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THE FREE COMBUSION OF KEROSINE IN AN OPEN VESSEL

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SUMMARY

A study has been made on the properties of a
kerosine fire burning in a vessel 30 cm diameter.
Observations have been,made on the rate of
burning, the upward velocity of the flames, the
composition of the kerosine after burning, and the
temperature in the liquid, the vapour zone and the
flames.   The kerosine burned as a non-hot zone
forming liquid, but the bulk of the vaporization
took place at the surface and not within a layer
0.5 in. below the surface as stated in earlier work
by Burgoyne and Katan.   The bulk of the heat
transfer to the surface of the liquid was by
radiation.

INTRODUCTION

To carry out tests on the efficiency of water sprays in
extinguishing a kerosine fire, it has been necessary to develop standard
fires on which the various sprays could be tested.   The first series
of tests[1] were carried out using a fire burning in a vessel 11.05 cm
diameter (96 cm^2).   More recently a series of tests have been carried
out on a fire contained in a similar vessel 30.0 cm diameter.   Although
the fire was designed primarily as a means of testing the efficiency of
different sprays it was possible to obtain from it information on the
way kerosine burns.   This information, as well as being of fundamental
importance in interpreting the results of the tests of the sprays on
the fire, is itself of intrinsic interest and details of the results
of the various measurements made on the fire are given in this note.

APPARATUS

The combusion vessel

Details of the combustion vessel and ancillary apparatus are
shewn in the diagram in fig. 1.   A was a thin walled brass vessel
30 cm diameter x 12.5 cm high.   The sloping bottom of A allowed a
smooth run-off of liquid into a draining pipe B, 2 cm diameter, which
sloped gently towards a valve C by which the draining of liquid from
A was controlled.   Six fittings D were provided in the bottom of the
vessel;   through one of these fittings a level indicating rod F was
inserted, thermocouples and sampling tubes could be inserted through the
others when necessary.   Side arms G and H led from the pipe B to an
overflow K and a water feed vessel L respectively;   this part of the
apparatus was used to control the liquid level in the combustion
vessel A.

The mounting of the apparatus is shewn in fig. 2. The apparatus rested on a rigid metal framework and the top of the vessel A was adjusted by levelling screws to lie in a horizontal plane 62 cm from the ground. On two sides of the vessel asbestos boards were provided to protect other apparatus and the person operating the overflow K from radiant heat. The latter person could observe the fire through a mica window in the asbestos board. The smoke from the fire was taken off through an asbestos hood which conducted the smoke into a cowl from which it was removed through a length of ducting to the outside. of the building by an extractor fan.

Thermocouples

Special thermocouples were designed to measure the temperatures below the surface of the burning liquid and in the vapour zone. It was necessary that these thermocouples

(a) would not cause an appreciable error in the temperature measurement due to conduction away from the hot junction,

(b) could withstand the action of the kerosine at high temperatures,

(c) could be adjusted to measure the temperature at a number of different points.

The arrangement shewn in fig. 3(a) was used to measure the temperature near the surface of the kerosine and in fig. 3(b) at some distance below the surface. The thermocouple wires used were 28 gauge copper and constantan. In the arrangement in fig. 3(a) a 2 ft length of each wire was threaded through a pyrex capillary A.A. 2 mm diameter and 10 cm long so that it projected a sufficient distance from one end to enable a junction to be made. Each wire was then sealed in its capillary at this end over a distance of 1 cm by heating in the reducing flame of a blowpipe. The other ends of the capillaries were sealed into a pyrex tube B, 8 mm diameter carrying a B.10 socket C so that the thermocouple wires passed through the tube and socket. The two capillaries were brought together to form a double capillary pencil which was bent at a right angle at the point D, 8 cm. from the free end. Over a length N of 1 cm at the free end the capillaries were sealed side by side and twisted through an angle of 90°. In the arrangement shewn in fig. 2(b) the length of the capillaries was only 2 cm but the pyrex tube was longer and was bent at the point T. The junction of the wires was made with a spherical blob of hard solder S, 1.5 mm diameter.

