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THE COOLING OF BURNING KEROSINE BY WATER SPRAYS

by

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Summary

Tests have been carried out in which water sprays, initially at room
temperature and ranging in drop sizes from 0.3 to 1.7mm and in delivery rate
from 0 - 2.0 g.cm$^{-2}$ min$^{-1}$ were applied to two kerosine fires burning in
vessels 11 and 30 cm diameter.  With the larger fire the pressure at which
the spray was produced varied between 5-85 lb/in$^2$.  In general the temperature
a little below the surface of the kerosine reached a steady value $\theta$ lower
than the temperature which would have been reached without spraying.  $\theta$
decreased as the flow rate reaching the kerosine surface increased.  The
flow rate required to reduce $\theta$ to the fire point, under which conditions
extinction took place, was approximately proportional to the drop size of
the spray and independent of the size of the fire.  $\theta$ did not depend notice-
ably on the pressure at which the spray was produced.  Some conditions of
spraying brought about a marked intensification of the fire by splashing and
gave rise to high values of $\theta$.  The phenomena observed have been discussed
on the basis of a heat balance between the heat entering the liquid from the
flames and the heat passing from the liquid to the spray drops.

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## Symbols

A   =   Surface area of liquid burning                            $L^2$

$A_1$ = Area of water drops in contact with oil           $L^2$

m   =   Rate of flow of spray per unit area reaching
burning surface during fire.                     $ML^{-2}T^{-1}$

h   =   Overall heat transfer coefficient between oil
and water.drops.                             $QL^{-2}T^{-1}\theta^{-1}$

t   =   Time                                           T

$C_1 C_1$ Constants

D   =   Mass median drop size of spray                  L

Ds = Mass median drop size of spray which caused
intense splashing.                                 L

H   =   Total heat transfer to surface of liquid      $QL^{-2}T^{-1}$

Ha = Heat transferred to liquid used to provide latent
heat for evaporating vapour.              $QL^{-2}T^{-1}$

Hb = Part of heat transfer to surface used to replace
sensible heat removed from liquid phase by
vaporisation at the surface temperature      $QL^{-2}T^{-1}$

Hs = Part of heat transfer to surface used to increase
sensible heat of liquid phase               $QL^{-2}T^{-1}$

K   =   Effective conductivity of oil            $QL^{-1}T^{-1}\theta^{-1}$

Ke = Eddy conductivity of oil                  $QL^{-1}T^{-1}\theta^{-1}$

P   =   Pressure                                 $ML^{-1}T^{-2}$

$\phi$   =   Temperature of water after passing through the
burning liquid.                                $\theta$

$\theta_m$ = A mean temperature of the water drops

$\theta$   =   Temperature of burning liquid near surface     $\theta$

$\theta_m$ = A mean temperature of the burning liquid       $\theta$

$\theta_s$ = Temperature in surface of burning liquid       $\theta$

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### Introduction

Water sprays have been used for many years in extinguishing fires in liquids, particularly in those liquids with fire points considerably higher than room temperature. However, little information is available which gives the effect of spray properties on the extinguishing efficiency or allows a basic understanding of the way extinction takes place. If the liquid has a fire point which is higher than the temperature of the water used, a possible mechanism of extinction is by cooling, since if the temperature at the vaporising surface is reduced to below the fire point, the fire cannot continue to burn. During the course of a series of investigations on the effect of water sprays on liquid fires, measurements were made on the temperature reached near the surface of burning kerosine when acted upon by water sprays of different properties. The results which are presented in this note allow a broad picture to be drawn of the way in which a burning liquid can be cooled and extinguished by water spray.

### Experimental

Two forms of apparatus were used, one with the fire burning in an 11cm. diameter vessel (fire A) and the other in a 30cm diameter vessel (fire B.) With fire A the sprays were produced with a battery of hypodermic needles (1), an apparatus giving a spray of fairly uniform drop size, placed 120 cm above the fire. With fire B two batteries of impinging jets (2) placed 170cm above the fire were used. Both these forms of apparatus could give a range of rates of flow of water spray of different drop sizes at the fire area; with the impinging jet apparatus the pressure at which the spray was produced could also be varied.

With both fires, before all tests the kerosine was present as a 6 cm. layer floating on water; the fire was allowed to burn for eight minutes and the spray was then applied either for a further twelve minutes, or until extinction if this took place sooner. During the whole test, the surface of the liquid was kept at a constant distance of 2.0 ($\pm$ 0.1) cm. below the top of the vessel by means of a levelling system. It was measured in most tests at points 5mm and 6 cm below the surface of the kerosine by means of copper-constantan thermocouple pencils which passed vertically upwards through the bottom of the vessel. In some tests, however, the upper thermocouple was placed in the surface of the burning liquid. These vertical thermocouple pencils had the disadvantage of giving low readings when there was a steep temperature gradient present in the oil, because of conduction along the pencil, and the corrections had to be applied in estimating the temperatures given in the results. With fire B, specially designed thermocouples were used (3), which read accurately in steep temperature gradients; in all tests these thermocouples were placed 3mm and 6.0 cms below the liquid surface. During the period of spray application the lower thermocouple was in the water layer below the kerosine.

The fire points of the kerosine as measured by the Cleveland open cup method (I.P. method 36/55), were 61°C and 58°C for the tests with fires A and B respectively, and under the particular conditions of the experiments the normal burning rates were 0.061 and 0.93 g.cm$^{-2}$min$^{-1}$ respectively. Further details of the properties of fire B have been given elsewhere (3). The water used for spray was initially at room temperature which varied from 13 – 23°C for the tests with fire A and 16 – 22°C with fire B.

In addition to measurements of temperature, the effect of the sprays on the rate of burning of the fire and on the fraction of water spray applied which penetrated through the flames and the kerosine layer were also determined. Details of the methods of measurement and the results have been given elsewhere (2, 4.)

## General Observations

In most tests the application of the spray brought about a reduction in the size of the flame. When coarse sprays were used there was usually a certain amount of splashing of the burning liquid into the flame; this augmented the rate of burning and also made the flame burn more brightly. At low flow rates of spray, fine sprays also produced a sputtering effect on the hot kerosine, but there was marked reduction in the amount of sputtering as the flow rate of these fine sprays increased. In those tests in which no extinction took place, fairly steady conditions were usually reached within 3 to 4 minutes of the beginning of application of spray. With some of the finer sprays, however, of drop size less than 0.5 to 0.6mm., occasional clearances of the flame over part of the area of the fire were observed during the application of the spray.

Tests in which extinction took place could be divided into two groups. In group 1 the flames were reduced gradually in size until in the last stages prior to extinction they existed either as small edge flames or as thin blue flames which moved rapidly about the liquid surface. After extinction the liquid was not reignited immediately when a lighted taper was placed near the liquid surface. The extinctions in group 2 were usually obtained with fine sprays and although there was a certain reduction of the size of the flames before extinction, the extinction was preceded by a sudden clearance of flame. The application of a lighted taper near the surface after extinction gave immediate reignition.

## Tests without extinction

Temperature readings. In those tests in which there was no extinction the temperature indicated by the thermocouple near the surface reached a fairly steady value after about 3 to 6 minutes of spray application. The temperature 6 cms. below the surface also tended to a steady value but quite often did not reach this during the 12 minutes in which the spray was applied. An example of a temperature-time record is shown in Figure 1.

Figures 2 and 3 show for fires A and B respectively, the relation between the mean temperature ($\theta$) reached below the surface of the liquid and the mean rate of flow of spray to the fire (m) for sprays of different drop size D. The temperature $\theta$ was the mean calculated over the last 5 minutes of the test and refers to a position 5 and 3 mm. below the surface for fires A and B respectively. In general, the temperature was fairly constant over the 5 minute period from which the mean was taken. The rate of flow m was the mean estimated from the amount of water collected below the kerosine layer after the test. According to the properties of the spray used the value of m varied between 20 and 90 per cent of the flow rate to the liquid surface in the absence of fire. m may be taken to be an estimate of the flow rate of spray which reached the liquid surface during the combustion of the fire and when the temperature below the surface was $\theta$.

Figures 2 and 3 show that for a given drop size D, $\theta$ was reduced as m increased and also in general for a given value of m, $\theta$ was reduced as D decreased. Figure 3 also shows that for given values of m and D, $\theta$ did not depend significantly upon the pressure at which the spray was produced; $\theta$ did not therefore depend markedly on the velocity with which the drops approached the burning liquid, which depended on the pressure.

A number of tests marked 'S' in Figure 3, representing tests in which intense splashing occurred, were excluded when drawing the best curves through the points for a given drop size. In these tests a higher value of $\theta$ was obtained than in tests with sprays of similar drop size and flow rate, but in which intense splashing was not produced.

