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THE EXTINCTION OF OPEN FIRES WITH WATER SPRAY

PART II

The effect of drop size of spray on the extinction of different liquid fires

by

D. J. Rasbash and Z. W. Rogowski

SUMMARY

Tests have been carried out to determine the effect of
three water sprays of different drop sizes on six liquid
fires.   The liquids were alcohol, benzole, petrol, kerosine,
gas oil and transformer oil.   The sprays had a rate of flow
to the fire area of 1.6 g $cm^{-2}min^{-1}$ and the drop sizes were
0.28, 0.39 and 0.49 mm.   It was found that the finest spray
was best for extinguishing the more volatile liquids, but the
coarsest spray was best for the less volatile liquids.   The
results suggest that the main mechanisms of extinction of the
fires were

(1) cooling the liquid to below the firepoint,

(2) smothering the flame by formation of steam
     at the hot burning liquid,

(3) extinction of the flame either by steam
     formation in the flame or cooling,

(4) for alcohol, by dilution.

The finest spray used, which was found effective against
volatile liquids, is finer than fire fighting sprays in
general use.   Methods of reducing the drop size of fire
fighting sprays are discussed.

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Introduction

In Part I (1) an account was given of the effect of sprays with a wide range of properties on the burning and extinction of a kerosine fire 30 cm diameter. This work has now been followed by experiments with three sprays on a number of different liquid fires. The three sprays were of such properties as to give an estimate of the effect of the drop size of the spray on its extinguishing efficiency.

Experimental

Apparatus

The apparatus used was identical to that described in Part I. The liquids burned in a vessel 30 cm diameter with an ullage of 2 cm, and the sprays were produced by two batteries of impinging jets placed 5 ft. 9 in. above the vessel.

Liquids tested

Six liquids were tested, alcohol (industrial methylated spirit) benzole, petrol, kerosine, gas oil and transformer oil, The main properties of these liquids and the fires they produced are given in Table I. The methods of measuring the properties of the fires have been given elsewhere (2) Fig. 1 and 2 show the alcohol and benzole fires after burning two minutes; these liquids gave respectively the smallest and largest flames.

Sprays tested

Tests were carried out with three sprays, all produced at a pressure of 85 Lb/in^2, and a rate of flow to the fire area of 1.6 g cm^{-2}min^{-1}. The properties of the three sprays are given in Table II. Two of the sprays, A and B, were produced by nipples containing 0.8 and 1.6 mm (1/32 and 1/16 in.) jets respectively. For the third spray no nipples were placed in the nipple holders of the impinging jets producing the sprays; this gave a jet diameter of ca 2.8 mm (7/64 in.) the mean internal diameter of the threaded nipple holder. The measurement of drop size, rate of flow and entrained air velocity were made in the manner described in Part I. The spatial pattern measurements were also made as described in Part I. The figure assigned to spatial pattern in Table II was obtained by dividing the mean rate of flow to the central portion by the mean rate of flow to the whole fire area and gives an indication of the extent to which there was either a peak or a trough in the pattern at the centre of the fire area. Table II shows that the main difference between the sprays was in drop size, the drop size increasing as the size of the jets producing the sprays increased. Spray C, however, had a somewhat larger entrained air velocity and a smaller spatial pattern factor than the other two sprays. Spray C was also different from the other sprays in that it gave a higher rate of flow to areas outside the combustion vessel. This is illustrated in Fig. 3 which shows the rate of flow per unit area of the three sprays at points along a horizontal line 30 cm directly above the centre of the combustion vessel. It will be seen that on those parts of the line which extended beyond the combustion vessel the rate of flow per unit area with spray C was greater than with the other two sprays.

Table I

PROPERTIES OF LIQUID FIRES

Liquid	Specific gravity	Boiling range °C	Properties of fire 30 cm diameter			
			Amount of priming for ignition	Rate of burning after 8 minutes preburn g/min	Temperature 1 mm below the surface after 8 minutes preburn °C	Mean temperature of the flames (by Schmidt method) °C
Alcohol	0·79	77-79	))Direct)))ignition	56	66	1218
Benzole	0·88	79-84		240	84	921
Petrol	0·76	30-200		96	108	1026
Kerosine	0·80	155-277	10 cc hexane	58	188	990
Gas Oil	0·84	214-350	10 cc "	53	238	n.d.
Transformer oil	0·87	295-393	40 cc "	49	282	n.d.

n.d. = not determined

Table II

Properties of sprays used

Rate of flow $1.6g$ $cm^{-2}min^{-1}$ $(0.33$ gal $ft^{-2}min^{-1})$

Spray Designation	Jet size		Mass median drop size mm	Spatial pattern factor	Entrained air velocity	
	mm	$1/64$ in.			cm sec^{-1}	ft sec^{-1}
A	0.8	2	0.28	1.02	344	11.3
B	1.6	4	0.39	1.04	338	11.2
C	2.8	7	0.49	0.89	376	12.4

Programme of tests

The main programme of tests consisted of two tests with each liquid at preburning time of 2, 5 and 8 minutes with each of the three sprays. This gave a total of 108 tests. Further tests were also carried out with spray C on kerosine and petrol. The temperature 1 mm below the surface was recorded continuously during the period of application of the spray by means of a thermocouple connected to an amplifier-pen recorder system with a response time of about $\frac{1}{4}$ second. In some of the tests with spray C, the change in electrical conductivity at a point 1 mm below the liquid surface was measured during the period of spray application; the object of this was to test for the formation of oil in water emulsion.

In all tests in which extinction occurred the spray was stopped immediately. In half the tests a lighted taper was applied 5-10 mm above the surface to test for reignition, and in the other half a sample of liquid was taken from a layer within one centemetre of the surface and examined. These operations were usually carried out within 2-3 seconds of extinction.

RESULTS

Extinction time

Table III shows the extinction time in the duplicate tests carried out with the three sprays on the six different liquids at preburning times of 2, 5 and 8 minutes. Table III also indicates whether the liquid was cooled to the fire point by the application of the spray.

In general the extinction time decreased as the volatility of the liquids decreased. With the aid of statistical analysis the following points of detail were also established.

(1) With benzole, petrol and alcohol the extinction time decreased from spray C to B to A i.e. with increasing fineness. There was no significant effect of the time of preburn on the extinction time. Fig. 4 shows the geometric mean extinction time of the six tests with each spray and each liquid plotted against the drop size of the spray.

(2) With kerosine at a preburn time of 2 minutes the extinction time decreased from C to B to A and at 8 minutes preburn from B to A to C, i.e. at two minutes preburn time the finest spray was best and at 8 minutes the coarsest was best. With spray A the extinction time increased as the time of preburning increased.

Table III

Extinction time (seconds) of different liquids with water sprays

Spray	Preburn time (min)	Replicate	Alcohol	Benzole	Petrol	Kerosine (fire point 60–68°C)	Gas oil (fire point 104–115°C)	Transformer oil (fire point 175–180°C)
A	2	a	8·6	6·1	9·3	1·6	5·4	3·6 [x]
		b	1·4	9·7	10·6	3·2	2·4	3·6 [x]
	5	a	15·4	14·0	12·4	5·8	5·5	7·5
		b	1·6	11·5	10·0	6·5	6·6	6·0[x]
	8	a	1·7	3·5	16·0	7·9	7·9	7·4
		b	1·3	14·2	8·6	7·3	8·6	9·2
B	2	a	89·2	46·1	59·0	24·2[x]	4·2	3·2[x]
		b	163	47·9	49·6	21·4[x]	6·0	3·4[x]
	5	a	217	169	39·8	9·5	6·2	7·0
		b	254	52·0	45·2	7·8	9·0	6·5
	8	a	80·0	39·2	10·6	10·2	7·8	9·1
		b	160	70·0	46·6	10·5	8·6	7·2
C	2	a	510	>240	215	46·4[x]	14·4[x]	2·8[x]
		b	465	>240	249	54·7[x]	2·6	4·3[x]
	5	a	475	>240	152	6·8	3·4	3·2[x]
		b	509	2·1	235	301[x]	5·4	3·2[x]
	8	a	525	211	2·2	5·6	2·6	2·6[x]
		b	509	71·0	158	4·5	4·2	3·4[x]

[x] Liquid cooled to the fire point at extinction.

[ẋ] Liquid cooled to the fire point in a few seconds after extinction and removal of spray.

(3)   With gas oil and transformer oil at preburn times of 5 and
8 minutes the most rapid extinction was obtained with the coarsest spray C.
At the preburn times of 2 minutes there was no significant difference
between the extinction times with the different sprays. The extinction
time increased with time of preburn for sprays A and B.