The socket C fitted over a stainless steel cone E and was secured by the springs G. A brass tube F $\frac{1}{4}$ in. o.d., 9/64 in. i.d. and threaded along its length with a $\frac{1}{4}$ in. B.S.F. thread was soldered to the cone. This brass tube could be passed through the bottom of the vessel through one of the six fittings mentioned above; this consisted of a gland H rendered leak tight by a lead packing K. The thermocouple wires passed through a 9/64 in. hole drilled through the cone and were insulated by porcelain tubes P which passed over the wires and pushed into the tubes F and B.

The heat loss from the thermocouple junction by conduction along the wires was minimised by making the junction large in comparison with the diameter of the wires and by inserting the thermocouple so that the length of wires leading from the junction ran along an isothermal (i.e. parallel to the surface of the burning liquid). The capillaries were twisted at right angles near the junction to ensure that any accidental deflection of the junction would tend to be along an isothermal. The position of the thermocouple junction was varied by screwing the brass tube through the gland and locking the tube in position with the nuts M. If the motion of the glass part of the thermocouple was restricted so that it could travel in a vertical plane only, then a vertical traverse with the thermocouple could be made in a single test. The threaded

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rod F was rotated from a distance by a chain and gear mechanism. This rotation caused the rotation of the cone within the socket so that the thermocouple was moved vertically through a distance equal to the pitch of the thread for every complete rotation of the rod.

EXPERIMENTAL

Test routine

The majority of the experiments were carried out according to the following routine. 4520 g of water followed by 3660 g of kerosine were introduced into the combustion vessel. The flash point, fire point, and distillation range of the kerosine are shewn in Table II. The depth of the kerosine layer was 6.0 cm and its surface reached a point about 2 cm from the top of the vessel. The level of the surface was gauged by a small sphere at the end of the indicating rod F (see fig. 1) the centre of which was 2.00 ± .03 cm from the top of the vessel. A trickle of water was allowed to flow into the vessel through L from graduated glass cylinders R and the overflow tube S was set so that the level of the surface corresponded to that of the centre of the small sphere. The kerosine was primed with 10 ml of hexane, ignited by a taper and allowed to burn for twenty minutes. The level of the surface was kept constant throughout by adjusting the position of the overflow tube so that the level of the kerosine was always at the small sphere. At the end of 20 minutes the fire was smothered with an asbestos board and the contents of the vessel drained, separated and weighed. The temperature and atmospheric humidity of the surrounding air were taken for each test, and for most of the tests the outside wind velocity and direction were also recorded.

Seven tests according to the above routine were carried out before a series of tests on the action of sprays on the fire was begun. During the series of tests with sprays, which will be described in detail elsewhere, a test was carried out about every 8-10 days for about eleven months. It was found important in the development of the fire that to obtain reproducibility it was vital that as far as possible stray draughts should be excluded from the laboratory, and even that movement of people about the laboratory should be kept to a minimum.

Temperature measurements

In all the tests mentioned above the temperature was measured at points 3 mm and 6 cm below the surface of the kerosine. A number of additional tests were carried out in which thermocouples were placed at 1, 8, 15 and 30 mm below the surface. In one test a traverse of the vapour zone between 4 and 12 mm above the surface of the liquid was made with the thermocouple.

To obtain the temperature of the flames, readings were taken with an optical pyrometer sighted at a point 30 cm above the centre of the vessel. Readings were taken with the light from the fire and the filament passing through a red filter and a green filter with maximum transmissions at .645 and .525 μ respectively. At the same time readings were taken on a total radiation pyrometer sighted on the same part of the flames.

Kerosine composition after combustion

In order to determine whether there was any change after burning in the composition of the kerosine near the surface samples of the kerosine were removed from points ½ mm and 3 mm below the surface of the kerosine. A sample from each position was taken in two tests between the 18th and 21st minute after ignition. In two other tests a sample was removed from a point 40 mm below the surface at this time. Distillation, flash point and fire point tests were carried out on these samples.