Figure 4 shows the rate of flow required at different drop sizes to reduce the temperature $\theta$ near the liquid surface to given values. The curves were obtained by interpolation and extrapolation of the curves in Figures 2 and 3. Figure 4 shows that for given high values of $\theta$, m increased with D

N.B. All drop sizes referred to are mass median drop sizes.

but not very markedly at coarse drop sizes. However, as $\Theta$ was reduced, then for a given value of $\Theta$, m tended to become directly proportional to D throughout the whole range of drop sizes. Figure 4 shows that for a given drop size of spray, the flow rates required to reduce the temperature $\Theta$ near the surface to given values was similar for the two fires. However, above a value of $\Theta$ of about 70°C fire B required a slightly higher flow rate than fire A, but below this temperature fire A required a higher flow rate than fire B.

Figure 5 shows the temperature $\emptyset$ of the water which passed through the kerosine layer, as indicated by the thermocouple 60mm below the surface, plotted against the steady temperature $\Theta$ reached near the surface. Only those tests in which $\emptyset$ reached a steady value during the 12 minute period of spray application, have been included in Figure 5.

For a given value of $\Theta$ there was no significant difference between the value of $\emptyset$ obtained for the two fires and no distinction between the two fires has been indicated in Figure 6. The drop size of the spray had some effect on $\emptyset$. Above a drop size of 0.6 mm the temperature of the water decreased somewhat as the drop size of the spray was increased. However, against this trend, a number of points shown for sprays of drop size less than 0.6 mm diameter gave water temperatures somewhat less than those obtained for sprays of drop size between 0.6 - 0.9 mm. The former points represented sprays in which there were momentary clearances of flame during the application of the spray.

Height of flames. In the tests with fire B, visual observations were made of the height of the flames and these have been plotted in Figure 6 against the steady temperature $\Theta$ reached 3 mm. below the liquid surface. Most of the points in Figure 6 fall about one curve which shows that the flame height decreased as $\Theta$ decreased. This curve may be extrapolated back to a zero height of flame at a temperature $\Theta$ between 60 and 70°C. A number of the points fall well above the curve; in all the tests appropriate to these points intense splashing was observed.

Drop size of spray causing intense splashing. In the above results reference has been made to certain tests in which intense splashing occurred. Although most sprays gave rise to a certain amount of splashing, intense splashing was said to occur when the consumption of kerosine during the test was as great or greater than that occuring in the tests without spray. With fire A this happened when the drop size of the spray was greater than 1.5 mm. In this case the drops may be considered as merely having fallen from the hypodermic needles.

With fire B the drop size at which intense splashing occurred depended on the pressure at which the spray was produced and was given by equation 1.

$$D_s^3 \ P \ = \ 5.0 \qquad \text{------------(1)}$$

where P was the pressure from 5 - 85 lb/in$^2$ and D the "splashing" drop size in millimetres. If it is assumed that the velocity of the drops hitting the kerosine was proportional to the square root of the pressure, then equation 1 indicates that for intense splashing to occur, the kinetic energy of the drops had to exceed a certain constant value.

Extinction

The temperature at the moment of extinction as indicated by the upper thermocouple is given in Table 1 for group 1 extinctions.

## Table 1

### Temperature near surface at moment of extinction
### Group 1 Extinctions

| Fire | Distance of thermocouple below surface (mm) | No. of tests | Range of temperature at moment of extinction °C | Mean temperature at extinction °C | Fire point °C |
|------|------|------|------|------|------|
| A | 5 | 6 | 56 - 68 | 60.8) | 61 |
| A | 0 | 5 | 52 - 69 | 60.0) | |
| B | 3 | 7 | 61 - 69 | 63.5 | 58 |

These extinctions were achieved mainly by cooling the liquid to the region of the fire point; after none of them was immediate reignition achieved when a lighted taper was brought close to the surface. However, Table 1 indicates that with fire B the temperature near the surface at extinction was consistently slightly higher than the measured fire point; this may be ascribed to somewhat different heat transfer conditions between the 30 cm. vessel in which the extinctions took place and the 6.4 cm. vessel in which the fire point was measured.

With group 2 extinctions, the temperature at the moment of extinction was usually well above 80°C. These extinctions cannot be ascribed to cooling alone, and they will be discussed elsewhere.

In Figure 7, points have been plotted for both fires showing the relation between m and D for the group 1 extinctions and also for a number of tests in which a substantial amount of cooling took place without extinction.

For those tests in which there was no extinction the value of m plotted is as defined above. However, for those which did give extinction, the actual rate of flow in the absence of fire has been used. The reason for this is that these fires cannot be regarded as having reached steady conditions and in the last stages of burning the flames were so small as to have had an insignificant effect in reducing the rate of flow of spray to the kerosine. Curve (i) indicates the limit above which extinction took place. This curve may be compared with (ii) and (iii) which were obtained by extrapolating the curves relating the temperature and the flow rate shown in Figures 2 and 3 to temperatures of 60 and 63.5°C respectively; these temperatures are the mean liquid temperatures at extinction for the two fires as indicated by table 1. The fair agreement in positions between curve (i) and the curves (ii) and (iii) indicate that extinction by cooling to the fire point was in these tests an extension of a process of cooling to steady conditions, which took place when the fire was not extinguished. Curve 1 has been drawn as a single curve for the two different fires since the position of the extinction and non-extinction points do not warrant any distinction being made. For practical purposes, over the range of drop sizes considered (0.35 - 1.4 mm), the critical value of m (in $g.cm^{-2}min^{-1}$) to produce extinction is directly proportional to the drop size and is given by equation (2).

$$m = 1.55D \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

## DISCUSSION

The main results of the preceding experimental investigation may be summarised briefly as follows:

(1) The application of water spray at room temperature to burning kerosine can bring about extinction by cooling the burning kerosine if the flow rate of spray is above a certain critical value. This critical value decreases as the drop size of the spray decreases.

(2) Below this critical value of the flow rate, steady temperature conditions may become established with a temperature near the liquid surface above the fire point.

(3) There is little difference in the steady temperature produced near the surface of an 11 cm. and 30 cm. diameter kerosine fire by sprays of the same drop size and flow rate. There is also little difference in the critical rate for the two fires.

(4) When intense splashing is developed the flow rate required to produce a given steady temperature near the surface is higher than if there is no intense splashing.

(5) For a given flow rate of spray the steady temperature near the surface decreases with decrease in drop size, but does not depend markedly on the velocity of the drops.

Insufficient is known about the properties of fires to allow a quantitative interpretation of the data obtained. Most of the above results however can be accounted for qualitatively.

## Occurrence of steady temperature $\theta$.

The occurrence of a steady condition when the flow rate of water spray is below a certain value may be ascribed to a balance of heat entering and leaving the burning liquid. This balance is illustrated qualitatively in Figure 8. Curve (i) represents the heat transfer (H) from the flames to the surface of the liquid, as a function of the temperature at this surface. An explanation of the shape given to this curve will be given below but it will be seen that it stretches between the fire point and the steady burning temperature. Curve (ii) represents that part (Hs) of the total heat (H), which would normally be used in increasing the sensible heat of the burning liquid phase. The rest of H is used to provide the latent heat of vaporisation at the surface (Ha) and to balance the sensible heat (Hb) carried away from the liquid phase by the liquid vaporising at the surface. The total Ha + Hb is represented by curve (iii). If water spray of given properties at a certain temperature lower than that of the surface reaches the surface, then heat will be abstracted from the liquid at a rate which increases with the flow rate and the difference in temperature between the water and the liquid surface. This cooling action of the spray has been represented in Figure 8 by the cooling C1 to C5 which represent the rate of heat abstraction from the liquid at a number of flow rates, increasing from curves C1 to C5. At certain surface temperatures $\theta 1 - \theta 5$ curves C1 – C5 intersect curve (ii). At these temperatures the rate of heat loss from the liquid to the spray will equal the net heat gain from the flames, and steady conditions will result. Figure 8 shows a decrease of the steady state temperature as the flow rate of spray is increased and also the occurrence of a critical rate (with curve C5) which is capable of removing heat from the liquid at all the rates Hs, represented by curve (ii).

Figure 8 shows that the relative proportion of Hs to H varies from 0 at the steady burning temperature to almost unity at the fire point. The reason is that with most liquids, the sensible heat in the liquid reaches a constant value when the surface is at the steady burning temperature and all the heat which reaches the liquid surface is used in these conditions to provide latent heat of vaporisation at the surface (Ha) and to balance the sensible heat carried away from the liquid phase by the vaporising liquid (Hb). However, as the temperature at the surface is reduced the amount of vaporisation which takes place at the surface is also reduced and a correspondingly larger fraction of heat is used to increase the sensible heat of the liquid phase. At the fire point the temperature of the liquid surface is at its lowest value for maintaining a fire and the value of $H_A + H_B$ under these conditions is a minimum.