In a number of tests shown in Table II the replicates gave quite
different extinction times.   This was especially so with spray C on
benzole, petrol, kerosine and gas oil at preburn times of 5, 8, 5 and
2 minutes respectively.   With kerosine and gas oil the liquid was cooled
to the fire point in those replicates with long extinction times. This
irregularity was further investigated by a series of additional tests on
kerosine with spray C, with preburning times of $\frac{1}{2}$ to 12 minutes. The
results of these tests are shown in Fig. 5. The extinction times fell
about two curves according to whether the liquid was cooled to the fire
point during the spray application.   Five further tests were also
carried out with spray C on petrol at a preburn time of 8 minutes.   Four
of these tests gave extinction times of 8, 19, 57 and 164 seconds; one
test did not give extinction within an application time of 480 seconds.
It was noted in all tests with spray C on petrol and benzole that on
first applying the spray the flames were pushed about over a large volume,
and moments when there was clearance of flame alternated with moments
when there were bursts of flame.   After 10-20 seconds application,
however, the flames would become established as a flat flame streching
across the vessel in the manner shown in Fig. 6.   The extent of the
disturbance during the initial period seemed to increase as the preburn
time increased and it was during this disturbed period that the occasional
rapid extinction occurred.   When the flat flame was established there
were random but infrequent partial clearances of the flame; an example of
such a clearance is shown in Fig. 7.   Extinction when it occurred usually
followed from one of these clearances.

Temperature of liquid

Typical temperature records obtained in the tests are shown in
Figs. 8 and 9.   After applying the spray there was a lag period of
0-4 seconds which was usually followed by a sharp drop in temperature.
The rate of drop in temperature varied widely even between replicate tests.
In Fig. 10 the drop in temperature which occurred within 2 seconds after
the lag period has been plotted against the temperature of the burning
liquid just before the application of the spray. This temperature
increased as the volatility of the liquid decreased and as the time of
burning increased.   Fig. 10 shows that for the hydrocarbon liquids the
rate of temperature drop increased as the temperature near the surface
increased and was greater for spray C than either sprays A or B.   For
alcohol, the temperature drop was greater that that which would have been
expected from the relationship for the hydrocarbon liquids.   In most
experiments the rate of drop in temperature decreased as the time of
application of the spray increased i.e. as the temperature near the liquid
surface was reduced.   In those tests with volatile liquids where a
prolonged application was necessary before extinction the temperature passed
through a minimum and increased again before reaching a steady value
(Fig. 9).

Reignition

Reignition was tested in replicate tests (b) shown in Table II.
In every test with the hydrocarbon liquids where the temperature had not
been reduced to the fire point and where a layer of froth had not formed
on the surface, immediate reignition occurred. With the gas oil and
transformer oil fires a layer of froth would often form after removing
the spray.   No inflammation occurred when the taper was held above the
froth layer.   However, as soon as the froth was touched by the lighted
taper it would ignite and burn easily.   The burning froth would then
ignite the liquid below it if it had not been cooled to the fire point.
In tests where the liquid had been cooled to the fire point it did not
reignite immediately and usually the liquid did not reignite even when
touched by the burning taper.   The spray A replicate (b) extinctions

with alcohol were all very rapid extinctions in which the fire appeared to be snuffed out; immediate reignition occurred when the taper was brought near the surface. The extinctions of the alcohol fire with sprays B and C, however, were much slower and the burning taper was held in place from 3-20 seconds before reignition occurred.

Composition near the liquid surface

In most of the replicate (a) tests, samples were taken after extinction from the top layers of the liquid. For the hydrocarbon liquids all the samples consisted of a suspension of water drops in the liquid, with occasional samples showing some turbidity. Vigorous boiling usually persisted for some time in samples taken from gas oil and transformer oil.

The water content of the samples are shown in Table IV; those for hydrocarbons were obtained by a centrefuge method and for the alcohol by measuring the density. With the hydrocarbon liquids the water content increased as the volatility of the liquid decreased and as the drop size increased. For alcohol the amount of water increased as the application time before extinction increased.

Table IV

Water content of burning liquids after extinction by water spray

Liquid	Time of burning (min)	Per cent water in samples drawn from surface after extinction		
		Spray A	Spray B	Spray C
Alcohol	2 5 8	13 8 8	20 43 21	n.d. 70 70
Benzole	2 5 8	0.2 0.1 <0.1	1.7 <0.1 1.4	No extinction 0.5 1.4
Petrol	2 5 8	<0.1 <0.1 0.3	0.1 < 0.1 <0.1	0.5 0.8 0.4
Kerosine	2 5 8	2.4 n.d 1.2	3.4 0.9 0.6	<0.1 1.6 0.5
Gas oil	2 5 8	1.6 2.9 0.6	3.4 3.0 3.1	0.7 3.2 4.3
Transformer oil	2 5 8	n.d 2.6 0.8	2.7 3.9 2.6	5.4 1.3 0.4

n.d. = not determined.

Electrical conductivity measurements.

The change in electrical conductivity at a point 1 mm below the surface during the spray application was measured for 13 of the 15 tests on hydrocarbon liquids with spray C replicate (a). The apparatus used measured the current flowing between two $1\frac{1}{2}$ mm diameter electrodes with a potential difference of 12 volts across them. When the electrodes were placed in a 50-50 emulsion of transformer oil in water, stabilised with one per cent lissopol a reading of 3.5 units was obtained. Water itself and water containing one per cent lissopol both gave a reading of 4.5 units. The minimum reading which could be obtained with the apparatus was 0.2×10^{-4} units. Table V shows the maximum readings obtained when the spray was applied to different fires.

Table V

Conductivity of burning liquids during application of spray C

Liquid	Reading (Units)		
	2 minutes preburn	5 minutes preburn	8 minutes preburn
Benzole	0.0	n.d.	2.5×10^{-4}
Petrol	0.0	1.5×10^{-4}	0.2×10^{-4}
Kerosine	2.1×10^{-4}	0.0	0.8×10^{-4}
Gas oil	0.0	0.0	1.0×10^{-4}
Transformer oil	0.0	0.0	n.d.

n.d. = not determined

In a few cases slight currents were detected some 3-4 seconds after the application of the spray. In no case was this current greater than $\frac{1}{10,000}$ part of the current which flowed when the electrodes were placed in the prepared emulsion. Moreover, a comparison between the currents obtained and the extinction times shown in Table II does not reveal any association between the detection of a current and the occurrence of a short extinction time.

DISCUSSION

Mechanism of extinction

There are eight possible ways in which the spray could have extinguished the fires. Five result from the action of the spray on the liquid.

(1) cooling the liquid to the fire point,

(2) evolution of steam at the hot burning liquid in sufficient quantity to inhibit combustion,

(3) formation of a froth at the surface which would prevent the vaporization of the liquid,

(4) formation of an oil in water emulsion at the surface which would also prevent vaporization,

(5)   for alcohol, by dilution of the surface layers until insufficient combustible vapour was evolved.

Three result from the action of the spray on the flames.

(6)   blowing the flames out, by the air current associated with the spray.

(7)   extinction of the flames by cooling with the spray,

(8)   extinction of the flames by steam formation in the flames.

Most of these extinction mechanisms were considered in part I for the kerosine fire alone.   However, the wider range of flammable liquids used in these tests can give a broader view of the extinction mechanism which was not possible in the previous tests.

In considering these mechanisms, it must be pointed out that although over a long period, a spray and a flame may have certain average properties, from moment to moment the properties may vary considerably due to turbulence.   With many of the above extinction mechanisms the momentary value of these properties would determine whether extinction takes place; as a consequence differences in the extinction time and even of the extinction mechanism under given experimental conditions were to be expected and were indeed obtained.

<u>Cooling the liquid to the fire point</u>   To cool the liquid to the fire point a spray has to cause the abstraction of heat from the surface layers of the liquid more rapidly than the flames can add heat to these layers. A direct assessment of these two factors is complicated since a spray can cause cooling of the surface layers by mixing them with cold layers below the surface as well as by direct heat transfer, and heat from the flames is used to evaporate the burning liquid as well as to increase its temperature.   For a given spray the rate of cooling of the surface layers was reduced as the temperature of these layers was reduced; on the other hand experiments without sprays showed that the rates of increase in temperature of these layers by the flames decreased as their temperatures increased.   It follows therefore that as the temperature of a burning liquid is reduced by a spray, the cooling capacity of the spray becomes less and the heating capacity of the flames becomes more.   If these two capacities become equal before the liquid is reduced to the fire point then, unless some other extinction mechanism operates, the liquid would remain burning with the surface layers at a steady temperature; this was noted for many of the tests described in Part I.   If at all temperatures above the fire point the cooling capacity of the spray were greater than the heating capacity of the flames then the liquid could be cooled to the fire point.   Table III shows that the kerosine, gas oil and transformer oil fires were occasionally cooled to the fire point; the probability of extinction by this mechanism decreased as the preburning time increased and as the drop size decreased.   It might also have been expected that the probability should increase as the fire point increased since a higher fire point should be more easily reached by cooling.   This was not found to be so with the coarsest spray.   This indicates that the coarsest spray some other mechanism could operate more readily with transformer oil and gas oil than it could with kerosine.