Velocity of the flames

.The upward velocity of the flames was assessed from a film of the
fire taken at intervals during the last eight minutes of a test. A
scale was placed beside the fire while the film was taken. . The speed
of the film was 32 frames per second and by comparing in consecutive
negatives the position of the top of the flame when the height of the
flame was increasing it was possible to estimate the upward velocity of
the flames at different heights above the burning liquid. It was also
possible from this film to obtain an estimate of the width of the flames.

RESULTS

Appearance of the flames and the burning liquid

After a few minutes burning the shape of the flames settled to
that shewn in fig. 4. Over a distance of 5-8 cm inwards from the edge
of the vessel the burning took place in a thin semi-transparent film
about 2 mm thick and shaped over the top of the vessel like an inverted
saucer. The edge of this film was about 2 mm above the edge of the
vessel and the average distance of this film from the level of the burning
liquid was about 3 cm. From this film ribs of yellow flame were formed
which converged above the centre of the vessel into a column of yellow
flames rising from about 5 cm. above the surface of the liquid. The
height of these flames appeared to reach about 150 cm. On examing the
film of the fire, however, it was found that the height of the continuous
column of flame above the fire varied between 30-110 cm and rarely exceeded
100 cm. Patches of flame continually broke off from the main column and
travelled higher.

During the burning a slight rippling of amplitude about 1 mm was
observed on the surface of the liquid. This was presumably due to the
variation in the flame. Also after burning for about 15 minutes very
fine bubbles of gas were observed to be coming to the surface. If a
solid object was placed within a few millimetres of the surface the
bubbling at that object was more pronounced than over the rest of the
surface. When a thermocouple was placed 3 mm from the surface there was
usually bubbling at the thermocouple junction during the last 2-3 minutes
of the test.

If the wind outside the building was coming from a northerly direction
it was noted that the fire burned somewhat more wildly than usual. The
disposition of the end of the ducting extracting the smoke in relation to
the roof, was such that a northerly wind may have tended to blow down the
duct more than winds from other directions and thus interfere with the fire.

Quantity of kerosine burned

In the seven consecutive tests carried out before the main series of
tests with sprays, the quantity of kerosine burned in 20 minutes varied
from 1141 to 1202 g with a mean of 1170 $\pm$ 19 g*. During the main series
of tests with sprays 38 blank tests were carried out; the quantity burned
in these tests varied from 1090 to 1237 g giving an average of 1163 $\pm$ 39.
In 30 of these tests the wind direction and velocity was taken and it was
found that in 10 of these tests in which the wind was between NNW and NNE,
the average quantity burned was 1189 $\pm$ 35. When the wind came from other
directions the quantity burned was 1149 $\pm$ 36. From these figures it may
be deduced that there was more than a 95% probability that a northerly wind
did increase the quantity burned presumably due to the interference with
the flames mentioned above.

Three tests were also carried out in which the combustion was stopped
after 8 minutes. In these tests the quantities burned were 431, 434 and
438 g i.e. a mean of 434 g. The average rate of burning in the first
8 minutes was therefore 54.3 g/min., in the last 12 minutes 60.9 g/min.
and over the whole test 58.4 g/min. It may therefore be assumed that

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* All deviations given in this note are standard deviations.

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after 8 minutes the fire reached a fairly steady rate of burning of
1.0 g./second or 50 kg/(m^2)(hr.).

The kerosine fire on which the first series of spray tests were
carried out gave an average quantity burned of 102.3 $\pm$ 6.7g. This fire
burned for 20 minutes in a brass vessel 11.05 cm diameter, at an ullage of
2 cm and with a constant vertical air draught of 30 cm/second flowing
past the fire. It will be noted that in spite of the variations caused
by the outside wind the larger fire was more reproducible than the smaller
fire. It had been noted in the experiments leading to the development of
the smaller fire that a better reproducibility could be obtained if the
fires were burned in a thin walled pyrex vessel at 5 mm ullage than if
they were burnt in the brass vessel at a 2.0 cm ullage. It may therefore
be concluded that the nature and extent of the vessel surface that is
exposed to the flames has an important influence on the reproducibility of
the fire. The smaller the ratio between this surface and the area of the
vessel and the smaller the conductivity of the wall, the easier it will be
to obtain a reproducible fire.