Effect of size of fire on $\theta$. A change in the dimension of the fire brings about a change in the heat transfer conditions from the flames to the surface. This heat transfer is due to both radiation and convection. Under conditions approaching steady burning without spray, the flames of a kerosine fire burning in a tank are large but separated from the liquid surface by a thick vapour zone, and radiation can account almost entirely for the heat transfer (3). An estimate of this radiation for the two fires A and B obtained from the measured rates of burning and the rate of heating of the liquid 20 minutes after ignition, was 0.20 and 0.30 cal $cm^{-2}Sec^{-1}$ respectively; the radiation from fire B was larger because of the larger flame. However, when the liquid temperature is near the fire point the flames are small and close to the

surface and the heat transfer is by convection. An estimate of the heat transfer under these conditions may be obtained from the results of certain experiments carried out by D. B. Spalding who passed kerosine at various rates over the surface of burners and measured the heat carried away by the kerosine and the rate of burning (5). From the data given it was estimated that just prior to extinction the heat transferred to the surface was 0.64 and 0.66 cal $cm^{-2}sec^{-1}$ for a spherical and vertical burner respectively. If it is assumed that the heat transfer under these conditions follows corresponding formulae for natural convection then the effective temperature of the flame close to the surface may be estimated from these data to be 1560°C. If it is further assumed that fires A and B used in these tests may be represented by flat horizontal plates facing upwards, then using the above temperature and the appropriate convection formula (6) the convection to the fires A and B may be calculated to have been 0.25 and 0.19 cal $cm^{-2}sec^{-1}$ respectively. Here the heat transfer for fire A is larger as the appropriate formula contains a - 0.25 power factor for the surface dimension. When the surface temperature is between the fire point and the steady state burning temperature there will generally be comparable contributions from both radiation and convection. It is not possible to state precisely what these contributions will be but they should take approximately the form shown in Figure 9. Because of an increase in flame height as the surface temperature increases (see Fig. 6.), the radiation increases as the surface temperature increases in the manner shown by curves Ra and Rb. However, convection shown as curves Ca and Cb will decrease as the surface temperature increases because of an increase in the outward flow of the vapour, and the development of a thick vapour zone. The total heat transfer for fires A and B will, therefore, be approximately as indicated by the curves A and B shown in Figure 9. It will be noted that these curves are quite close together and that they cross at a temperature not much higher than the fire point.

It may be assumed that the difference between $H_S$ and H will depend only on the surface temperature and not on the size of the fire. With this assumption, the curve for $H_S$ for the two fires would differ by the same amount as the curves for H. A spray with a given cooling capacity will therefore reduce the surface temperature of both fires to approximately the same value.

In the above experiments, although the temperature $\Theta$ was measured at a point a little below the surface, it was unlikely in most experiments to be more than 2 - 3°C less than the temperature in the surface. The above explanation can therefore account for the relatively small effect which the size of the fire was found to have on $\Theta$.

Effect of splashing on $\Theta$. Figure 6 shows that splashing causes an enlargement in the size of flames above the liquid for a given temperature near the liquid surface. It was also noticed that the flame was different in that the small flames burning about the fuel drops were much brighter than the background flame. The contribution of heat transfer by radiation from such a flame was therefore likely to be considerably greater than from flames in those fires at a similar liquid surface temperature in which there was not intensive splashing. The effect of this splashing would therefore be to displace the curves (i) and (ii) in Figure 8 upwards because of the extra radiation, and therefore would result in a larger flow rate of spray being necessary to reduce the temperature at the surface to a given value.

Effect of spray properties on $\Theta$. The effect of spray properties such as drop size and drop velocity is to vary the rate of heat abstraction from the liquid; this would alter the slopes of the cooling curves C1 - C5 in Figure 8. For a given temperature of the water at the surface and surface temperature of the liquid, variation in the spray properties can vary the rate of heat abstraction from the liquid by the water spray by bringing about a change in two main factors; $R_1$ the rate at which heat is transferred from the surface to the bulk of the oil and $R_2$ the rate at which heat is transferred from the bulk of the oil to the water drops. $R_1$ and $R_2$ may be expected to be given by equations (3) and (4).

$$R_1 = \frac{KA}{L} (\Theta_s - \Theta_m) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

$$R_2 = hA_1 (\Theta_m - \phi_m) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

where K = effective conductivity of oil
  A = cross sectional area of oil layer (area of burning surface)
  $\Theta_s$ = temperature in surface of oil

$\Theta_m$ = a mean temperature of the oil layer.

h = an overall heat transfer coefficient between the oil and water drops.

$A_1$ = total surface area of water drops in the oil.

$\emptyset_m$ = a mean temperature of the water drops.

L = a length dimension.

Under steady conditions $\Theta_m$ will assume such a temperature that

$$R_1 = R_2 = H_S A \quad . \quad . \quad ... \quad ... \quad ... \quad (5)$$

If L can be assumed to be a function only of the depth of the liquid, then with constant depth the rate of heat abstraction under steady conditions may be determined either by the effective conductivity K or the product $hA_1$ according to whether $\frac{KA}{L} \ll$ or $\gg hA_1$ respectively.

On the basis of available information estimates have been made on the way the spray properties affect K and $hA$ (see appendix). These estimates are summarised in Table 2.

## Table 2

Effect of spray properties on factors controlling abstraction of heat from oil by water sprays

| Factor | Exponent with drop size (D) | Exponent of drop velocity in oil (V) | Exponent of flow rate of water spray to unit area of oil (m) |
|---|---|---|---|
| Effective conductivity (K) | $D^{+1}$ | $V^{+2/3}$ | $m^{+\frac{1}{3}}$ |
| Heat transfer factor ($hA_1$) | $D^{-(1\frac{1}{2} \text{ to } 2)}$ | $V^{-(\frac{1}{2} \text{ to } 1)}$ | $m^{+1}$ |

It may be assumed that, unless intense splashing is developed, a given equilibrium temperature $\Theta$ obtained near the surface of the liquid, corresponds to a given amount of heat $(H_S A)_\Theta \emptyset$ which is transferred down into the liquid and is abstracted by water spray from the burning liquid; in particular, if a change in the properties of the spray does not change $\Theta$, then it does not change $(H_S A)_\Theta \emptyset$. It was found that for a given drop size and flow rate of spray, $\Theta$ did not depend on the initial velocity of the drops at the surface. Although the information in Table 2 refers to the velocity at a given point within the oil rather than at the liquid surface, this finding is concordant with the prediction in Table 2 that the rate of heat abstraction should vary between some power of V between (-1 and + 2/3), according to whether $hA_1$ or K is the controlling factor. Similarly, it was found that to obtain a given value of $\Theta$ the flow rate had to be increased by approximately the 0 - 1 power of the drop size, i.e. for a given rate of heat abstraction $mD^{0-1}$ was constant. From Table 2 it may be deduced that to obtain a given rate of heat abstraction if K is the controlling factor, $mD^3$ should be constant, but if $hA$ is the controlling factor, $mD^{-(1.5 \text{ to } 2)}$ should be constant; the experimental relationship between m and D lies between the two predicted theoretical relationships.

## Practical Implications.

A number of approximations have been made in the above analysis, and for this reason it can be expected to give only a broad interpretation of the observed phenomena.

However, if the analysis is accepted a number of consequences follow. For a given spray the critical rate for extinction by cooling the surface will depend mainly on two factors, the absorption of heat from the flames by the liquid and the difference in temperature between the spray and the liquid. The maximum heat absorption is likely to take place at a temperature slightly above the fire point; under these conditions a large fraction of the heat transfer is due to convection. An increase in the fire point of the burning liquid will have the effect of moving the whole of the curves (i') and (ii) in Figure 8 bodily to the right without having very much effect on the position of the curves C1 to C5. As a result the critical flow rate will decrease. The imposition of a wind will have the effect of increasing the heat transfer from the flames to the liquid near the fire point; this should bring about an increase in the critical rate of flow. A wind would also reduce radiation from the flames by reducing the size of the flames above the fire; this effect, however, is unlikely to be important unless the spray is such as to cause a large splashed oil flame in the absence of wind. An increase in size of the fire is unlikely to have much effect since the reduction of heat transfer by convection would tend to be balanced by the increase in heat transfer due to radiation.