A mechanism of extinction which may be put forward is that the spray intervenes between the flames and the liquid and absorbs the radiation which provides the latent heat of vaporization.   A similar mechanism has been suggested to account for the extinguishing efficiency of dry powder.[3] However, the rate of evaporation is determined primarily by the temperature at the liquid surface; this controls the partial pressure which acts as the driving force for vapour transfer into the flame.   If the heat transfer from the flames to the surface is cut off, the sensible heat of the liquid itself will be used to provide the latent heat of vaporization; this will continue until the liquid temperature has been cooled to the fire point.   Therefore this mechanism in itself can only bring about extinction by allowing the liquid to be cooled to the fire point.   It

cannot be expected to operate in liquids with fire points below room temperature since there is practically an inexhaustible supply of heat for vaporization in the general surroundings at room temperature and in the water spray itself.

Steam formation at the liquid   If the surface layers of the liquid are heated during a preburning period to a temperature higher than $100^{\circ}C$, then steam may be formed there when a spray is applied to the fire. With most of the tests with kerosine, gas oil and transformer oil, vigorous boiling was indeed observed when sprays were first applied. It is difficult to estimate from the spray and fire properties the ability of a spray to extinguish a fire in this way, since not only is the process of steam formation in the liquid complex, but also the amount of steam which has to be formed would also vary with the amount and drop size of the liquid incidentally sputtered or splashed into the flame. However, an idea of the test conditions under which this mechanism may have predominated may be obtained by considering the effect of preburning time on H, the heat content of the liquid above $100^{\circ}C$, in conjunction with the effect of preburning time on the extinction time. H is the maximum amount of heat available for steam formation and is plotted against the preburning time in Fig. 11 for the three high boiling liquids. For a given liquid H increased with preburning time, and it would therefore be expected that the chance of extinction of the fire by steam formation at the liquid would also increase. This probably accounts for the two curves representing the extinction of the kerosine fire with spray (shown in Fig. 5); either the kerosine was extinguished quickly by steam formation at the hot liquid or it had to be extinguished much more slowly by being cooled to the fire point and the chance of the former mechanism operating increased as the preburning time increased. It would also be expected that if this mechanism were predominant then the extinction time should decrease as the preburning time increased. There is some evidence that this occurred with spray C acting on the high boiling liquid fires but spray A acting on these fires gave the reverse effect. It will also be noted in Fig. 11 that for a given time of preburning the heat content increased as the fire point of the liquid increased. It would therefore also be expected, if this mechanism were predominant, that the chance of extinction by this mechanism should increase as the fire point of the liquid increased. This may account for the fact that with spray C rapid extinction without prior cooling to the fire point took place more frequently with gas oil and transformer oil than with kerosine.

Froth and emulsion formation   A certain amount of froth was usually formed during the application of the sprays to the kerosine, gas oil and transformer oil fires. This froth was produced as a result of the boiling and probably consisted of air and water vapour bubbles in oil. However, as a rule this froth covered only a part of the liquid surface and it was not until the spray was stopped that there was any tendency for the surface to become completely covered with froth. It appeares, therefore, that during the tests the impact of the spray drops destroyed the froth as it was formed and it is unlikely therefore that this mechanism contributed substatially towards the extinction. The samples taken after extinction and the electrical conductivity measurements did not indicate any significant formation of an oil in water emulsion in these tests.

Dilution   There is little doubt that sprays B and C extinguished the alcohol fires by dilution since after extinction the surface layers contained a high percentage of water and immediate reignition was not obtained when a light was applied above the surface. In all tests with these sprays on alcohol the flame was immediately pushed into a flat thin flame burning close to the liquid surface. After a certain time, which was considerably greater for spray C than for spray B, a small area free of flame formed at the centre of the vessel; this area gradually increased until in the last few seconds before extinction only a few small flames $\frac{1}{2}$ in. high burning at the edge of the vessel were present. In two tests on alcohol with spray A in which the extinction

times were respectively 8.6 and 15.4 seconds, the fire went through
the same series of stages but in a very much more rapid sequence than
with either spray B or C. It therefore appears that in these two tests
the fire was also extinguished by dilution but very much more efficiently
than when sprays B and C were used. With the other four tests on
alcohol with spray A, however, the fire went out quite suddenly within
2 seconds of application and without going through these stages; moreover
immediate reignition was obtained soon after extinction. These extinctions
cannot be accounted for by dilution.

Extinction of the flames   None of the above mechanisms can account for
the extinctions obtained in the tests on the petrol and benzole fires or
indeed in many of the tests on the other liquids. It may therefore be
assumed that these fires were extinguished by the direct action of the
spray on the flames. It is unlikely that the blowing effect of the
air stream entrained with the spray played the predominant part in the
extinctions. If this were otherwise little difference would have been
expected in the ability of sprays A, B and C to extinguish the petrol and
benzole fires since there was little difference in the velocity of the
entrained air stream for the three sprays. Moreover Spalding reports (4)
that a kerosine fire burning on a $\frac{1}{8}$ in. rod may be extinguished occasionally
by a turbulent air stream of velocity 1370 cm/sec (45 ft/sec); Table II
shows that the entrained air velocity of the sprays used in these tests
was much less than this. It may be assumed that the main action of the
air stream was to tend to blow the flame into a flat shape similar to
that shown in Fig. 6 although it is possible that after a clearance of
the bulk of the flame as shown in Fig. 7, the entrained air stream might
have helped extinguish the smaller tongues of flame left burning at the
vessel edge.

It follows that the extinction of many of the fires was mainly a
result of heat transfer between the flames and the spray drops. In
Part I (p.19) it was estimated that for a kerosine flame approximately
0.7 cal/sec would have to be transferred from one cubic centimetre of
the flame to the spray if extinction were to be obtained entirely by
cooling the flame, and only 0.02 cal/sec if all the heat transfer
resulted in the formation of steam. Later information given in detail
in Appendix I has indicated that the latter figure is an underestimate
and should be about 0.1 cal/sec. This figure should not vary
appreciably with the nature of the hydrocarbon liquid burning. It may
therefore be generally stated that water sprays should be able to abstract
about 0.1-1 cal/sec from a cubic centimetre of flame before extinction
is likely to take place, the amount varying according to the amount of
vaporisation taking place. By using methods described in part I it was
estimated that sprays A, B and C could abstract 0.44, 0.19, and 0.14 cal/
sec from 1 cm³ of flame. These values are of the same order as the
estimated quantity required and do provide some positive evidence that
these sprays could extinguish flames by a heat transfer process.

The effect of drop size on the extinction time

The effect of drop size on the extinction time varied with the
liquid. As the drop size was reduced from 0.49 to 0.28 mm petrol,
benzole and alcohol showed a marked decrease in extinction time whereas
transformer oil and gas oil showed on the whole an increase in extinction
time; kerosine was intermediate between the two groups of liquids. It
would be expected that the mechanism of extinction should have had an
effect on the best drop size to use at any given rate of flow and
pressure. For high boiling liquids with high fire points in which
extinction would take place quickly either by formation of steam at the
burning liquid or by cooling to the fire point it is necessary that the
spray should penetrate straight through the flames to the burning liquid.
It would be expected that once the spray reaches the burning liquid the
finer the spray the better; however, qualitative observations during the
tests showed that the finer sprays incurred the disadvantage of

increasing the violence of the fire during the first few seconds of application by causing an increased amount of sputtering. With petrol and benzole in which extinction takes place following heat transfer in the flames it is important that the spray should penetrate to the lower part of the flames but not necessarily to the burning liquid; moreover the fine spray which reaches the burning liquid does not cause any sputtering because the liquid is not hot enough. It is interesting to note that in those tests with alcohol in which the extinction mechanism was mainly by dilution of the surface layers a decrease in drop size from 0•49-0•28 mm decreased the mean extinction time from 499 to 11 seconds. The explanation of this is probably that the coarser sprays caused more mixing into the surface layers of alcohol below the surface.

