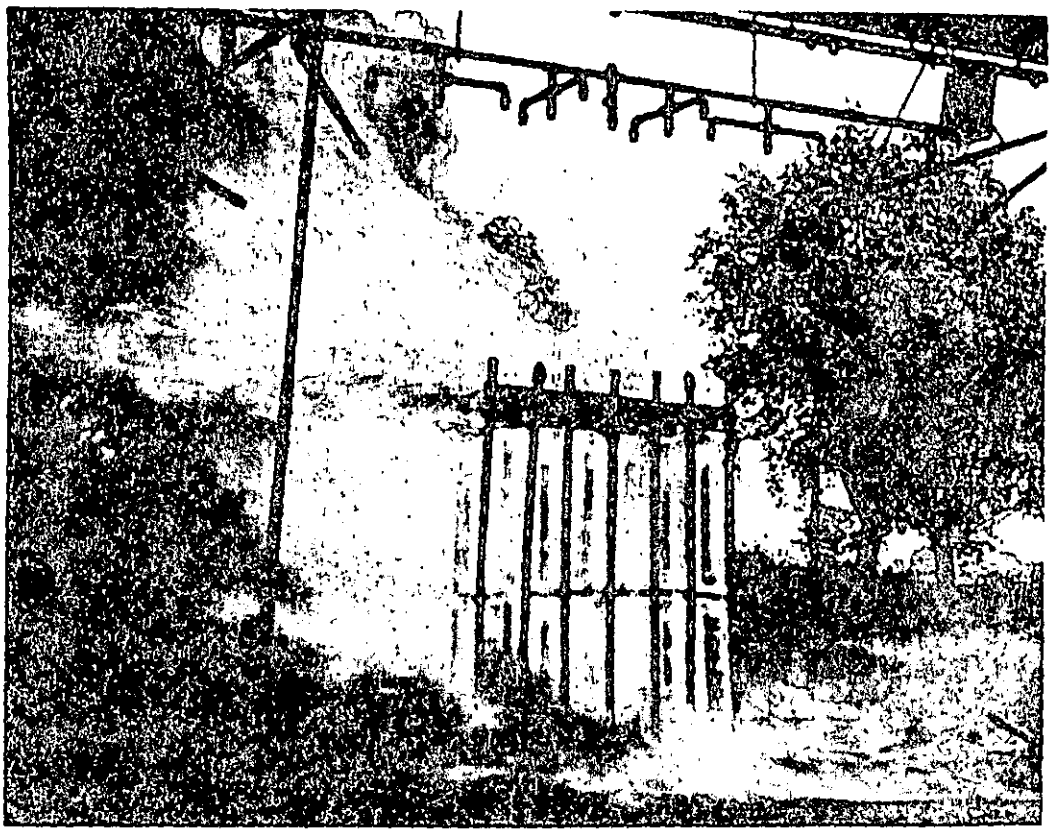


PLATE. 3. FULLY INVOLVED TUBE BANK

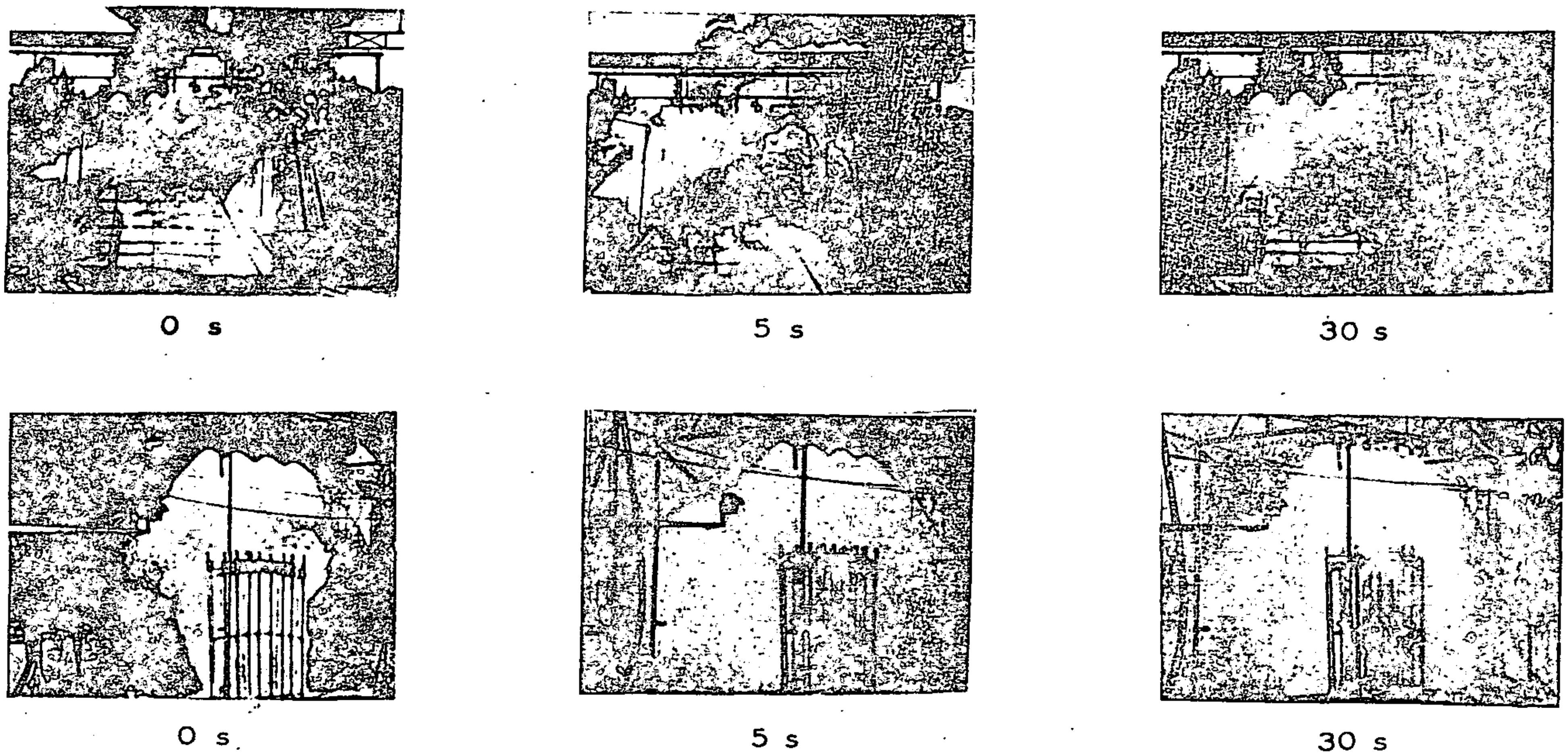
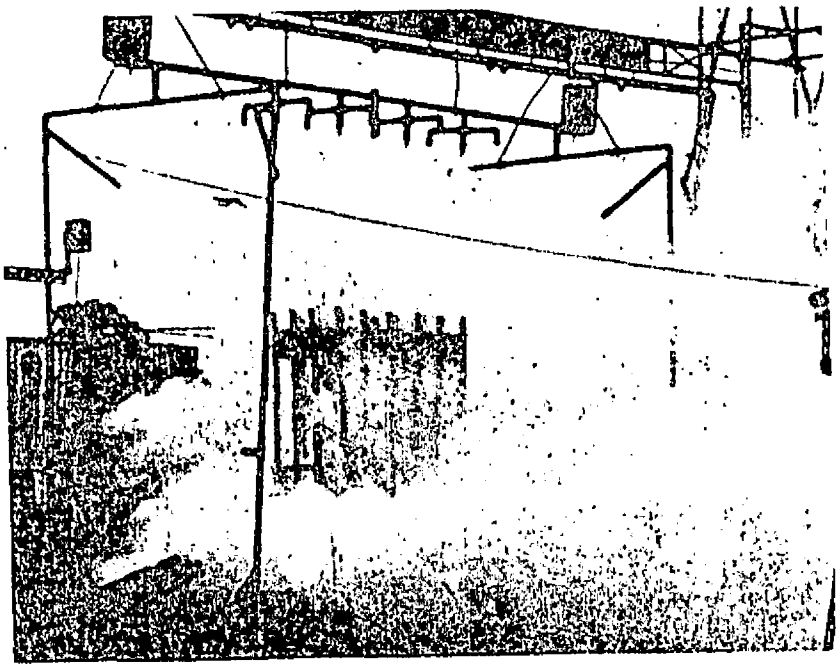
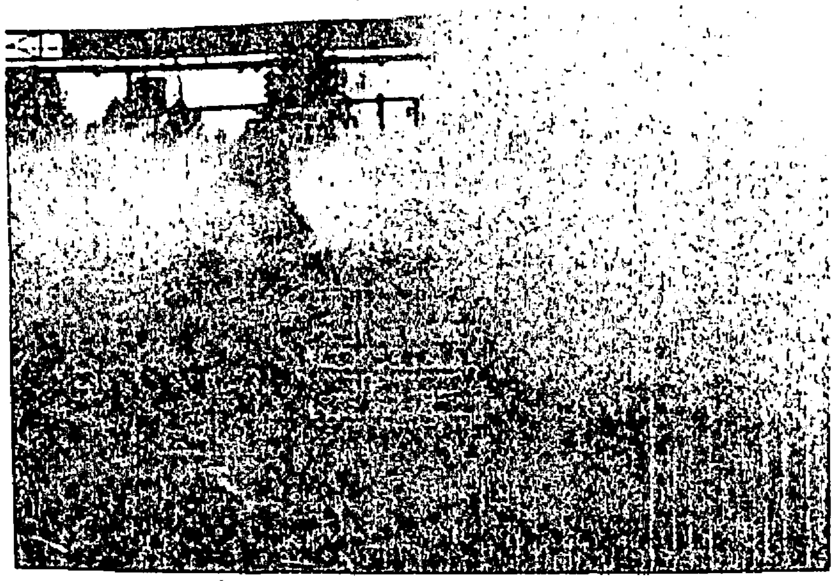