At flow rates slightly greater than the critical flow rate it would be expected that the extinction times would be long. In none of the tests described in this report in which extinction was obtained by cooling was the extinction time less than four minutes. However, if the flow rate is increased to values considerably greater than the critical flow rate, then a corresponding decrease in extinction time would be expected. This aspect of extinction has been discussed in greater detail elsewhere.

## References

(1) Rasbash, D. J. J. Sci. Inst. 1953 30 p. 189 - 192.
(2) Rasbash, D. J. and Rogowski, Z. W. D.S.I.R. and F.O.C. F.R.Note No.58.
(3) Rasbash, D. J. Rogowski, Z. W. Stark, G. Fuel 1956, 35, 94.
(4) Rasbash, D. J. Skeet, G. D.S.I.R. and F.O.C. F.C.Note No. 41.
(5) Spalding, D. B. Fuel, 1950, 29, p. 25.
(6) Fishenden M. and Saunders, O. A. Introduction and Heat Transfer. F.R. Note No. 204. Oxford 1950, Clarendon Press.
(7) W. Ranz, and A. R. Marshall. Chem.Eng. Progress 1952.
(8) L. Prandtl. Essentials of Fluid Dynamics, London 1954. Blackie & Son, Ltd.
(9) R. V. McDowell and J. V. Myers. A.I.Ch.E. Journal 1956, 2 p. 384.
(10) H. Kramers. Physica 1946. 12

## Appendix

Effect of spray properties on K and hA1.
Effective conductivity K.

For practical purposes, the spray drop size is of the order 0.3 to 2.0 mm and the drops approach the oil with a velocity of 500 - 1000 cm/sec. This velocity is so high that the drops in the oil are initially well within the range of the turbulent law of frictional resistance.

$$\frac{V dV}{dx} = \frac{dV}{dt} = -0.33 \frac{\rho_o}{D \rho_w} V^2 + g \left(1 - \frac{\rho_o}{\rho_w}\right) \qquad \dots \qquad \dots \qquad (1)$$

where $V$ = drop velocity $\rho_o$ = oil density, $\rho_w$ = water density g = acceleration due to gravity.

During most of the deceleration the second factor on the right hand side of equation (1) is small compared with the first and may be neglected.

Also within the range of the turbulent law of resistance, the resistance of the oil may be considered as being due entirely to form drag, so that in deceleration, the energy in the drop is given to the oil as kinetic energy rather than as heat. A motion of the oil is therefore established which probably takes the form of eddies arising from the impact and deceleration of each drop. This motion gives rise to an eddy conductivity of the oil $K_e$ which can increase enormously the total effective conductivity.

If molecular conductivity is neglected then $K_e$ will be given (9) by equation 2.

$$K_e = c_0 \rho_0 \, l u \quad \text{or} \quad K \propto l u \qquad \ldots \quad \ldots \quad \ldots \quad (2)$$

where $C_0$ $\rho_0$ are the specific heat and density of the oil and l and u are respectively the mixing length and velocity of the eddies. The velocity u is such, that the rate at which energy is imparted to the unit volume of oil by the retarding water spray drops $\left(\frac{dE_w}{dt}\right)$ is equal to the rate at which the eddies are dissipated as heat by friction within unit volume of oil $\frac{dE_0}{dt}$.

The energy $E_w$ of the spray drops within unit volume of oil is proportional to the product of the mass of drops within unit volume and the square of the velocity of the drops.

$$E_w \propto \frac{m}{V} \cdot V^2 \propto m V \qquad \ldots \quad \ldots \quad \ldots \quad (3)$$

(since the mass of drops per unit volume is equal to the flow rate of drops per unit area (m) divided by the drop velocity.)

$$\therefore \quad \frac{dE_w}{dt} = \frac{d(mV)}{dt} = m\frac{dV}{dt} \qquad \ldots \quad \ldots \quad \ldots \quad (4)$$

From equation (1) $\frac{dV}{dt}$ ~ proportional to $\frac{V^2}{D}$

$$\therefore \quad \frac{dE_w}{dt} \sim \quad m\frac{V^2}{D} \qquad \ldots \quad \ldots \quad \ldots \quad (5)$$

The rate of dissipation of turbulent eddies has been given by Prandtl (9).

$$\frac{dE_0}{dt} \propto \rho_0 \frac{u^3}{l} \qquad \ldots \quad \ldots \quad \ldots \quad (6)$$

Equating (5) and (6) gives

$$m\frac{V^2}{D} \propto \rho_0 \frac{u^3}{l} \qquad \ldots \quad \ldots \quad \ldots \quad (7)$$

$$\therefore \quad u \propto m^{\frac{1}{3}} V^{\frac{2}{3}} l^{\frac{1}{3}} D^{-\frac{1}{3}}$$

Substituting for u in equation 2 gives

$$K \propto m^{\frac{1}{3}} V^{\frac{2}{3}} l^{\frac{4}{3}} D^{-\frac{1}{3}} \qquad \ldots \quad \ldots \quad \ldots \quad (8)$$

Since the eddies are formed from moving drops it would be expected from dimensional considerations that the mixing length 1 would be proportional to the drop size D. Making this substitution in equation 8 gives:

$$K_e \propto m^{\frac{1}{3}} V^{\frac{2}{3}} D \qquad \ldots \quad \ldots \quad \ldots \quad (9)$$

An appropriate estimate of the order of the value of K may be obtained from the information on the rate of heat abstraction given in Fig. 8 and the temperature drop across the whole oil thickness given in Fig. 5. This estimate shows that K would be of the order of 0.1 C.G.S. units compared with a molecular conductivity of about $3 \times 10^{-4}$ units. This suggests that the eddy conductivity $K_e$ given above may be equated to the effective conductivity K.

Factor for heat transfer to drops $hA_1$.

McDowell and Myers have shown (10) that when water drops fall through oil the predominant resistance to heat transfer is the resistance of the film outside the drops. Under these conditions it might be expected that a relationship given in equation (10) similar to that found for the evaporation of water drops in air (8) or the heating of steel spheres in a fluid (11) would control the heat transfer from oil to drop.

$$Nu = C + C_1 (Re)^{\frac{1}{2}} \qquad \cdots \quad \cdots \quad \cdots \quad (10)$$

Where $Nu$ = Nusselt No. = $\dfrac{hd}{k}$

and $C$ and $C_1$ are constants which may be a function of the Prandtl Number.

$Re$ = Reynolds No. = $\dfrac{Vd\rho}{\mu}$

On the basis of equation (1) it may be shown (11) that the product $hA_1$ will vary with the spray properties in the manner shown in equation (2).

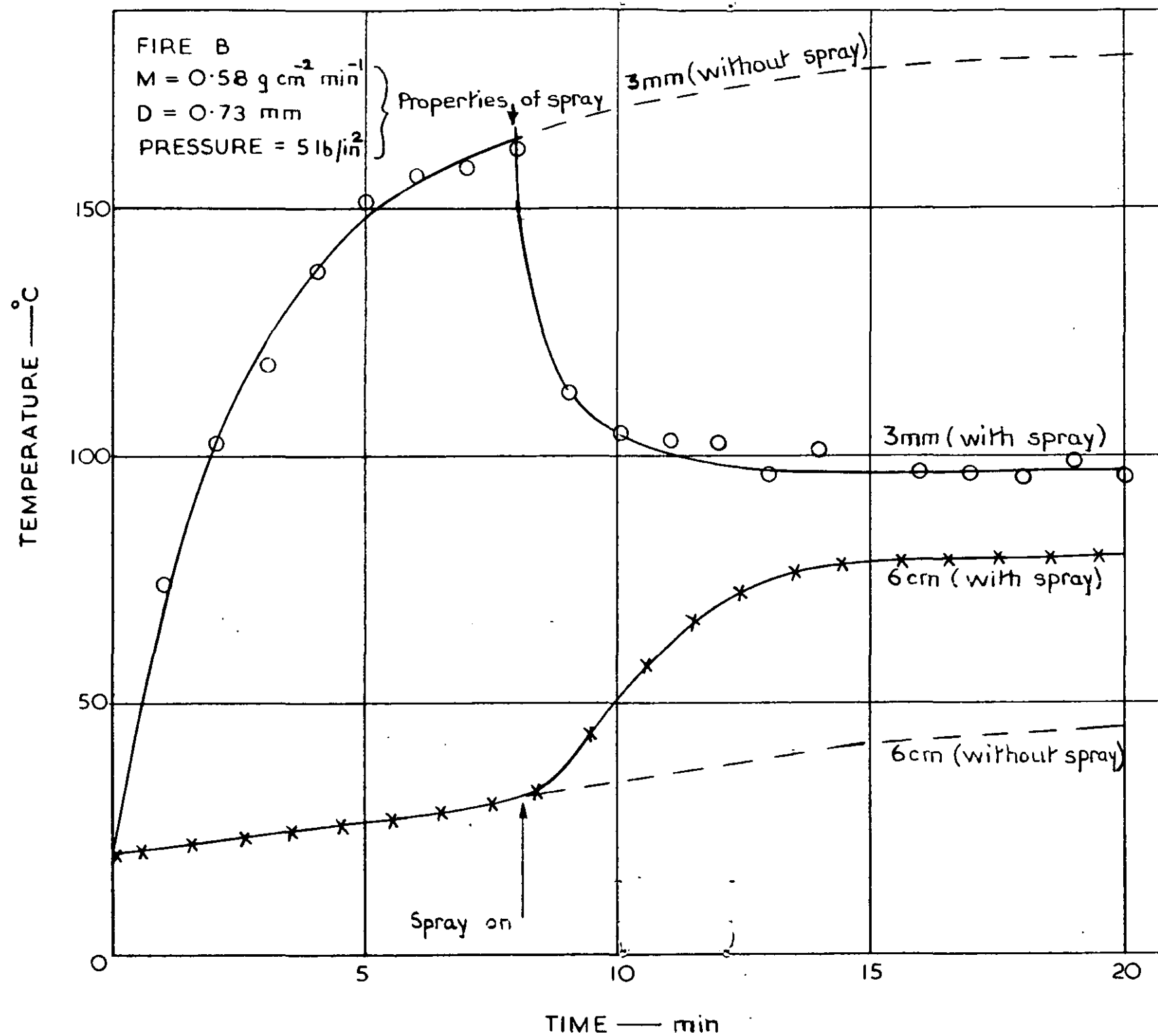$$H = mV^{-(\frac{1}{2} \text{ to } 1)} D^{-(1\frac{1}{2} \text{ to } 2)}.$$