The rate of burning per unit area of the larger fire was considerably
larger than the rate of burning per unit area of the smaller fire
(35 kg/(m^2)(hr.)). This was in spite of the fact that there was a forced
draught with the smaller fire which would make it burn faster than under
conditions of natural ventilation. Katan[2], Khudyakov[3] and Leir[4]
have all reported that the rate of burning of a liquid fire increases as
the scale increases; the latter two authors, however, state that this
effect is small.

Velocity and width of the flame

It will be seen in the film strip in fig. 5 that the upward motion
of the flame could be followed by following the motion of the top of the
flame in successive photographs. From readings obtained in this way
it was possible to assess the velocity of the flames as they passed
points 45, 55, 65, 85 and 105 cm above the surface of the liquid. The
results are shewn in Table I.

TABLE I

Upward velocity of flames at various heights

Height cm.	No. of readings taken giving velocities falling within given range						Total Number of readings	Mean Velocity cm/sec $\overline{V}$	Standard deviation σ	$\frac{\sigma}{\overline{V}}$
	280 cm/sec.	280-380	380-480	480-580	580-700	700 cm/sec.				
45	2	3	1	0	0	0	6	326	69	.21
55	1	13	5	1	0	0	20	374	62	.17
65	3	17	13	7	1	0	41	416	93	.22
85	3	22	20	13	5	2	65	451	138	.31
105	0	4	13	7	2	1	27	496	125	.25

At any given height the upward velocity of the flames varied over
a wide range. However, the mean velocity of the flames increased as
the height increased from 45-105 cm. Moreover, the last column indi-
cates that the amount of variation about the mean also increased as
height increased.

Readings of the width of the flame were taken on 87 photographs.
At heights of 15 and 35 cm the average width of the flames was 16.0
and 18.1 cm respectively.

Temperature in the liquid

Fig. 6 shews the temperatures at different depths below the surface
of the liquid plotted against time. The curve for 3 mm below the liquid
surface is the mean of 19 tests; the other curves are the means of two
tests. It will be seen from fig. 6 that the temperature at a given depth
rose to a fairly steady value which decreased as the depth increased.

In fig. 7 the temperature at different times has been plotted against
the depth of the thermocouple. These curves may be extrapolated to a
temperature in the surface of about 215° C. A single test was carried
out in which the thermocouple was in the surface; this test gave a steady
temperature after 6 minutes burning of 212° C. This observation differs
from that of Burgoyne and Katan[5] who found that the temperature in the
surface of a non-hot-zone-forming liquid is at, or may even be higher than,
the final boiling point of the liquid. The liquid tested by Burgoyne and
Katan nearest in properties to the kerosine used in these tests was "Pool
Vaporising Oil" which had an I.B.P. of 145° C. and an F.B.P. of 273° C.[6]
When burning in an insulated 22 in. diameter tank this gave a surface ·
temperature of 321° C. Burgoyne and Katan state, however, that their
thermocouples, which were 6 mm diameter would have been partly exposed to
the flame for an appreciable time before the temperature was obtained.
It is likely, therefore, that radiation from the flames could have given
high temperature readings in their work.

Temperature in the vapour

After about 12 minutes burning the temperature registered by the
thermocouple at a given height above the surface remained steady; at a
height of 4 mm it was 340° C. and a height of 12 mm 360° C. It must be
emphasised that these were not the temperatures of the vapour but were
equilibrium temperatures taken up by the thermocouple at which the heat
received by the thermocouple by radiation from the flames was equal to the
heat lost by the thermocouple mainly by convection to the vapour.
Nevertheless since the radiation falling on the thermocouple was practi-
cally independent of its position, the difference in temperature registered
by the thermocouple at 4 mm and 12 mm does give a reasonable estimate of
the temperature difference in the vapour at the two positions. The
temperature gradient in the vapour was therefore about 25° C./cm.