PLATE 4. EFFECT OF SPRAY ON FIRE

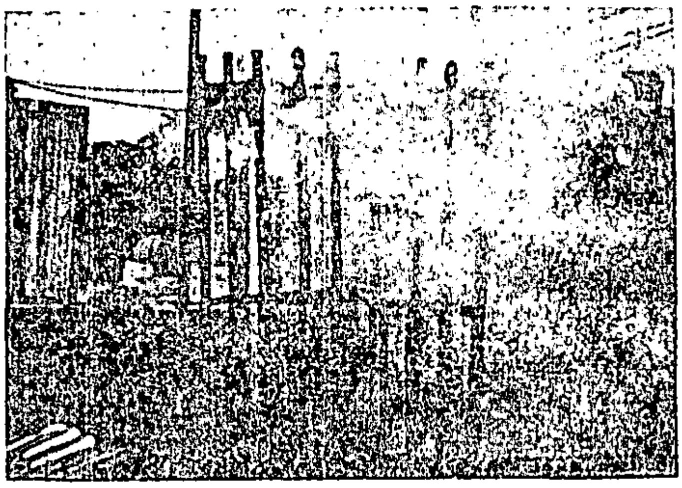


Vertical bank



Horizontal bank

PLATE. 5. RESIDUAL FLAME ON TUBE BANK



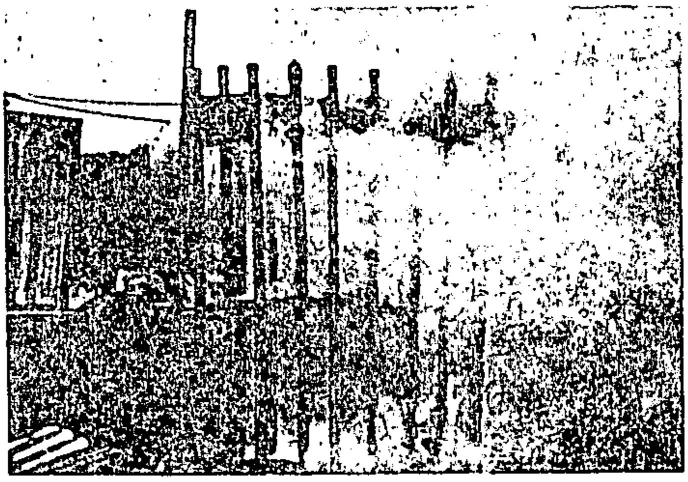


PLATE. 6. RE-IGNITION OF TUBE BANK

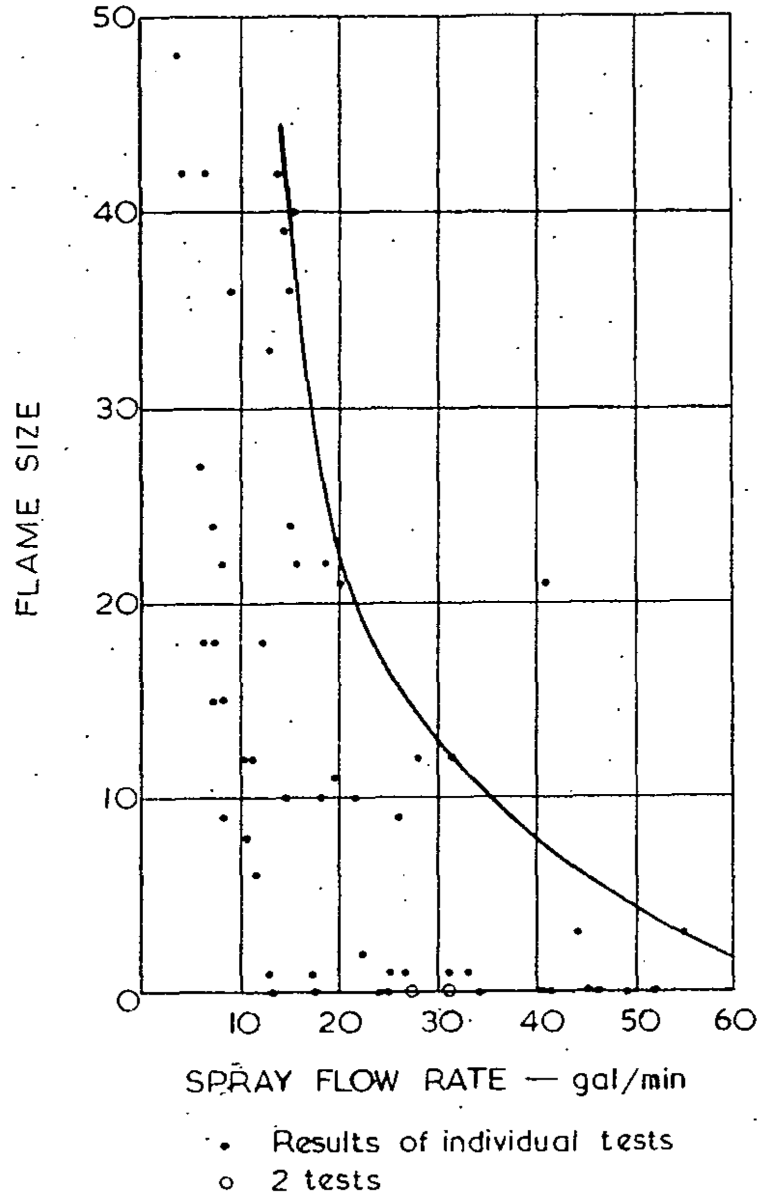


FIG.1. EFFECT OF FLOW RATE ON FLAME SIZE
PRELIMINARY TESTS

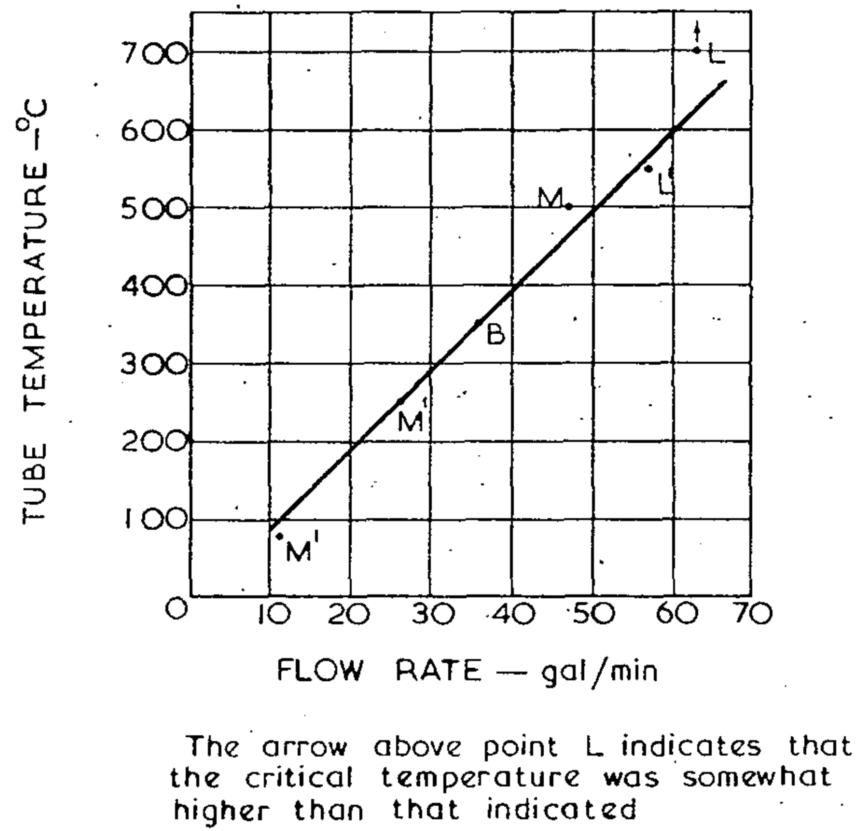
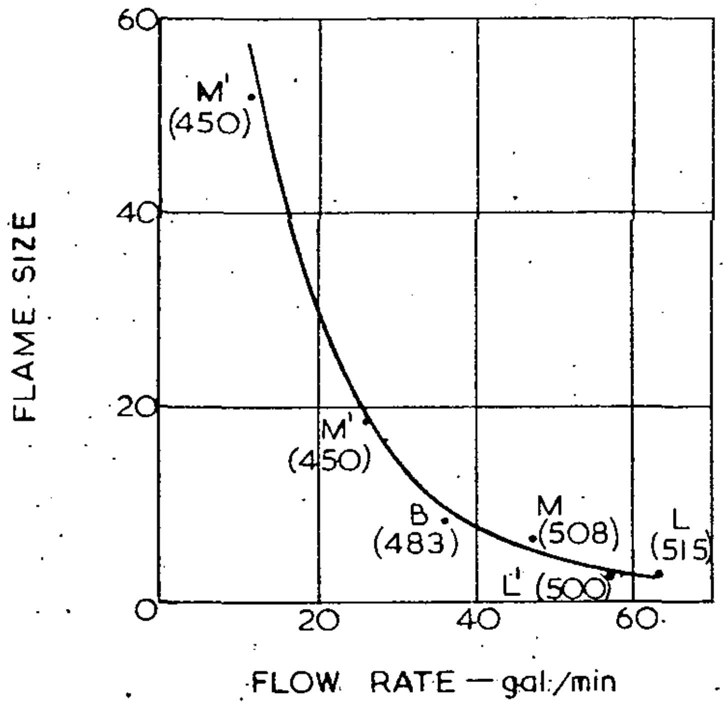