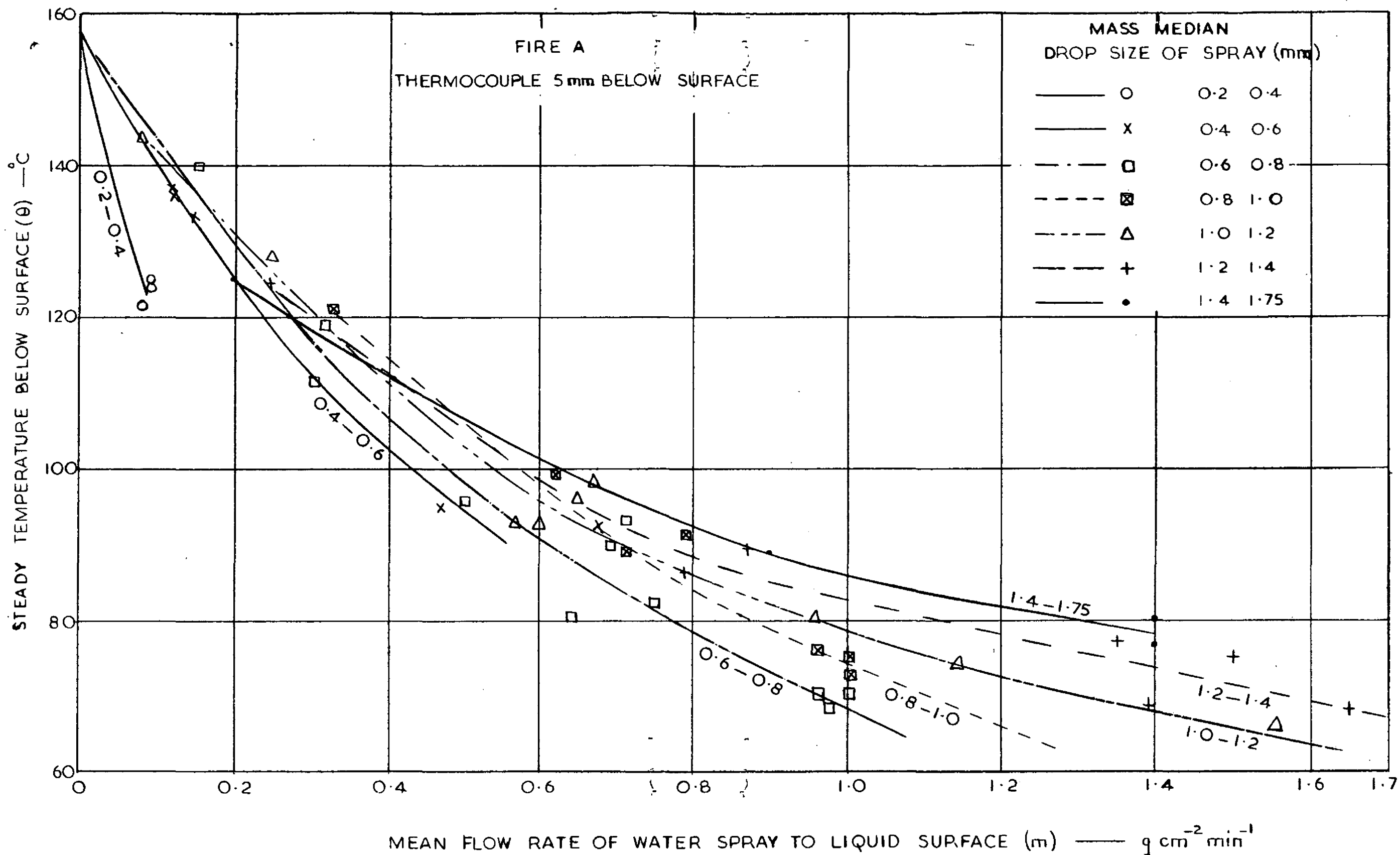FIG.I. EFFECT OF A WATER SPRAY ON THE TEMPERATURE BELOW THE SURFACE OF BURNING KEROSINE