Temperature of the flames

For a height of 30 cm above the liquid surface four readings with
the optical pyrometer gave a mean of 1077 ± 2 and 1118 ± 8° C. for the
red and green filters respectively. The reading obtained on the total
radiation pyrometer corresponded to that which would be obtained from a
black body of 660° C. The intensity of radiation from the flames in
the direction of the pyrometer was therefore 1.54 cal/(cm^2) (sec.).
It is difficult to obtain the true flame temperature and emissivity from
these readings without making some assumptions on the dependence of
emissivity on wave length, and the chemical composition of the flame.
The total radiation is made up of two factors, the radiation from the
soot particles (luminous radiation) and the radiation from water vapour,
carbon dioxide and other radiating gases which may be present (non-lumi-
nous radiation). The visible radiation may be considered as emitted
entirely from the soot particles; therefore observations with the optical
pyrometer may be related only to the amount of radiation given by the
soot particles. It has been estimated, however[7] that the temperature
of the soot particles will differ by only 1-2° C from the temperature of
the flame, and may for practical purposes be considered as the temperature
of the flame.

Sobolev and Schetinin[8], have found that in a kerosine spray flame 19 cm diameter in which kerosine was being consumed at the rate of 2 kg/sec., the emissivity of the flame was independent of wave length in the visible region, i.e. the flame was grey in this region. If it is assumed that the kerosine flame in the present test has similar properties then the temperature of the flames and the emissivity in the visible region may be deduced from the above observations as being 1330°C. and 0.072 respectively. On the other hand Hottel and Broughton[9] found for a row of 6 amyl acetate flames each about 1 cm diameter that the emissivity depended on wave length as follows:

$$E = 1 - e^{-\frac{kL}{\lambda^a}} \quad \dots\dots\dots\dots\dots(1)$$

E = emissivity

k = a constant

λ = wave length

L = flame thickness

a = 1.39 for values of λ up to 0.8μ, and 0.9 for values of λ from $0.8 - 10\mu$. (for a grey body a would be zero at all wavelengths).

According to these data the temperature of the kerosine flame would be 1210° C. and the emissivity of the luminous radiation would be 0.05. Naeser and Pepperhof[15] found that the coefficient a in equation 1 varied from 0.80 to 1.35 for various flames; they did not, however, measure a for a kerosine or similar flame.

If it is assumed that complete combustion has taken place by the time the flame reaches a point 30 cm above the surface then the amount of non-luminous radiation due to carbon dioxide and water vapour in the direction of the total radiation pyrometer may be calculated if the flame temperature is known. At flame temperatures of 1330° C. and 1210° C. this radiation would be 0.63 and 0.50 cal/(cm^2)(sec.), if the absorption of non-luminous radiation by the soot particles is neglected. The luminous radiation would be 0.32 cal/(cm^2)(sec.) according to Hottel and Broughton's data and 0.65 cal/(cm^2)(sec.) if the radiation were considered grey at a temperature of 1330° C. Therefore, a reading on the total radiation pyrometer of 0.82 cal/(cm^2)(sec.) would be expected if Hottel and Broughton's data were followed and 1.28 cal/(cm^2)(sec.) if Sobolev and Schetinin's data were followed. The reading of 1.04 cal/(cm^2)(sec.) which was actually obtained indicates that a value of a in equation (1) intermediate between 0 and 1.39 probably operates in the kerosine flame. There is some justification therefore for taking the mean of the two calculated values of the temperature, i.e. 1270° C. as an approximate value for the temperature of the flame. Further experiments are being designed by means of which a more accurate value of the flame temperature will be obtained.

Composition of the kerosine after burning

The distillation curves for an original sample of the kerosine and for the samples taken from points 0.5, 3.0 and 40 mm below the surface between the 18 and 21st minute after ignition and shewn in Table II and fig. 8. The distillation analyses for the samples taken at 0.5 and 3.0 mm were almost identical and are represented by one curve (a). Similarly the analysis of the 40 mm sample was almost identical with the original and these are represented by curve (b). The sample taken at 40 mm below the surface may be considered as unchanged in respect to the original sample; the kerosine near the surface, however, contained less of the lighter fractions and more of the heavier fractions. This is confirmed by the fact that the flash and fire points of the samples taken near the surface, were definitely higher than those of the original sample.