FIG.2 CRITICAL TEMPERATURE
STANDARD CONDITIONS OF TES



Figures in parentheses are mean tube temperatures °c for each group of tests

FIG 3. RELATION BETWEEN FLOW RATE AND FLAME SIZE AT 30 s STANDARD CONDITIONS OF TEST

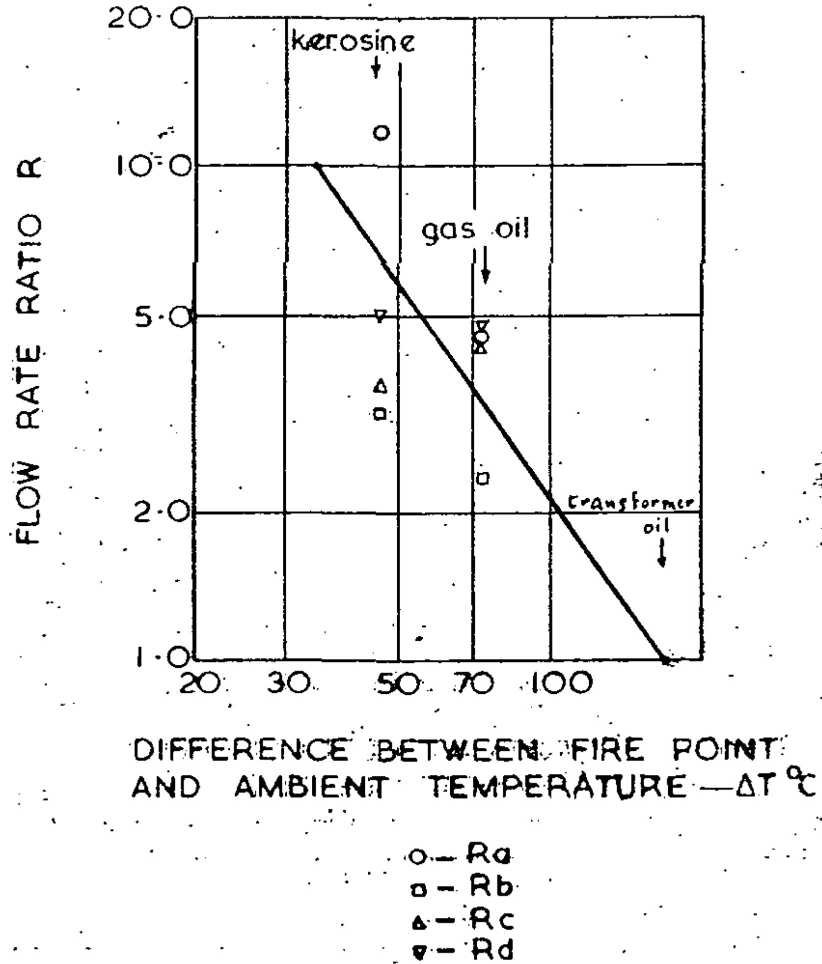


FIG. 4 EFFECT OF FIRE POINT OF OIL ON FLOW RATIO

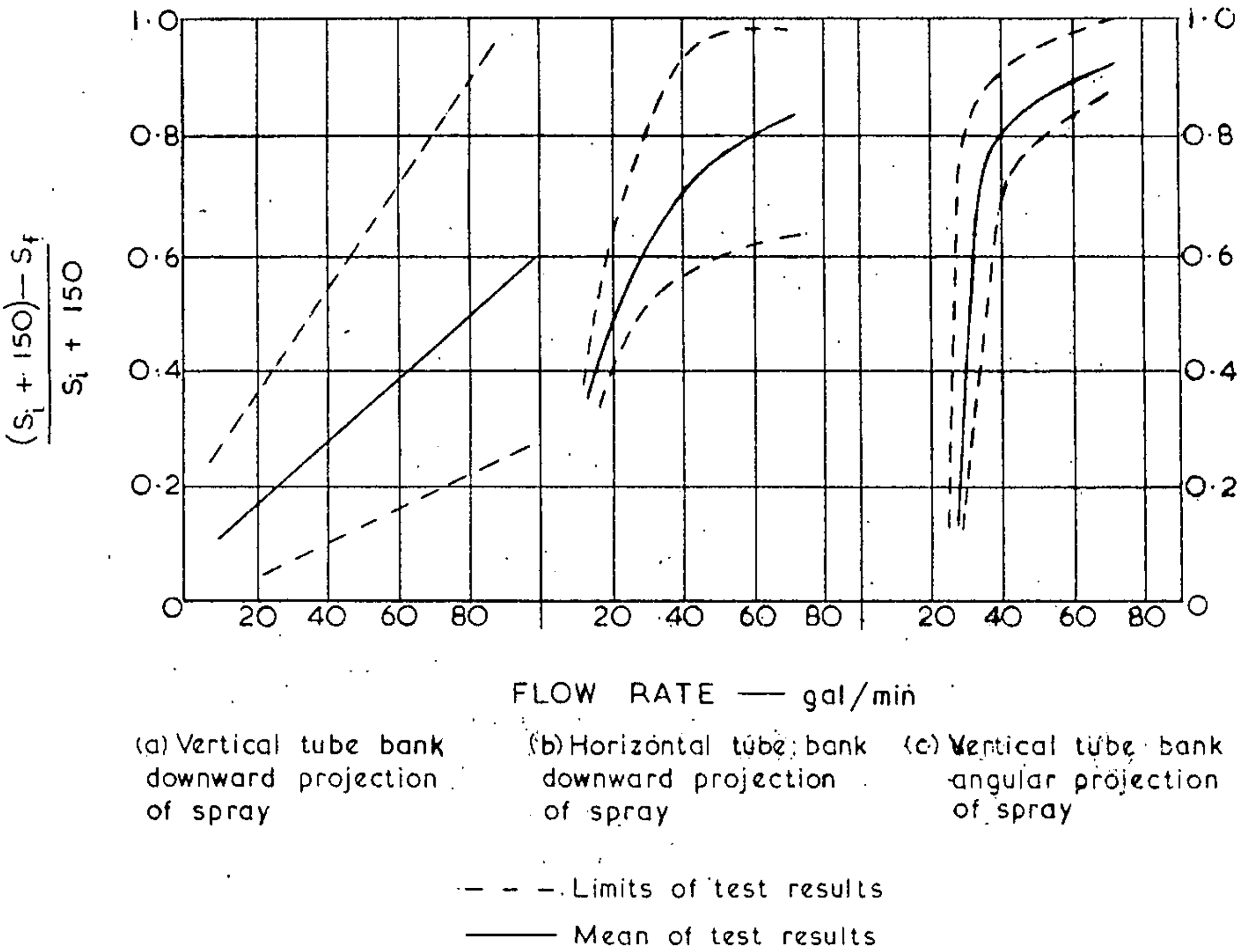