A point which cannot be explained simply is the tendency of the coarsest spray (spray C) to give an occasional very rapid extinction with a petrol and benzole fire. Spray C was not quite unique in this respect; Table III shows that with spray B on the petrol fire there was an extinction time of 10•6 seconds at the 8 minutes preburn which was not only considerably less than its replicate (46•6 seconds) but also well below the extinction times of the other 4 tests with this spray on the fire. These rapid extinctions are probably associated in some way with the disturbance caused when the spray is first applied to the fire. During this initial period the flame is changed in shape from a vertical column to a horisontal plate, for petrol and benzole this change was accompanied by a period of instability during which extinction may have been facilitated. With spray C the flames were more unstable during this period than with the other sprays, which may account for the fact that the two shortest extinction times of this spray on the petrol and benzole fires (about 2 seconds) were far less than any of extinction times with these fires using either of the other sprays. This greater disturbing effect of spray C was probably due to two factors. Firstly the entrained air velocity was somewhat more than that of the other two sprays and secondly the spray was much wider than the others. The latter factor would enable the flames that were pushed outwards during the disturbance to meet more spray at distances well outside the vessel; this would have helped to increase these disturbances and also extinguish these parts of the flames.

Practical implications

The above discussion has shown the complexity of the process of extinction of a liquid fire with water sprays and any extrapolation of the detailed results of this investigation to full scale fire fighting equipment must be accepted with reserve until large scale tests have been carried out. Nevertheless a broad picture of the behaviour of sprays of different properties against different fires does emerge which can help to lay the foundations for the design of fire fighting equipment.

Sprays for liquid fires   The results show that water sprays can be an effective and reliable method for the extinction of fires in liquids with high fire points (e.g. transformer oil, lubricating oil, gas oil, fuel oil). Not only can rapid extinction be frequently obtained by a process of steam formation at the hot liquid, but it is possible also for the spray to cool the liquid quickly to below the fire point. Cooling the liquid to below the fire point is highly desirable since the liquid will not then be reignited easily by stray sources of ignition; it may be added that if the liquid has a fire point above 100°C then the water which remains in suspension near the surface would assist in resisting reignition, since this water will have to be vaporized before the fire point can be reached. The tests showed that a relatively coarse spray (drop size 0•5 mm) was quite effective when used against this class of fire and that there was no advantage, and indeed under some conditions there was a disadvantage in using finer sprays. A spray of this drop size is within the scope of ordinary fire fighting nozzles acting up to pressures of 100 lb in^{-2}. In the present tests a rate of flow of 1•6 g cm^{-2} min^{-1} (0•33 gal ft^{-2} min^{-1}) was found effective. However for large

scale fires it would be expected that a greater flow may be necessary to penetrate the larger volume of upward moving flame. On the other hand in practice a fire fighter would direct the spray through the sides of the flame rather than against the upward current as in the present tests and for this reason penetration of the spray to the burning liquid would be easier. For these liquids, moreover, it would not be vital that the spray should cover completely the area covered by the fire, since the spray could be moved about to cool the liquid gradually to the fire point over the whole burning area.

With the volatile liquid fires the finest spray used (0·28 mm) was much better than the others. However, other work [6] has shown that a spray of this drop size may not extinguish a petrol and benzole fire easily when the preburning time is less than 6-8 seconds, and this spray cannot therefore be regarded as reliable under all conditions. Further details of this phenomenon will be described in part III. Nevertheless the tests described in this report indicate that a spray of properties similar to that of the finest spray used would be effective against volatile liquid fires under a wide range of conditions, as long as the spray is sufficiently large to cover the whole area of the fire at any given moment.

The production of fine fire fighting sprays   It has been seen that for volatile liquids the efficiency of a water spray increases as the drop size of the spray is reduced. There is little doubt, that as long as the entrained air velocity is sufficient to push the flames away and allow the spray drops to penetrate to the lower part of the flames, the efficiency will continue to increase as the drop size of the spray decreases. In this series of tests, the only really effective spray for the volatile liquids was the finest tested, which had a drop size of 0·28 mm. This drop size is already much finer than those of fire fighting sprays generally available at about 100 lb/in². The reason for this is that the orifice diameter used in the production of this spray (1/32 in.) is finer than that generally used in fire fighting sprays.

There are three main ways in which the drop size of fire fighting sprays may be reduced.

(1)   By reducing the size of orifice from which the spray is projected.

(2)   By increasing the pressure.

(3)   By changing from pressure atomisation to gas atomisation.

The jet size in fire fighting nozzles is rarely less than 1/16 in. Although it might be possible to introduce 1/32 in. jets, great care would have to be taken to avoid blockages. Thus it would be most ill advised to introduce jets with this degree of fineness into protective installations, since under these conditions it would be very unlikely that the nozzles would have the constant inspection necessary to ensure freedom from blockage. For a single pair of impinging jets or for a single swirl spray, at a given pressure, the drop size of the spray is approximately proportional to the square root of the orifice diameter. However, to maintain the rate of flow, say from a nozzle made up of a number of impinging jets, the number of jets used must increase as the jet size is decreased. In order not to make a nozzle cumbersome the pairs of jets have to be placed fairly close; this results in interference between the sprays from different pairs resulting in coalescence of the spray drops. For a given rate of flow from single nozzles, the reduction in drop size is not therefore as great on reducing the jet size as that indicated above for single pairs of jets.

Little information is yet available on the effect of pressures above about 100 lb/in.² on the drop size of water sprays used for fire fighting. However, information on the drop size of water spray at lower pressures (7) (11) and the drop size of fuel sprays at high pressures (8) suggest that the effect on drop size reduction of increases in pressure from say 100-1000 lb/in.² would be much less than for increases in pressure from say

10-100 lb/in.^{2} Some guidance on the performance of high pressure sprays
on volatile liquid fires may be obtained from direct tests carried out
by the American Army Engineers [9] on the extinction of petrol fires
with sprays produced at pressures from 100-1500 lb/in .   Although the
sprays used were of the impinging jet type, no information was given of
the size of jets used nor were any drop size measurements carried out.
The relation between the extinction times obtained and the drop size of
the spray was therefore obscure.   Nevertheless these workers did find
that at a given rate of flow an increase in pressure did decrease the
extinction time. It has been shown, however, [7] that, on the whole,
this increase in efficiency was not sufficient to warrant the use of
high pressure sprays, since in practice it would not have been sufficient
to counteract the considerable reduction in efficiency due to a necessary
reduction in rate of flow when high pressures are used.   However,
more information will have to be obtained on the properties of high
pressure sprays and on their action on volatile liquid fires before
a definite opinion may be given on their efficiency for this type
of fire.

Under certain conditions it may be feasible to reduce the drop size
of fire-fighting sprays by changing from pressure nozzles to gas
atomisation nozzles.   The difficulty here would be to provide the
atomising gas.   From information given by Hoare [10] it may be estimated
that the amount of air required to atomise water to a spray of mass
median drop size 0·16 mm is 13 ft.^{3}/lb. of water if the air pressure is
5 lb/in^2.   It may be estimated from these figures that a blower several
tons in weight would be required to supply sufficient air to a nozzle
giving 30 gallons/minute.   However, if the exhaust gas from a jet engine
can be used to produce the atomising gas, the weight of the engine need
only be a few hundred pounds.   Whichever way the atomising gas is
produced, however, it is clear that the nozzle would be far less
manoeuvreable that the sprays from pressure nozzles, and probably would
only find use as spray monitors.

Acknowledgment

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Appendix I

Estimation of the heat transfer required to produce enough steam from water drops to smother flames from combustible liquids

In order to estimate the heat transfer required to produce enough steam to smother flames, it is necessary to know the "safe limit ratio" for steam (R_{H_2O}) which is the minimum ratio of steam to combustible vapour which is non ignitable with any admixture with air. For methane this ratio may be obtained directly from inflammability limit tests carried out under standard conditions and the value is 4·2. For other vapours and gases an indirect calculation may be made, using the known safe limit ratios of either carbon dioxide (R_{CO_2}) or nitrogen (R_{N_2}). These ratios are shown in Table VI. Also given in this table is the ratio R_{CO_2}/R_{N_2}, which does not vary appreciably for different combustible vapours and gases. On the assumption that a similar law would hold for a corresponding ratio for water vapour such as R_{CO_2}/R_{H_2O} then an estimate of this ratio for one substance may be used to predict the values of R_{H_2O} for other substances. R_{CO_2}/R_{H_2O} is 0·833 for methane; the values of R_{H_2O} for other combustible vapours estimated from this figure are shown in the last two columns of Table VI. The last column gives the ratio by weight and shows that this ratio varies only between 3·5 and 3·9 for the higher saturated hydrocarbons and benzene.

Yeaw and Shnidman [12] obtained the minimum volume ratio of steam to combustible to suppress flame propagation in a spherical vessel; for hydrogen, carbon monoxide and benzene they obtained values of 7·7, 3·3 and 16·5 respectively. The value for hydrogen differs markedly from the estimated value of 12·5 shown in Table VI, but for carbon monoxide and benzene there is very good agreement.