FIG. 2. TEMPERATURE BELOW LIQUID SURFACE AGAINST FLOW RATE
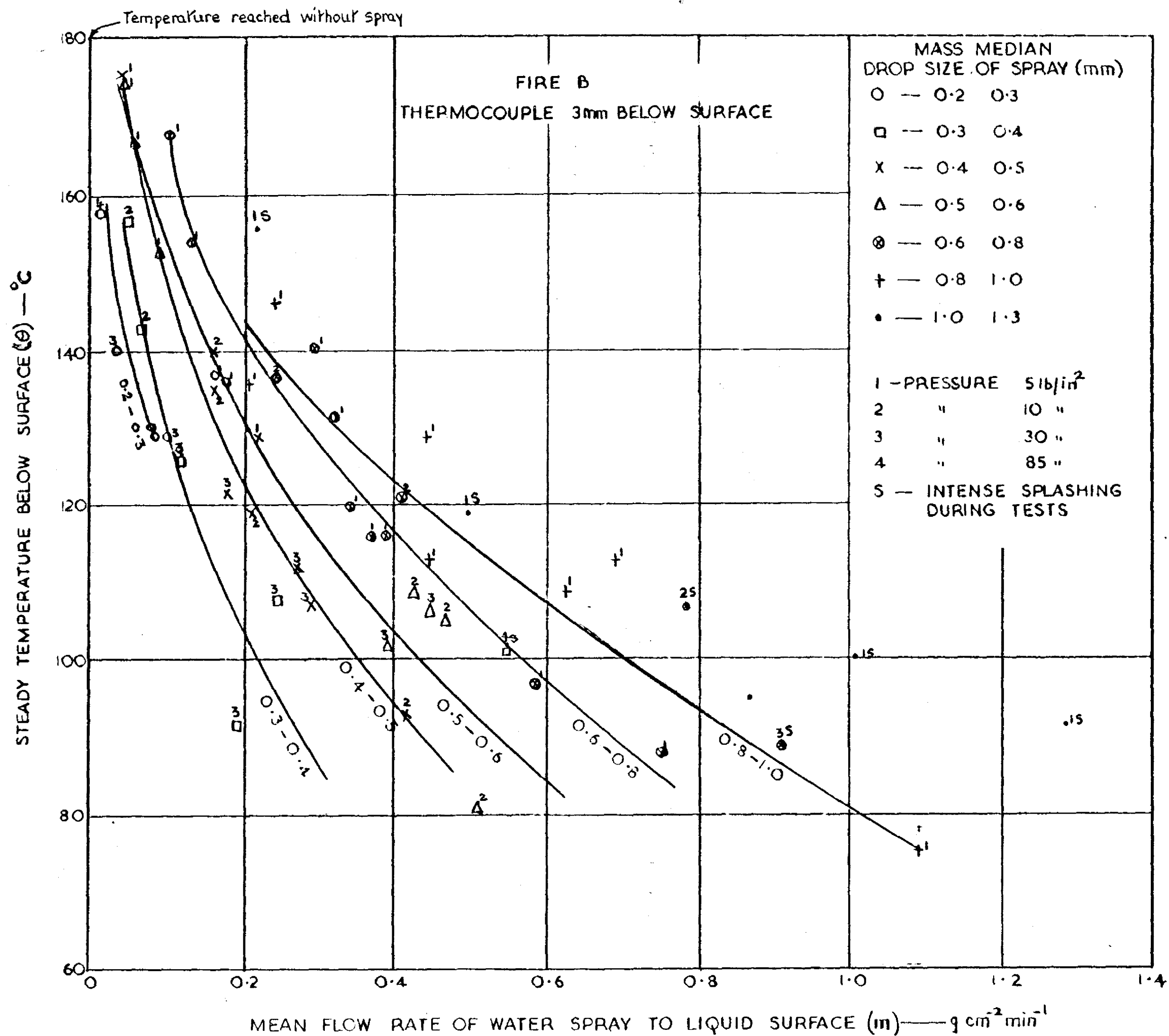OF WATER SPRAY

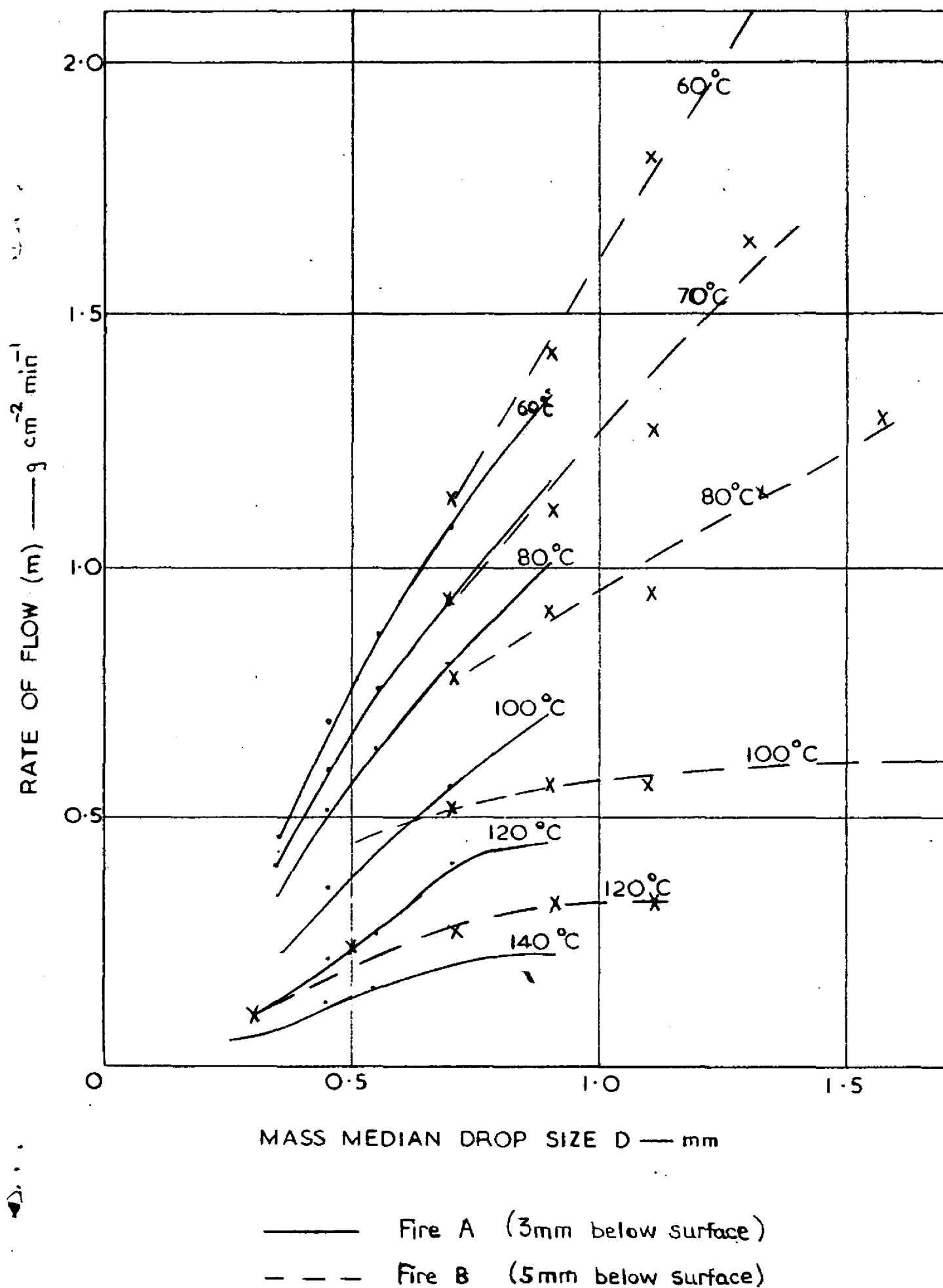FIG. 3.  TEMPERATURE BELOW LIQUID SURFACE AGAINST FLOW RATE OF WATER SPRAY

FIG. 4. RATES OF FLOW REQUIRED TO COOL
SURFACE LAYERS OF BURNING
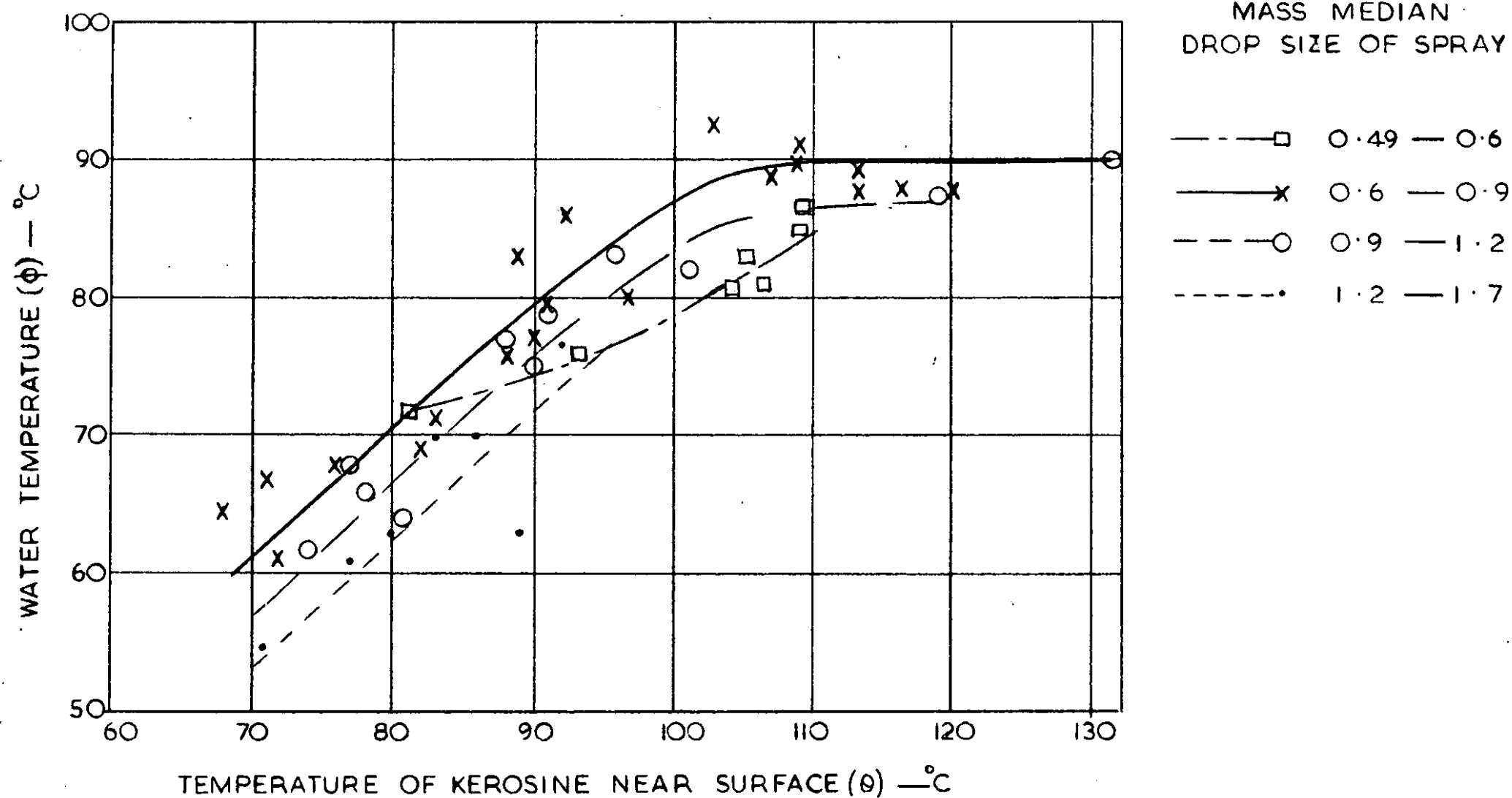KEROSINE TO DIFFERENT
TEMPERATURE