FIG.5. EFFECT OF FLOW RATE ON COOLING OF TUBE BANK TRANSFORMER OIL FIRES DIRECTIONAL NOZZLES OPERATED AT 90 Lb/in²

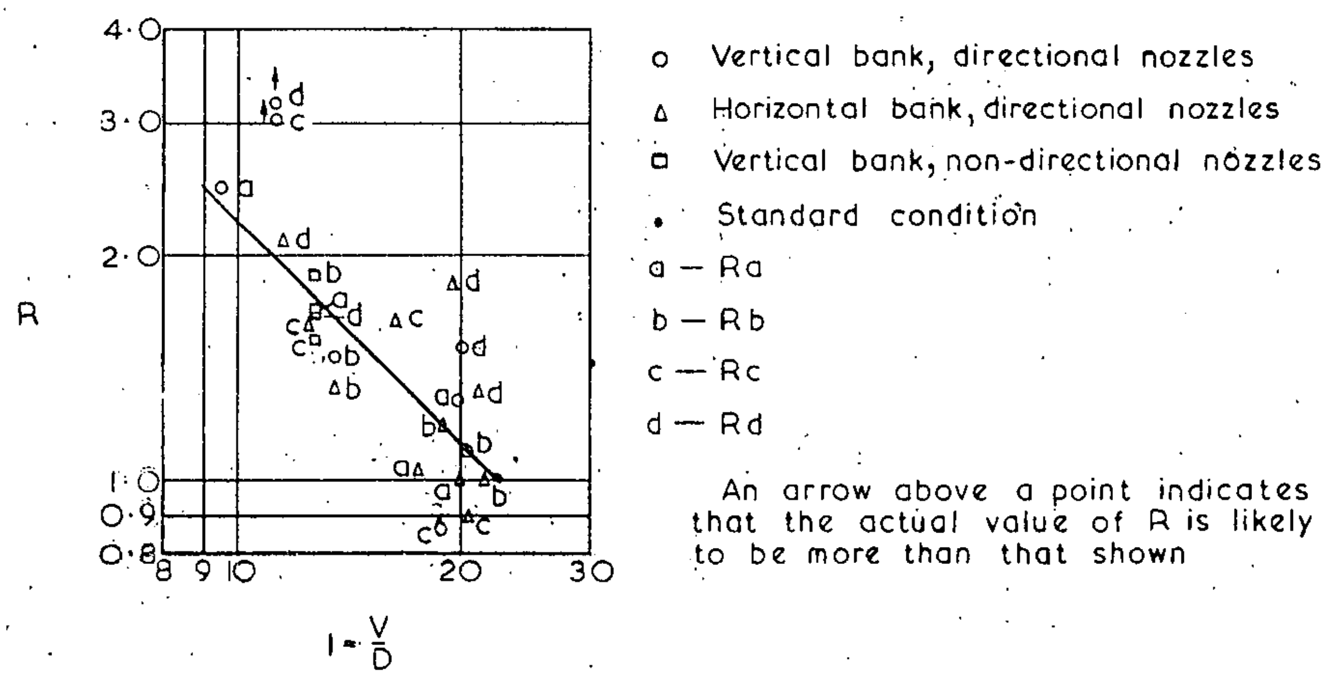


FIG. 6. RELATION BETWEEN FLOW RATE RATIO AND DROP VELOCITY/SIZE PARAMETER

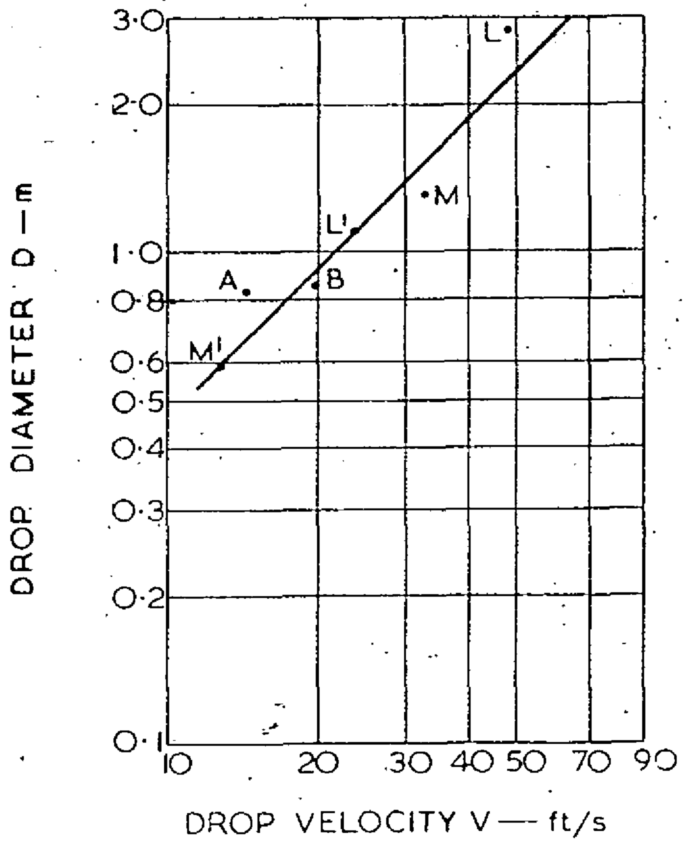


FIG. 7 RELATION BETWEEN DROP VELOCITY AND DROP SIZE.