From information given elsewhere [2] on the rates of burning and the size of flames of benzole, petrol and kerosine fires, it may be estimated that the mean consumption of combustible vapour in unit volume of the flame is $0·45 \times 10^{-4}$ g cm^{-3} sec.$^{-1}$ Assuming that 3·6 times this weight of water must evaporate to form the safe limit mixture then the heat transfer required would be $0·45 \times 3·6 \times 10^{-4} \times 620 = 0·1$ cal cm^{-3} sec^{-1}.

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Table VI

Suppression of flame by carbon dioxide, nitrogen and water vapour

Combustible material	SAFE LIMIT RATIOS			R_{CO_2}/R_{N_2}	Calculated limit for water vapour R_{H_2O} vol/vol	Calculated limit for water vapour wt/wt
	Carbon dioxide R_{CO_2} vol/vol	Nitrogen R_{N_2} vol/vol	Water vapour R_{H_2O} vol/vol			
Hydrogen	10·45	16·55		0·631	12·5	113·0
Carbon monoxide	2·77	4·75		0·582	3·3	2·1
Methane	3·50	6·30	4·2	0·555		4·7
Ethane	7·85	13·40		0·586	9·4	5·6
Propane	7·97	15·40		0·517	9·6	3·9
Butane	9·59	17·60		0·545	11·5	3·5
Pentane	12·35	21·60		0·571	14·8	3·7
Hexane	14·50	25·30		0·572	17·4	3·6
Ethylene	9·76	16·95		0·575	11·7	7·5
Propylene	8·13	14·4		0·564	9·8	4·2
Butadiene	12·07	19·6		0·615	14·5	4·8
Benzene	13·49	21·5		0·628	16·2	3·7
Cyclopropane	8·11	13·65		0·594	9·7	4·2
Gasoline	14·53	23·5		0·618	17·4	
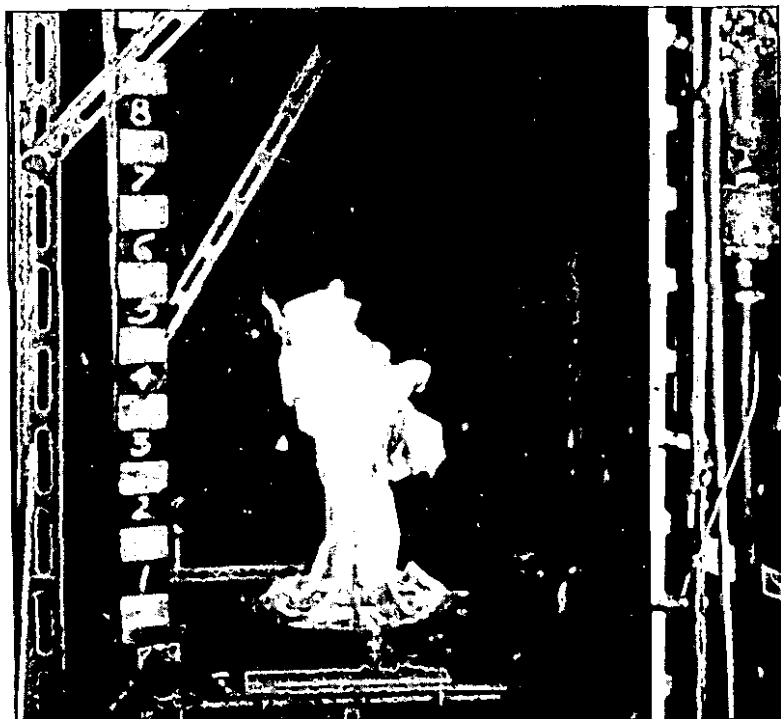
FIG.I.   BURNING OF AN ALCOHOL FIRE.
(Scale marked in 10 cm lengths)
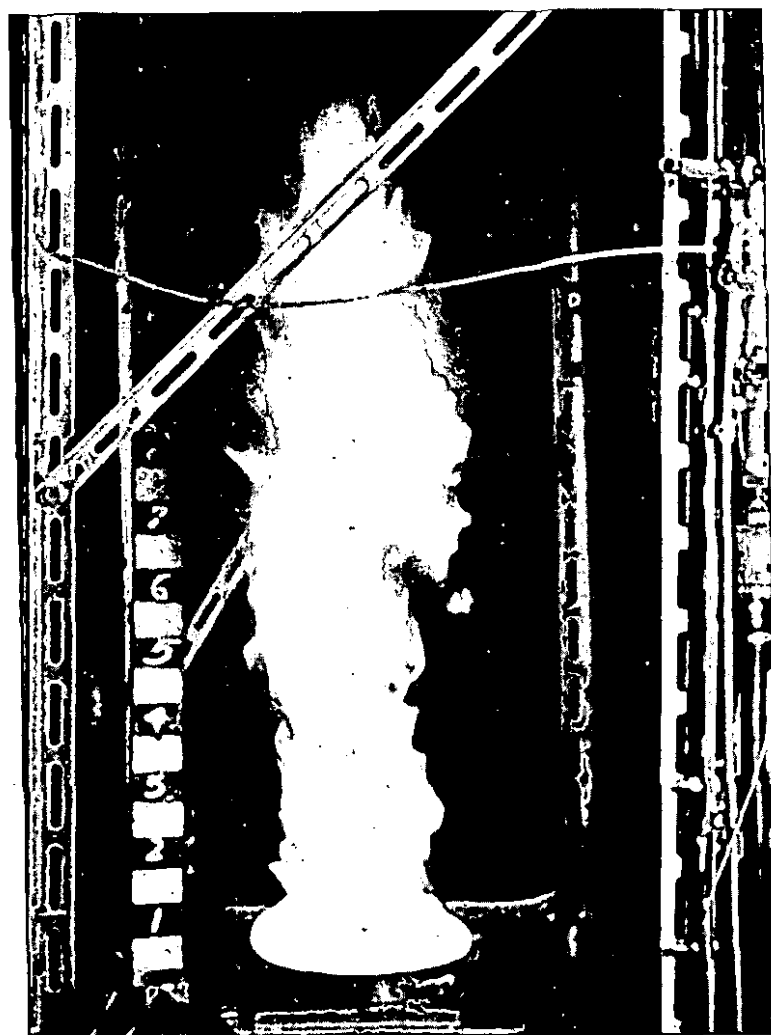
FIG.2.   BURNING OF A BENZOLE FIRE
(Scale marked in 10 cm lengths)
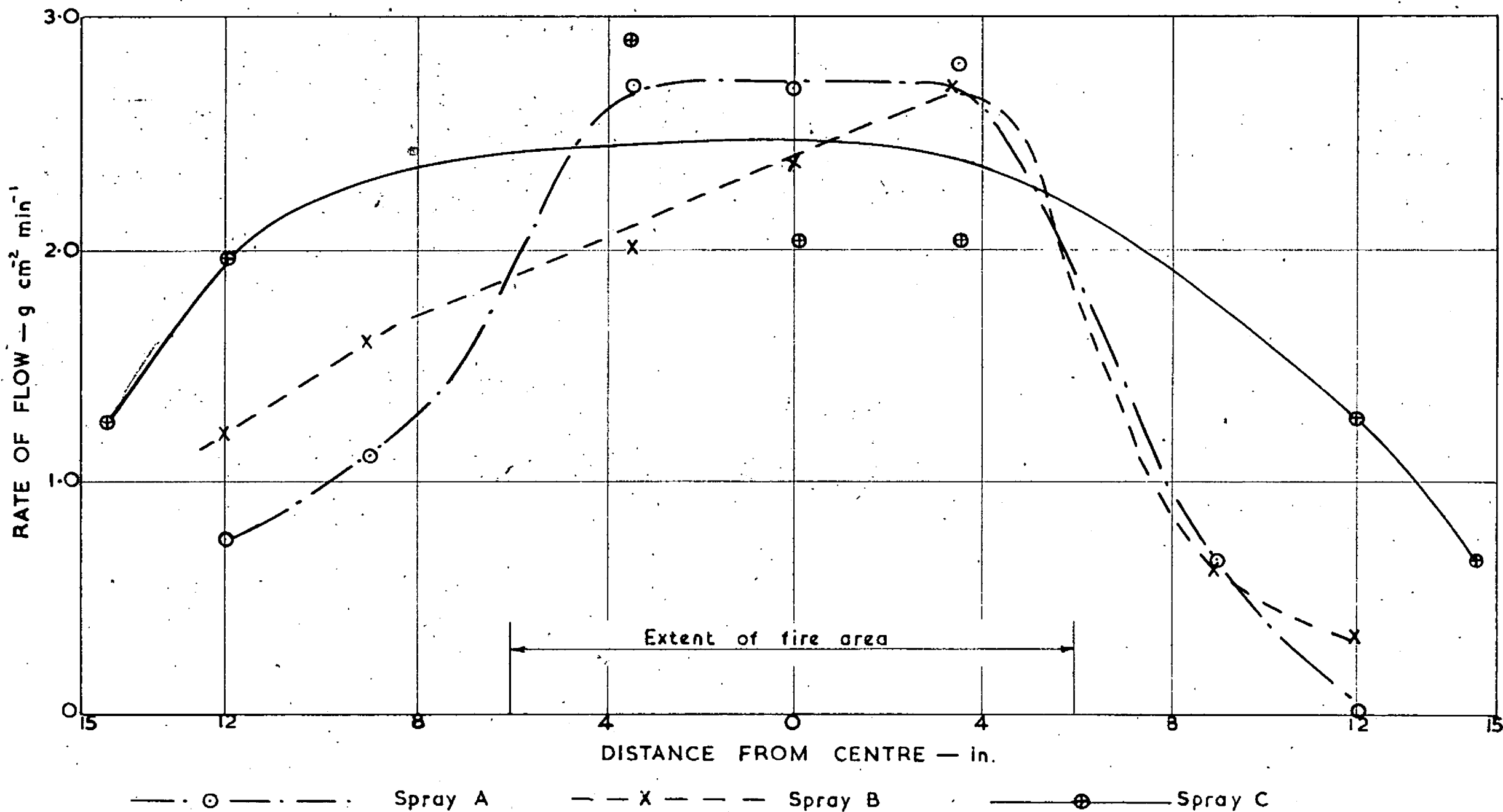
FIG. 3. RATE OF FLOW OF THE SPRAYS IN A PLANE 30 cm ABOVE THE FIRE AREA
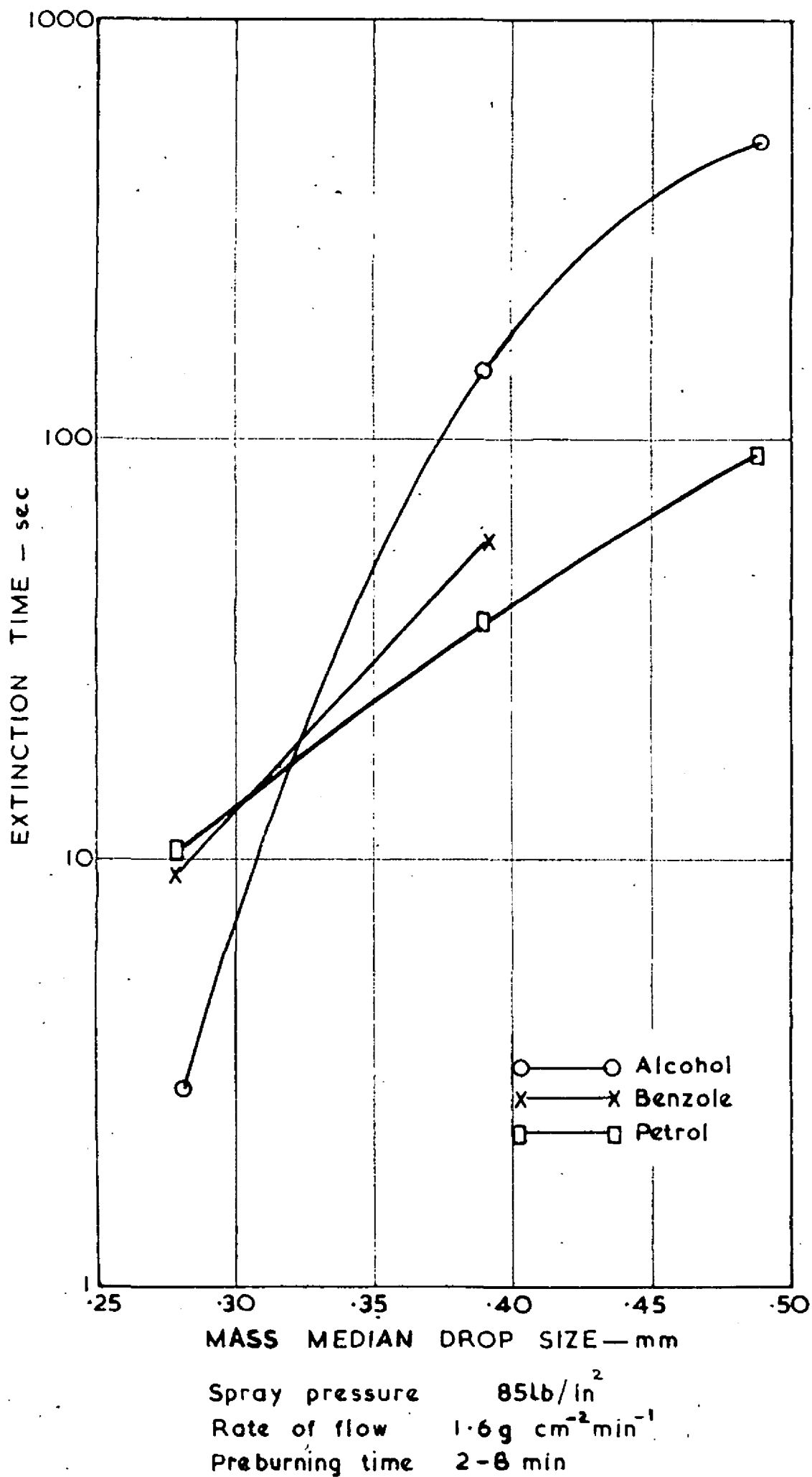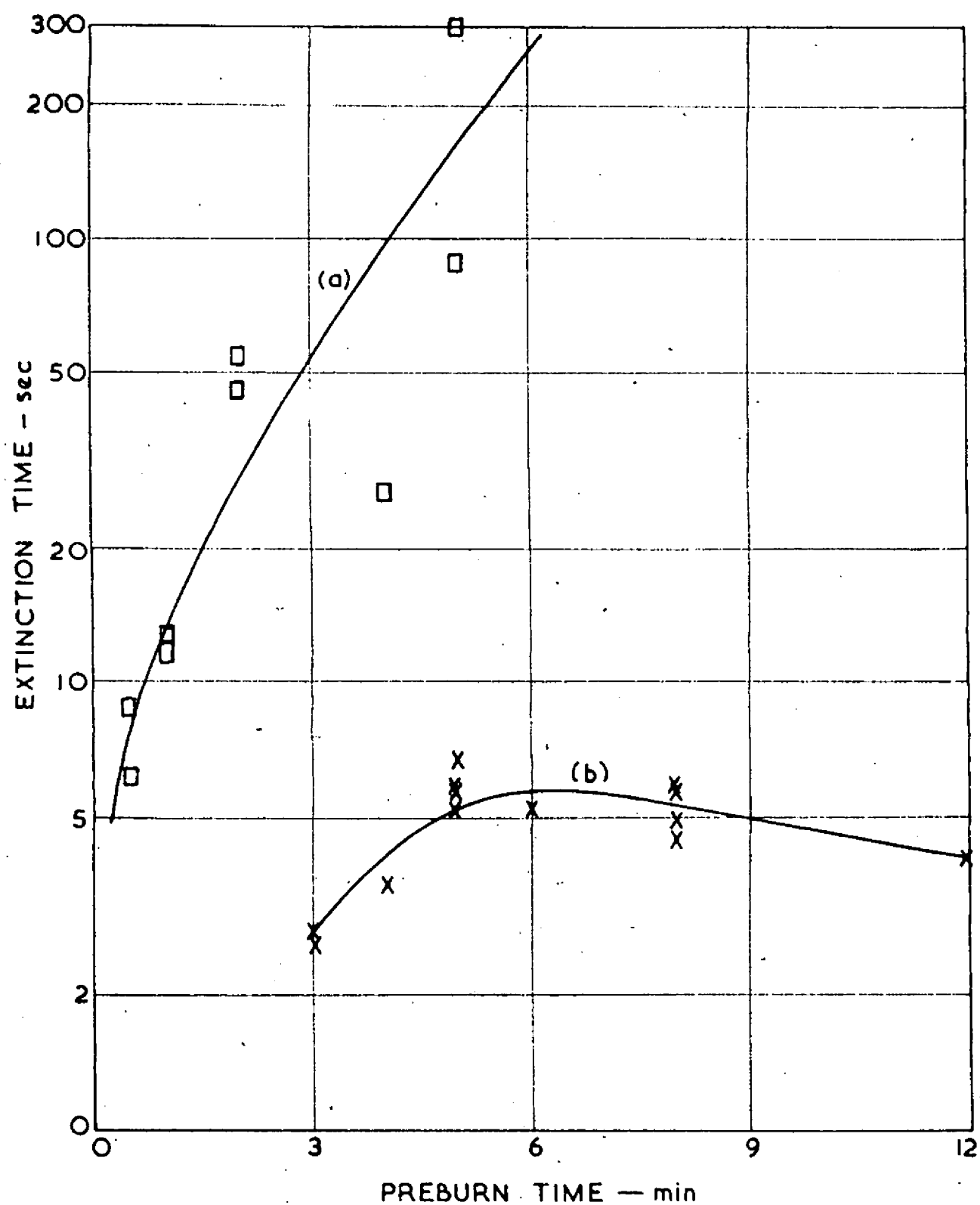
FIG. 4. EXTINCTION TIME (GEOMETRIC MEAN OF SIX TESTS) OF VOLATILE LIQUIDS WITH WATER SPRAYS OF DIFFERENT DROP SIZE