TABLE II

Properties of the original kerosine, and that removed from the
combustion vessel after burning

Sample	Original	After Burning		
		Taken 40 mm below surface	Taken 3 mm below surface	Taken ½ mm below surface
Flash Point °F Abel °C	104 40	105 41	115 46	115 46
Fire Point °F Cleveland Open Cup °C	136 58	141 61	154 68	154 68
Distillation	°C	°C	°C	°C
I.B.P.	157	156	161	160
5%	165	165	174	173
10%	171	170	179	178
20%	178	178	187	186
30%	185	185	195	195
40%	194	194	205	205
50%	203	203	215	215
60%	213	213	225	225
70%	225	224	236	236
80%	237	237	248	248
90%	253	253	261	261
F.B.P.	277	276	282	282

DISCUSSION

Mechanism of burning of a non-hot-zone-forming liquid

When the burning of a non-hot-zone-forming liquid has reached a steady state, a steep temperature gradient is established within a few inches of the surface; below this distance the liquid does not change in properties as the burning progresses. A consequence of this phenomenon is that when the steady state has been reached the composition of the vapour which leaves the surface must be the same as the composition of the original unchanged liquid, since otherwise in the course of time a hot zone would become established. Burgoyne and Katan[5] shewed that many petroleum fractions behave in this way, kerosine being one of them. The mechanism of vaporisation of the burning liquid which they put forward may be summarised as follows. The temperature of the surface is at the final boiling point and the composition of the liquid in the surface corresponds to the heaviest fractions of the oil. At a certain plane below the surface the temperature of the liquid is at the initial boiling point; between this plane and the surface the complete range of distillation takes place. They mention a depth of about $\frac{1}{2}$ in. for the depth below the surface in which distillation takes place. A point which does not seem to have been taken into account, however, is that of the mixing action of the vapour rising in the $\frac{1}{2}$ in. zone below the surface. If the composition of the kerosine were equated to that of undecane and if perfect gas laws are assumed, then it may be estimated from the rate of combustion that the volume of vapour rising from the surface would be 1900 cc/(m^2) (sec) at N.T.P. Burgoyne and Katan found [6] that with a kerosine fire burning in the 22 in. diameter vessel a rate of air stirring of 0.10 ft^3/min. (190 cc/(m^2)(sec) cleared the surface of flame in $3\frac{3}{4}$ minutes; i.e. this rate of flow was capable by a mixing action to reduce the temperature at the surface to below the fire point. Therefore if all the distillation were indeed taking place in the $\frac{1}{2}$ in. zone below the surface, there would have almost certainly been a sufficient flow present to obliterate the existing temperature gradient.

In the fire described in these tests a steep temperature gradient was established below the surface of the liquid. After about 15 minutes burning this temperature gradient remained relatively unchanged with time; this fact indeed indicated that the kerosine was burning as a non-hot-zone-forming oil. The observations on the temperature and composition of the kerosine at the surface, however, do not support the views of Burgoyne and Katan on the mechanism by which the kerosine vaporises. Indeed, the evidence seems to suggest that the bulk of the vaporisation took place at the surface. It is true that some vapour reached the surface as bubbles but the number and size of these bubbles, as judged by a visual estimation, were such as to account only for a very small fraction (about 0.1-1%) of the volume of vapour which would have had to rise to the surface if all the vaporisation were taking place below the surface.

It seems likely that during the initial stages of burning, the lighter fractions because of their higher volatility were vaporised preferentially from the region near the surface. When the steady state had been reached, the surface layers had been denuded of their lighter fractions to such an extent that the relative amounts of lighter to heavier fractions vaporised was the same as the proportions existing in the original liquid. This would account for the presence of a smaller amount of lighter fractions in the surface than in the original liquid. Presumably the lighter fractions reached the surface of the liquid by diffusion because of the concentration gradient which had been established below the surface. There is, however, a point of inconsistency in the results which must be mentioned. The temperature $\frac{1}{2}$ mm below the surface was found to be 210°C., yet the kerosine which was drawn off from this point had an initial boiling point of 161°C. The latter temperature existed at a point of 5 mm below the kerosine surface. A possible explanation of this discrepancy is that the surface layers of the kerosine were transparent to radiant heat which was then absorbed by the thermocouple; the thermocouple would therefore read