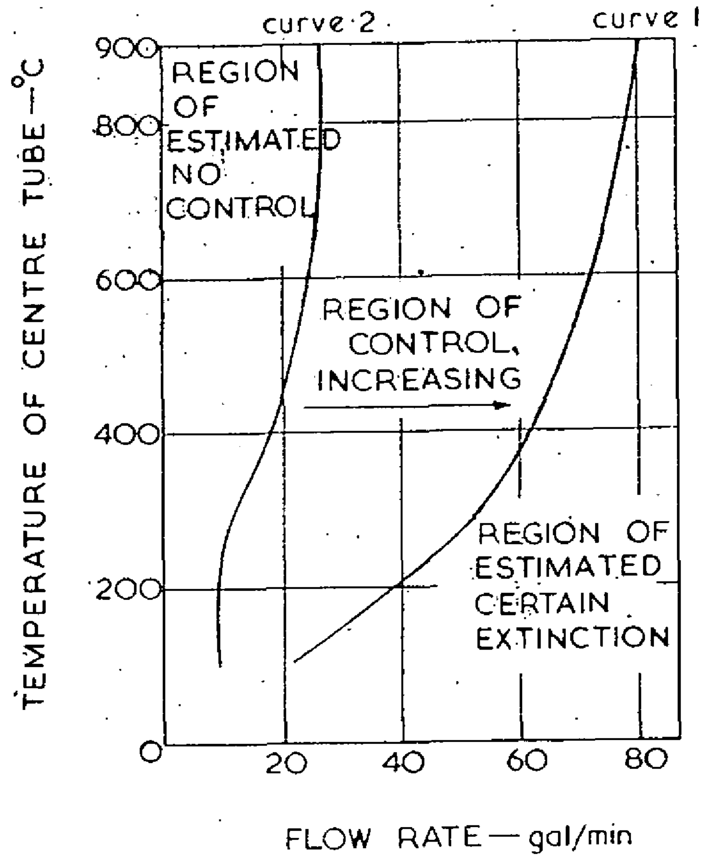


FIG. 8 CONTROL AND EXTINCTION OF TUBE BANK FIRES. LIMITING CURVES. TESTS UNDER STANDARD CONDITIONS.