a □ . Liquid cooled to below 68 °C before extinction
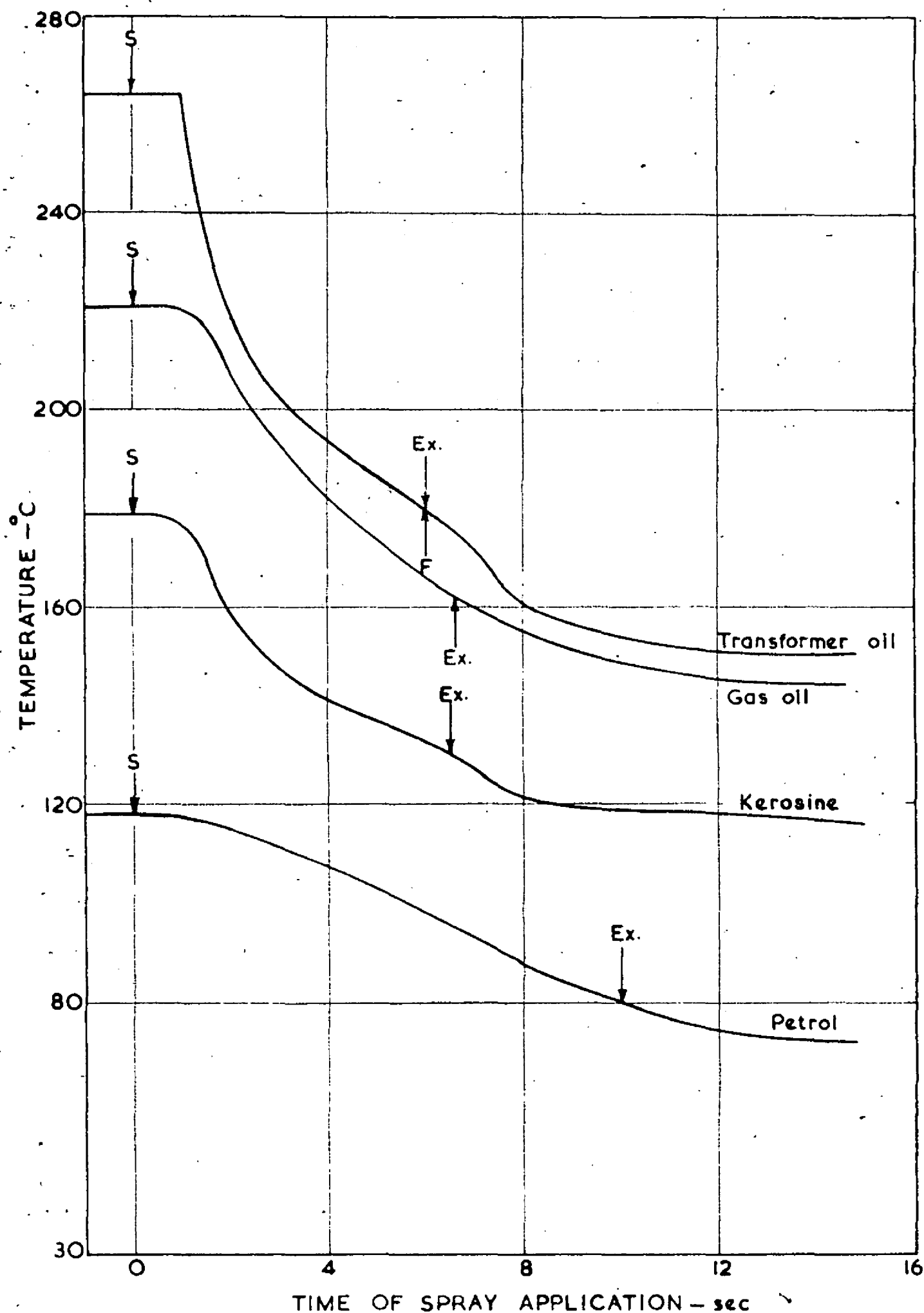b x   Liquid not cooled to below 115 °C before extinction

FIG. 5. EXTINCTION TIME OF A KEROSINE FIRE
WITH SPRAY C   (SEE TABLE 1)

FIG. 6. FLAME OBTAINED BY THE ACTION OF
SPRAY C ON A PETROL FIRE.

FIG.7. CLEARANCE OF FLAME DURING THE ACTION
OF SPRAY C ON A PETROL FIRE.