high. It was estimated, however, from information on the transmission of infra red by dodecane [16] that the error due to this was unlikely to be more than $5^{\circ}C$. when the thermocouple was 1 mm below the surface, or more than $\frac{1}{3}^{\circ}C$. when the thermocouple was 2 mm below the surface. It would therefore appear that there was a considerable amount of superheating in the kerosine at and immediately below the surface; some support is given to this supposition by the observation that boiling would often but not invariably take place at a solid object introduced within a distance of about 3-4 mm below the surface. It is possible that in hot-zone-forming oils, the temperature at the surface is raised to such an extent that natural boiling begins to take place. This would completely mix the material in the zone in which there was an appreciable quantity of rising bubbles and establish a hot zone. However, owing to the extremely complicated composition of kerosine, it was not possible to test quantitatively the above conceptions, and the detailed mechanism of the burning of oils must remain an open question until information on much simpler mixtures is available.

Mechanism of Heat Transfer to the Surface

The rate of burning of kerosine in the fire was 1g/sec; therefore the heat which reached the surface must at least have provided sensible and latent heat to vaporise this amount. From data given by Spiers[10] it was estimated that this would be about 160 cal/sec. From the temperature gradient in the vapour ($25^{\circ}C$./cm) and the conductivity of the vapour (c.a. $1-2 \times 10^{-4}$ C.G.S. units); the amount of heat conducted to the surface of the burning liquid was estimated to be about 3 cal/sec., a very small fraction of what was required. From the reading on the total radiation pyrometer, and the average dimensions of the column of flame the amount of downward radiation through the base of this column of flame was estimated to be about 190 cal/sec. Not all this heat would have been absorbed by the kerosine since account has to be taken of absorption of radiation by the vapour, the geometrical factor of the surface in relation to the base of the flame and the emissivity of the surface. Little is known about the absorption of thermal radiation by kerosine vapour. However, the absorption of luminous radiation is likely to be quite small until temperatures above $1000^{\circ}C$. are reached [11] and it may be expected from the infra red absorption spectra of lower hydrocarbons at room temperature [16] that the kerosine vapour will be transparent to the bulk of the infra red radiation. The absorption of radiation by the kerosine vapour may therefore be neglected. If the bottom of the flame is considered to be a uniformly diffusing plate the amount of radiation which reaches the kerosine surface may be calculated from a formula given by McGuire [12] to be 163 cal/sec. If the emissivity of kerosine is taken to be 0.9 [6], it will be seen that the radiation transmitted to the kerosine through the base of the column of flame is of the same order as that required to bring about vaporisation. It may therefore be concluded that the bulk of the heat was transferred to the surface of the liquid by radiation.

Spalding [13] has developed a theory by means of which the rates of burning of liquids may be calculated. This theory is based on mass transfer and conductivity equations in the films of vapour and diffusing combustion products next to the surface; the effect of radiation is neglected. He found that rates of burning predicted from this theory gave rates of burning of the same order as those actually obtained with kerosine flowing down a vertical plate and a sphere. Since in the fire described in this report the bulk of the heat transfer was by radiation, it is clear that this theory cannot be applied without considerable modification.

Some interesting consequences may be expected to follow from the fact that for a fire burning in an open vessel, radiation from the flames is the main factor bringing about the evaporation of the liquid. Firstly the imposition of a wind will tend to blow the flames away from directly above the vessel and therefore decrease the radiation. No controlled

experiments have been carried out on the effect of wind velocity on the
rate of burning, but general experience of oil fires runs contrary to
this prediction.   Secondly increasing the size of the fire would increase
the size and therefore the emissivity of the flames.   The radiation would
thus be increased and therefore the rate of burning per unit area would
increase.   This is in accord with experimental work already carried out,
although Katan ascribed this effect to the smaller proportion of heat
losses through the vessel walls as the size of the fire is increased.