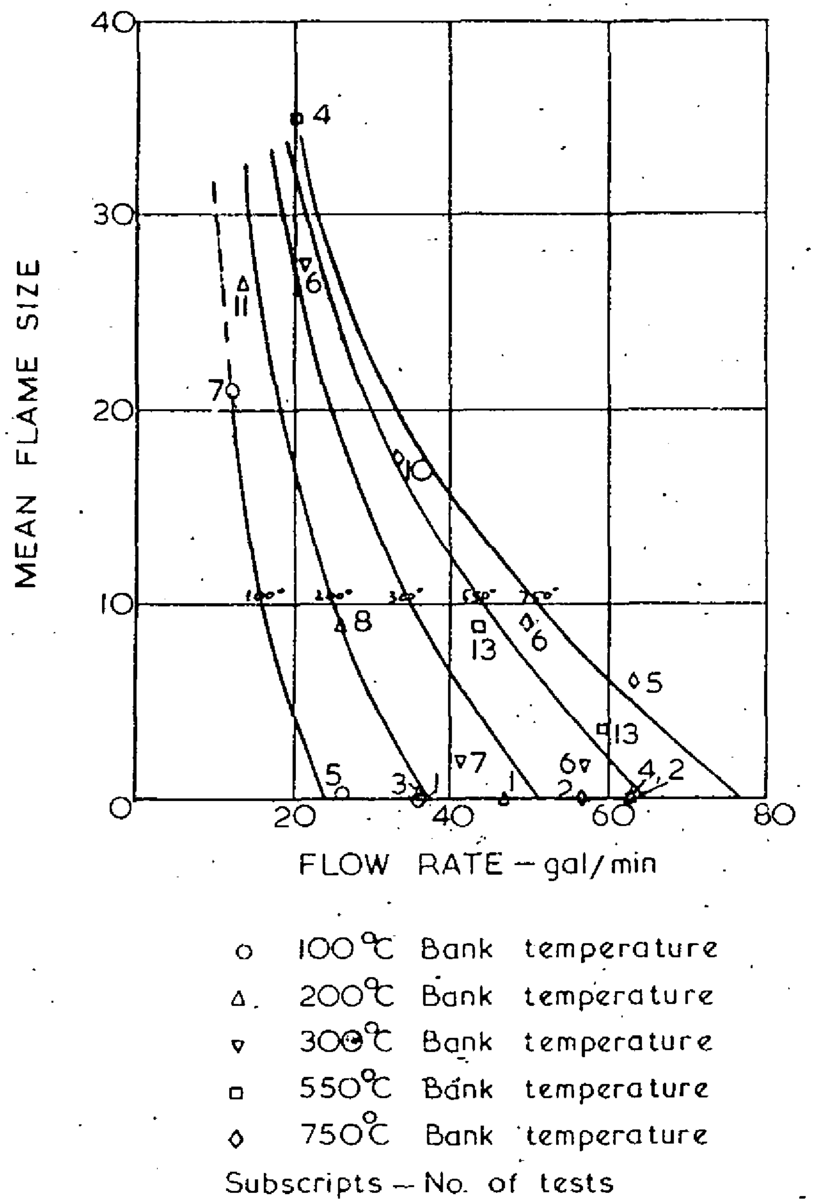


FIG. 9. RELATION BETWEEN FLOW RATE AND MEAN FLAME SIZE