S. Spray on
Ex. Extinction and spray off
F. Fire point of liquid

FIG. 8. EFFECT OF SPRAY ON THE TEMPERATURE
1mm BELOW THE SURFACE OF BURNING
LIQUIDS. (SPRAY A, 5min PREBURN TIME)
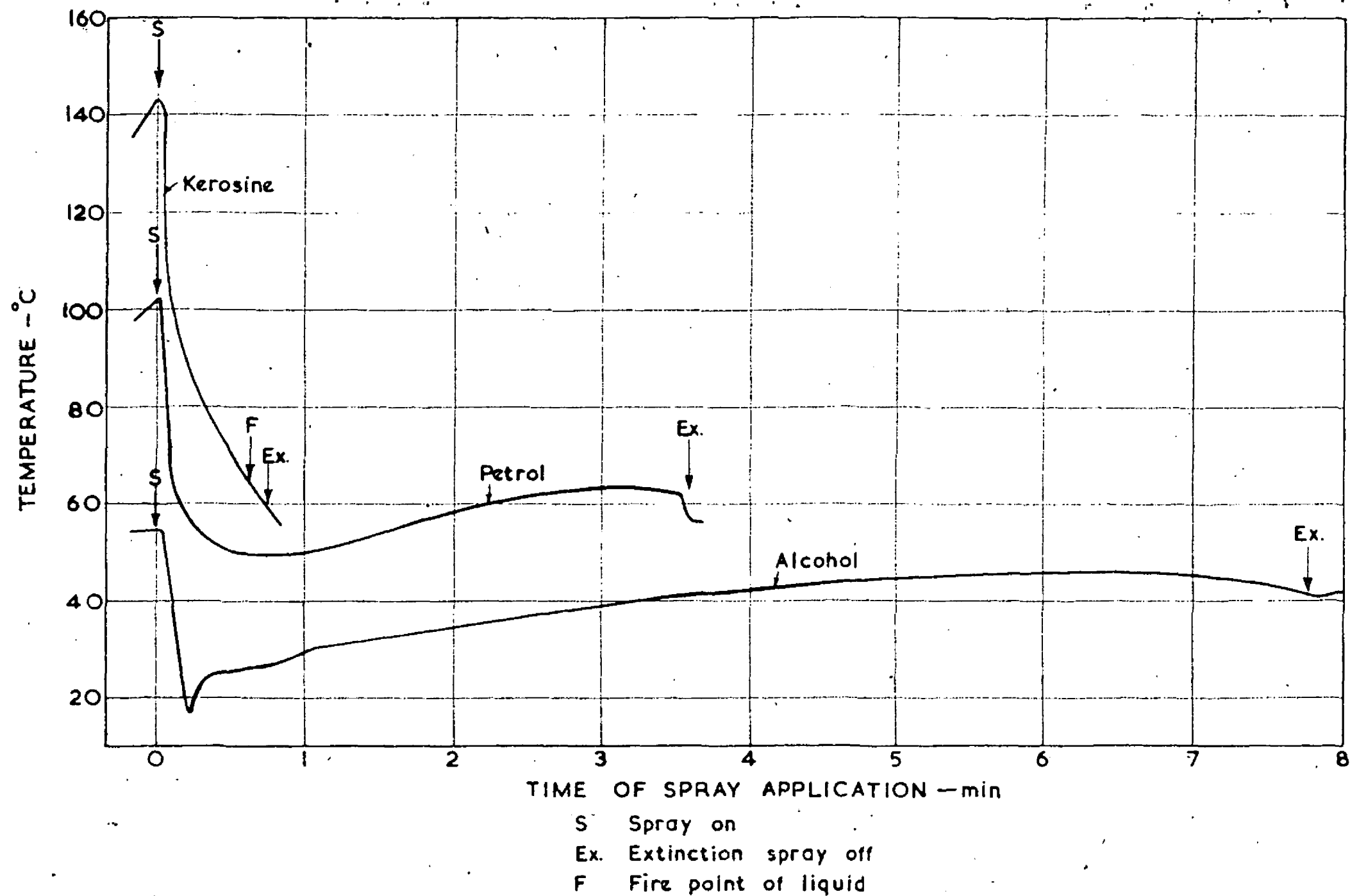
FIG. 9. EFFECT OF SPRAY ON THE TEMPERATURE 1mm BELOW SURFACE. SPRAY C, 2min PREBURN TIME
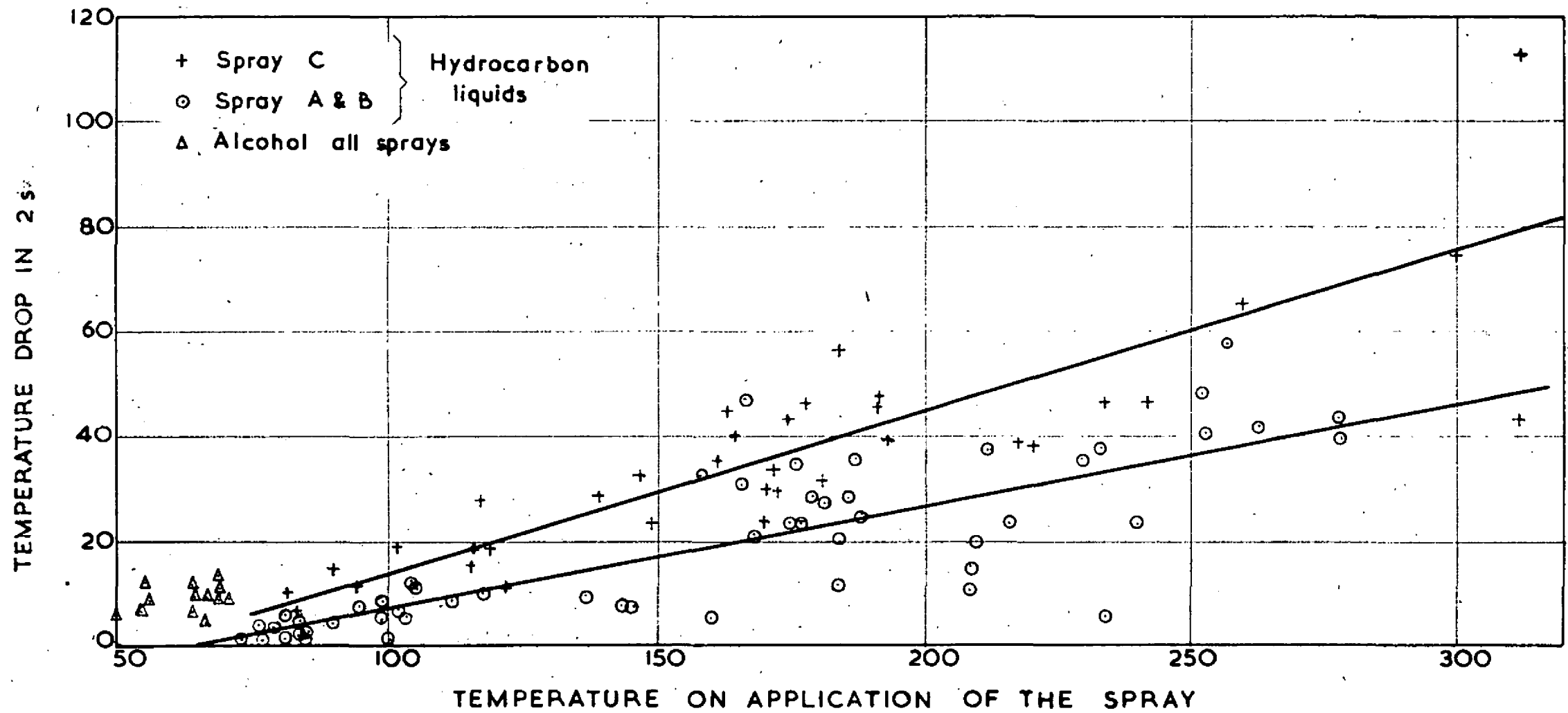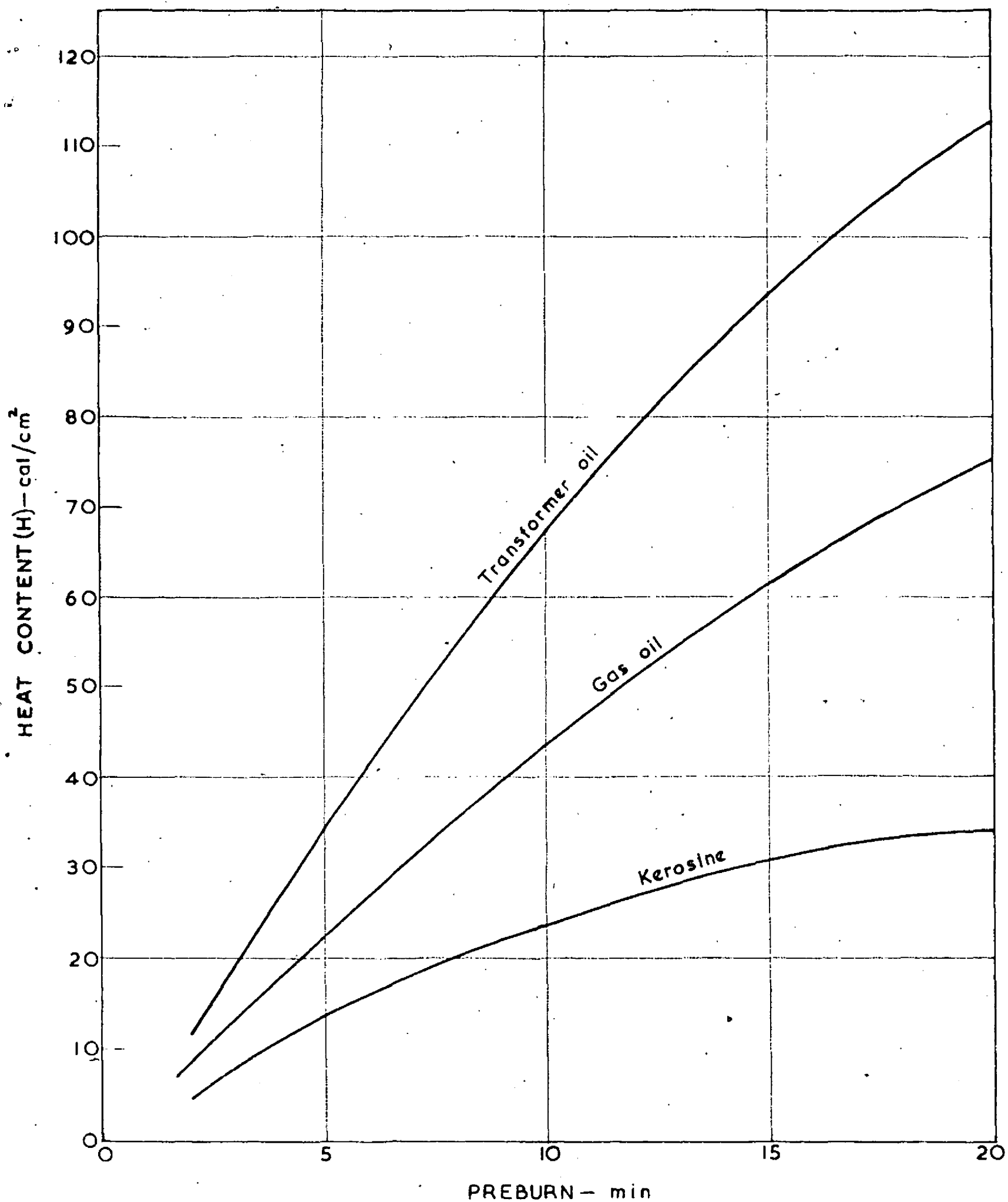
FIG. 10. EFFECT OF INITIAL TEMPERATURE 1mm BELOW THE LIQUID SURFACE ON THE DROP IN TEMPERATURE CAUSED BY THE APPLICATION OF THE SPRAY FOR 2 SECONDS

EFFECT OF PREBURN TIME ON THE HEAT CONTENT ABOVE 100 °C
OF BURNING LIQUIDS

fig. 11

(H)