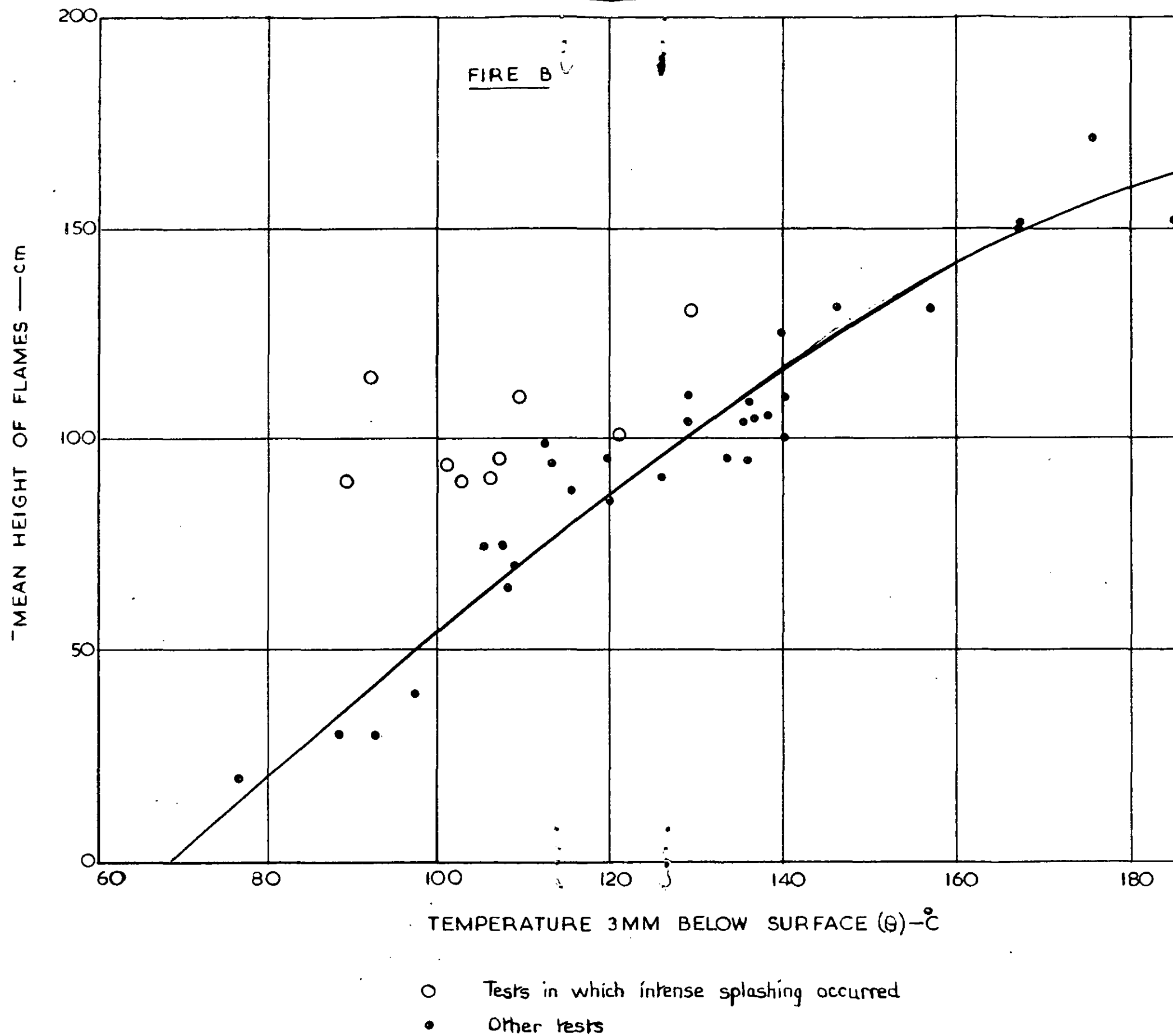FIG. 5. TEMPERATURE OF WATER SPRAY AFTER PASSING THROUGH BURNING KEROSINE

FIG. 6.  RELATION BETWEEN HEIGHT OF FLAMES AND STEADY TEMPERATURE NEAR THE SURFACE
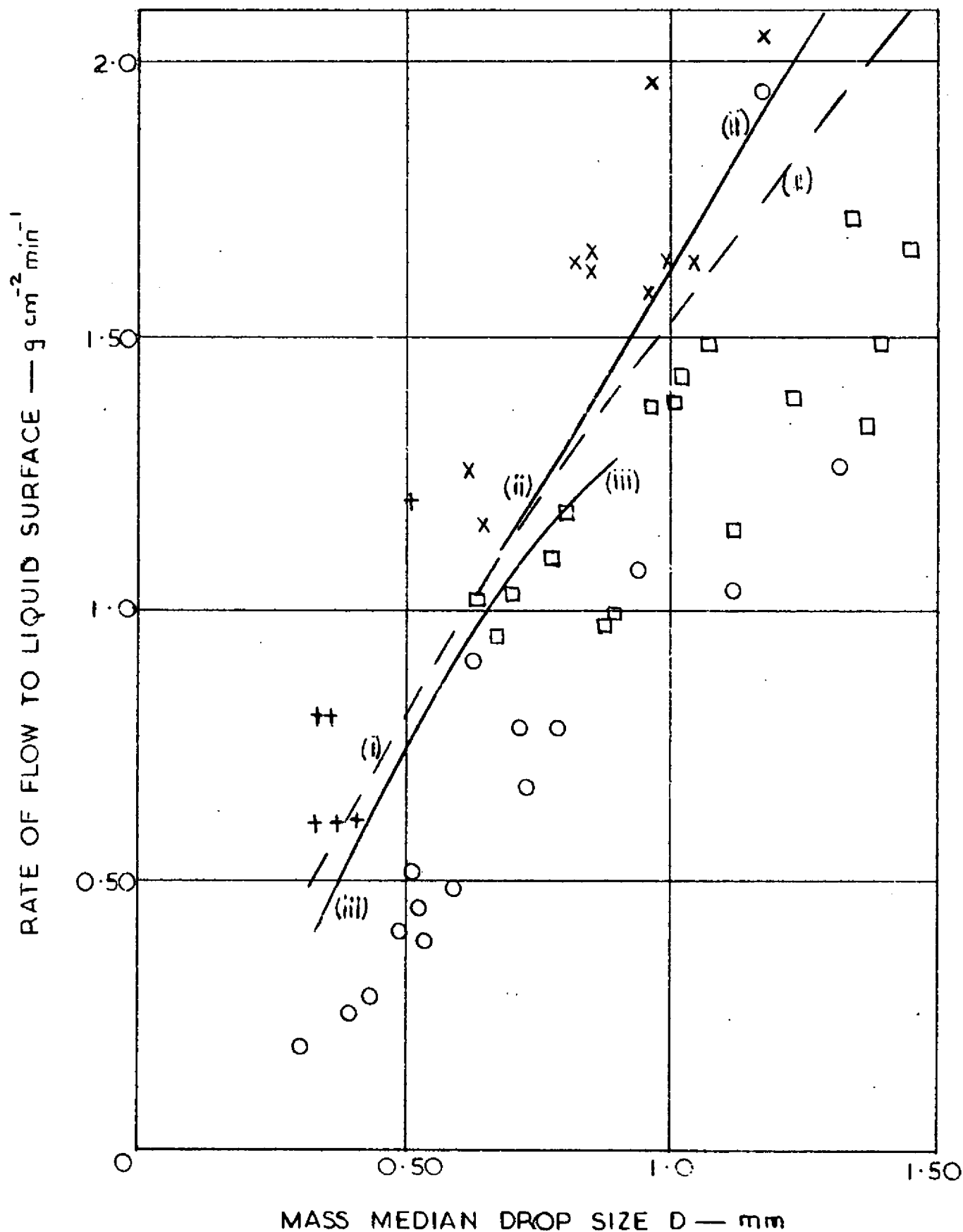
| | | |
|---|---|---|
| X | Fire A | extinction |
| + | Fire B | extinction |
| □ | Fire A | no extinction |
| O | Fire B | no extinction |