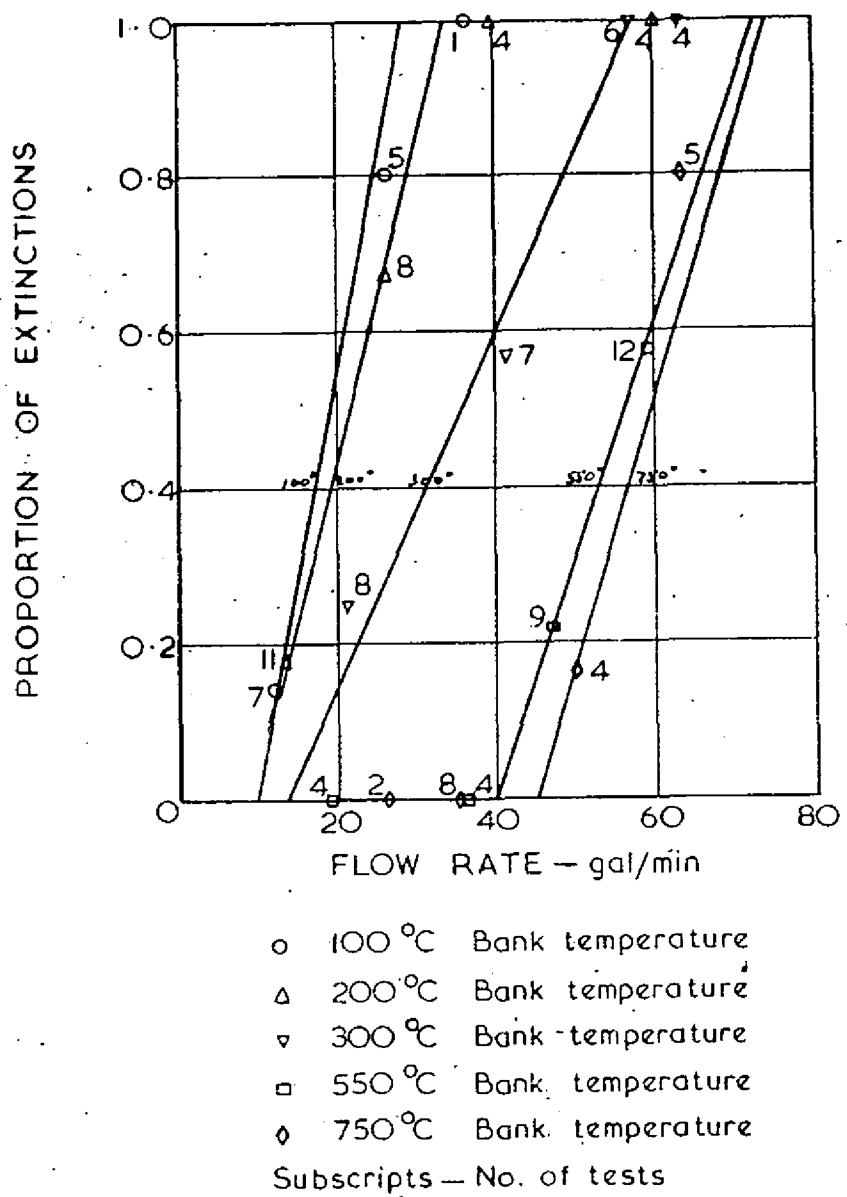
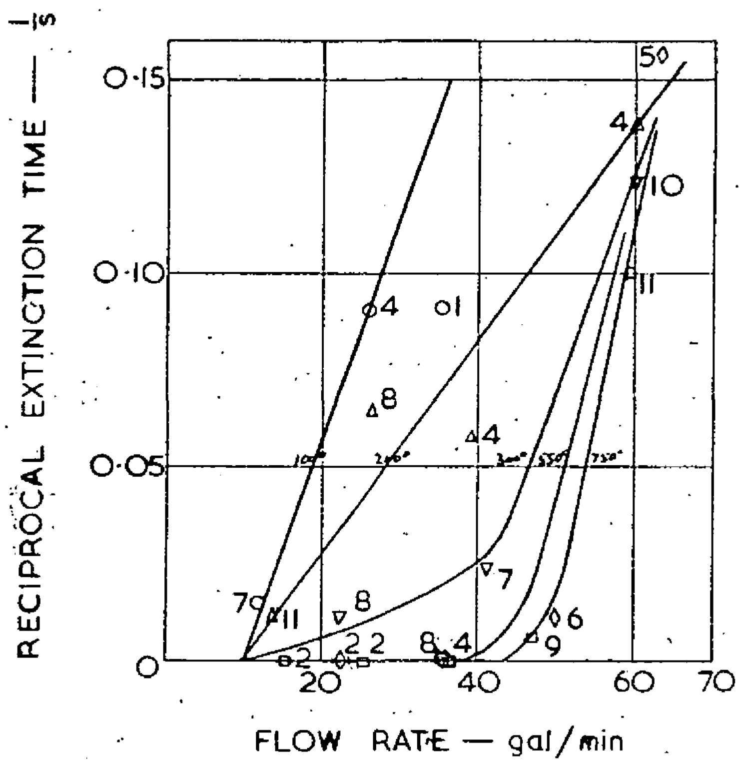
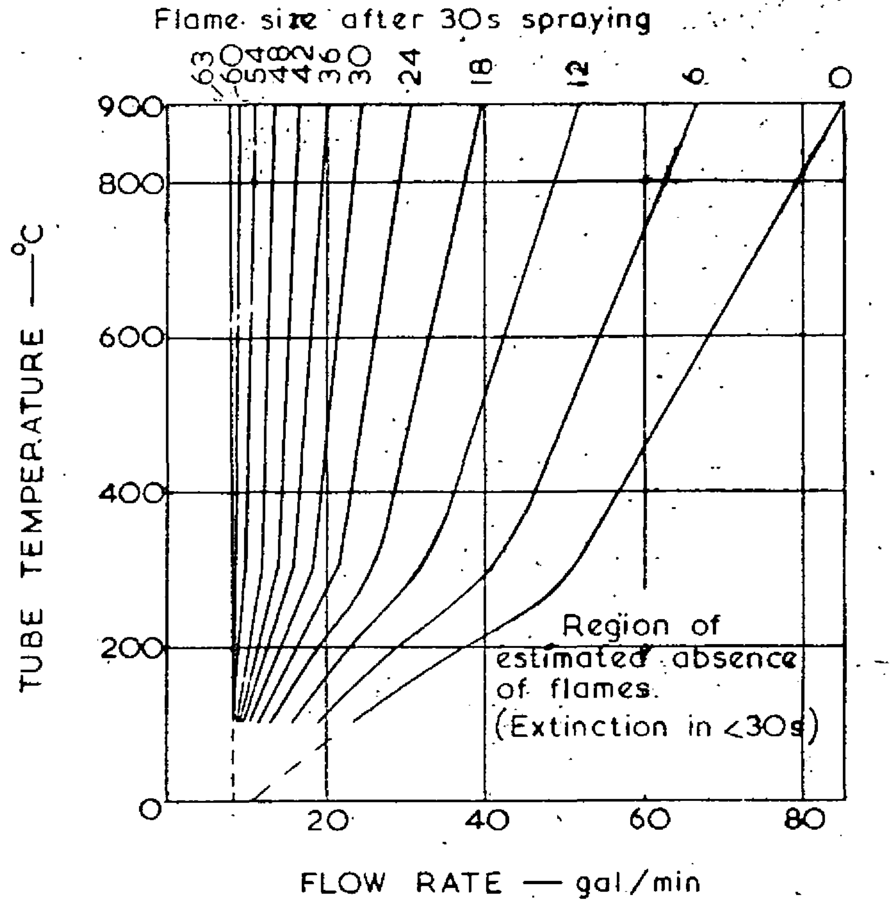


FIG. 10. RELATION BETWEEN FLOW RATE AND PROPORTION OF EXTINCTION



o 100°C Bank temperature
Δ 200°C Bank temperature
Δ 300°C Bank temperature
□ 550°C Bank temperature
◊ 750°C Bank temperature
Subscripts — No. of tests

FIG.11. RELATION BETWEEN FLOW RATE AND RECIPROCAL OF EXTINCTION TIME



Curves have been estimated for flame sizes > 30

FIG.12. RELATION BETWEEN TEMPERATURE, FLOW RATE AND FLAME SIZE STANDARD CONDITIONS

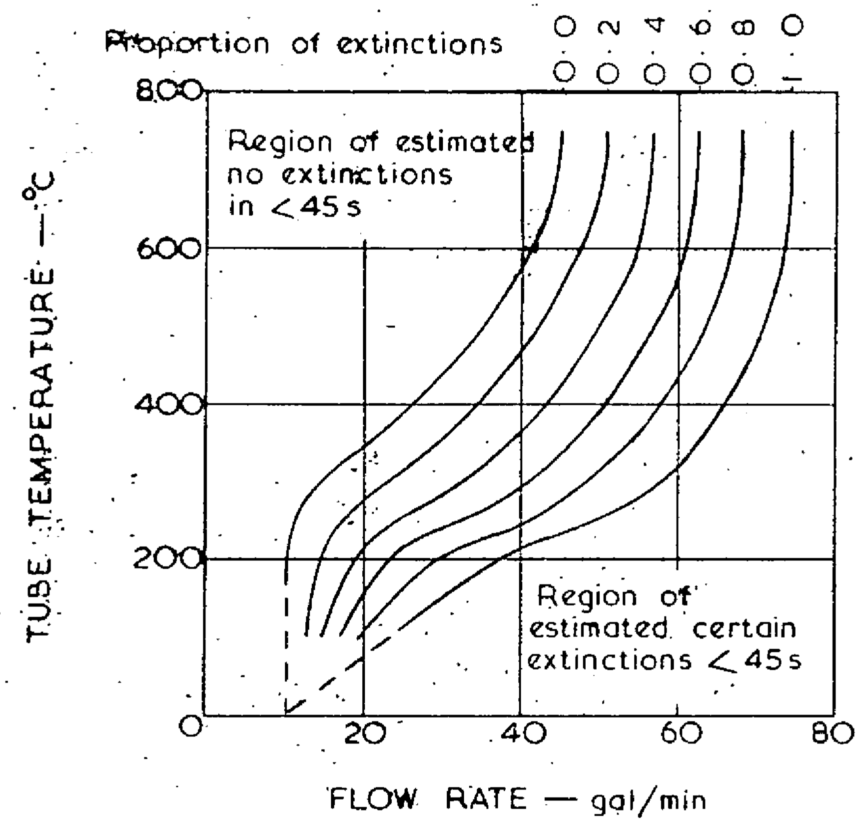


FIG.13. RELATION BETWEEN TEMPERATURE, FLOW RATE AND PROPORTION OF EXTINCTIONS

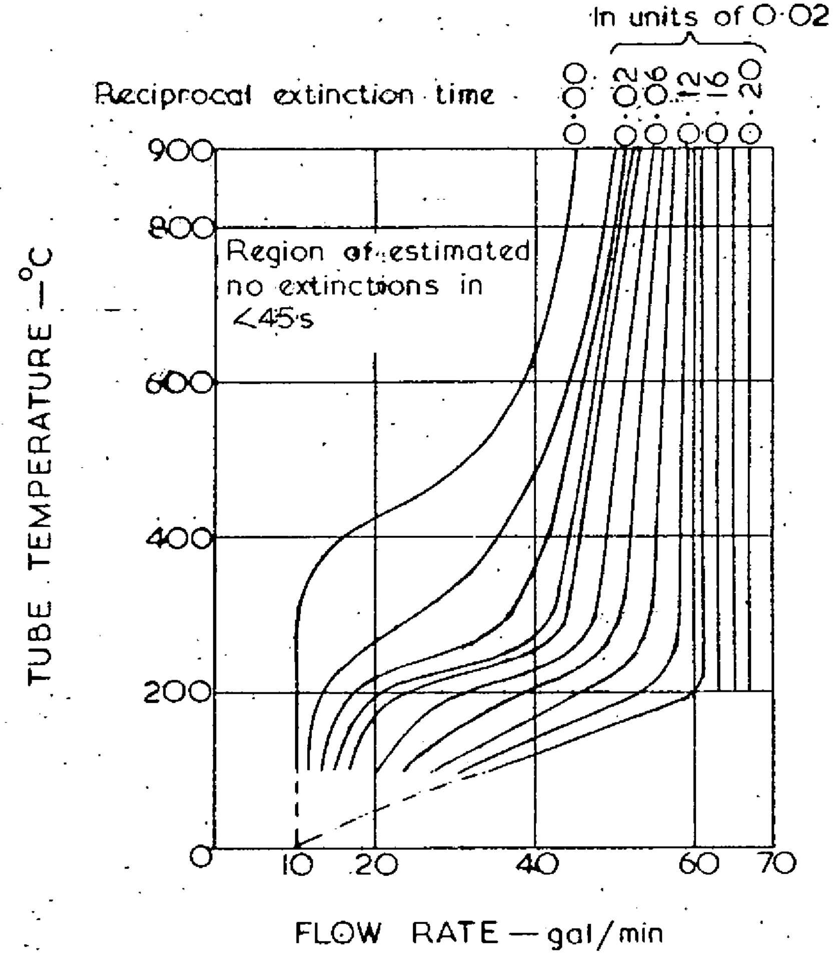


FIG.14. RELATION BETWEEN TEMPERATUR[E] FLOW RATE AND RECIPROCAL EXTINCTION TIME