(I)  Limiting curve between extinction and non extinction

(II) (III)  Extrapolated curve for cooling to extinction temperature for fires A and B respectively

FIG. 7. RELATION BETWEEN m AND D FOR EXTINCTION BY COOLING

**Y-axis label:** HEAT TRANSFER TO AND FROM LIQUID PER UNIT AREA OF SURFACE (arbitrary units)

**X-axis label:** SURFACE TEMPERATURE OF BURNNG LIQUID

**Labels within figure:**
- (i) H
- (iii) Ha + Hb
- (ii) Hs
- θ5, θ4, θ3, θ2, θ1
- c5, c4, c3, c2, c1
- Increasing flow rate of spray
- Temperature of water at surface
- Fire point
- Steady burning temperature

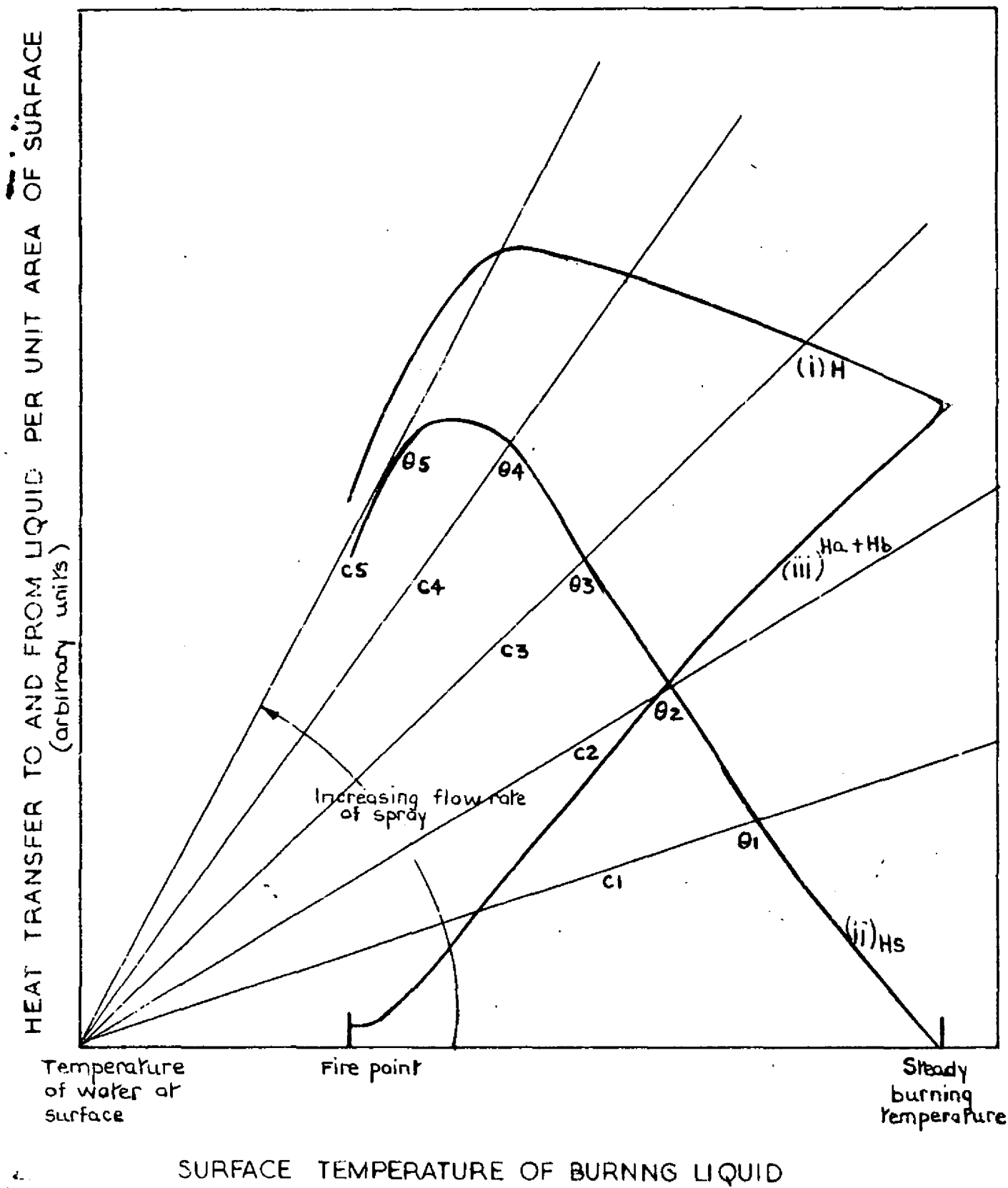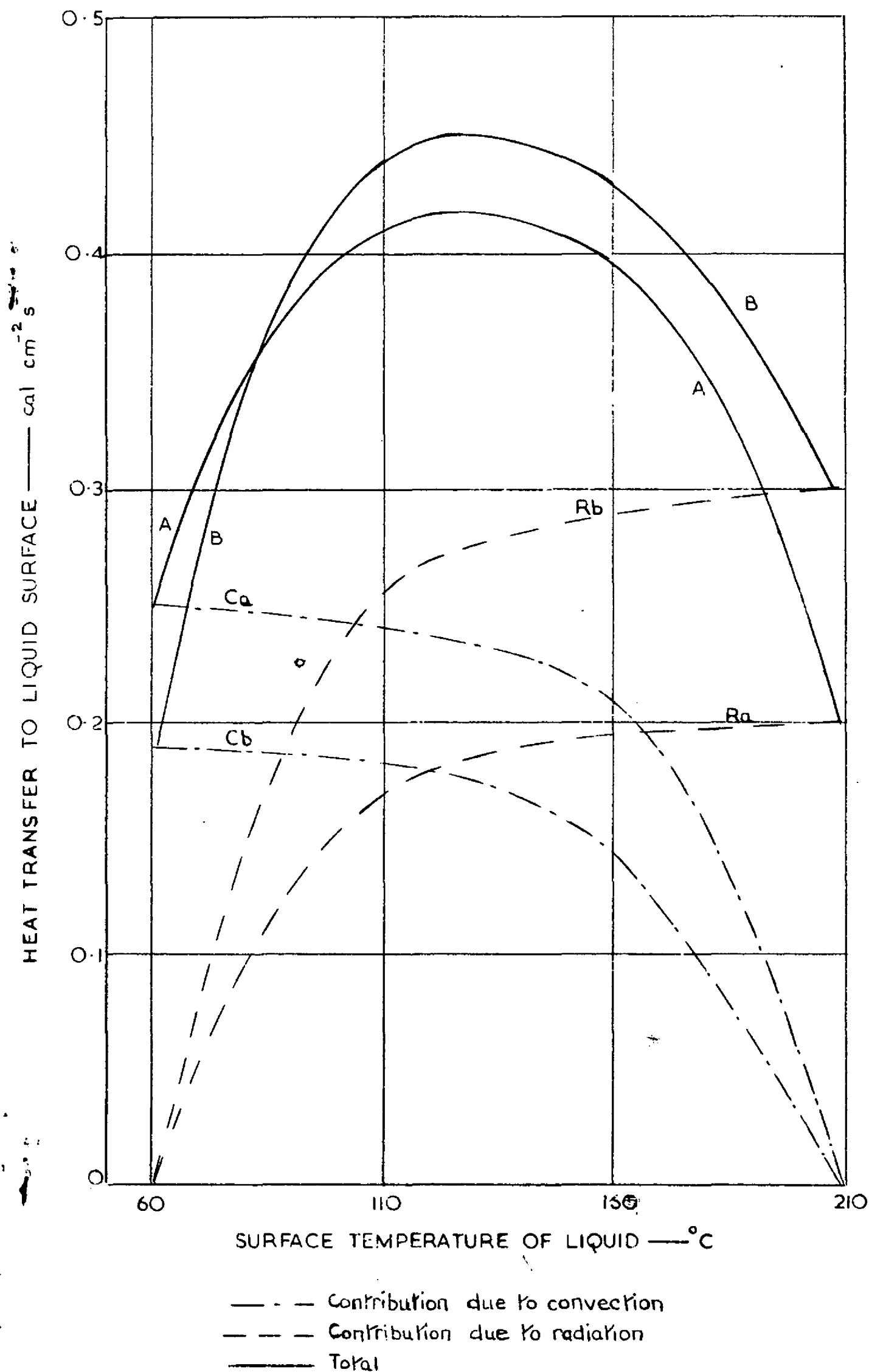## FIG.8. HEAT BALANCE IN BURNING LIQUIDS SPRAYED WITH WATER

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FIG 9 ESTIMATED HEAT TRANSFER TO THE
SURFACES OF FIRES A AND B