Acknowledgement

11.

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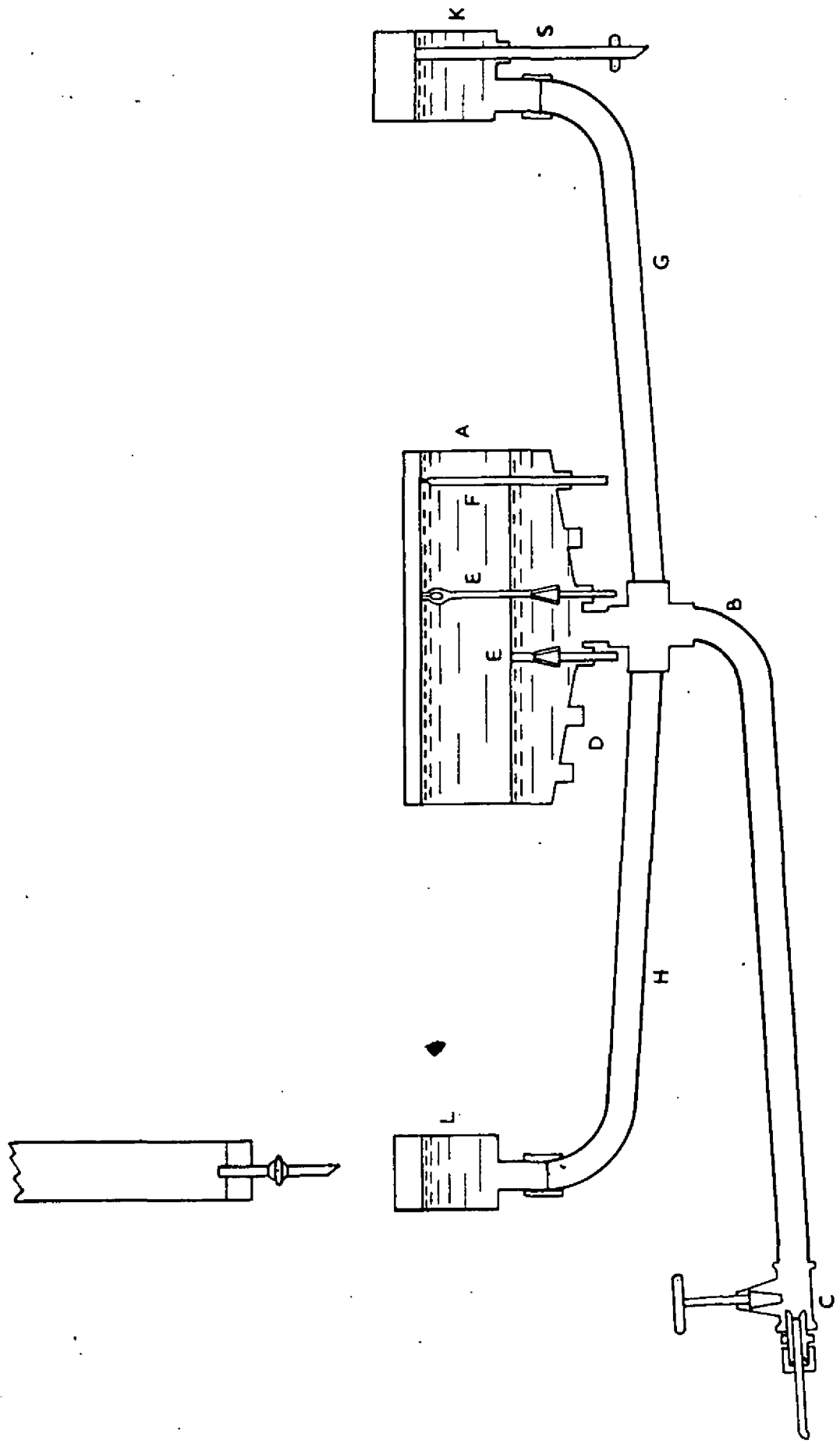16. W.M. Coblentz. Carnegie Inst. of Washington, Pub. 35 1905 p.166-170 and p.218.

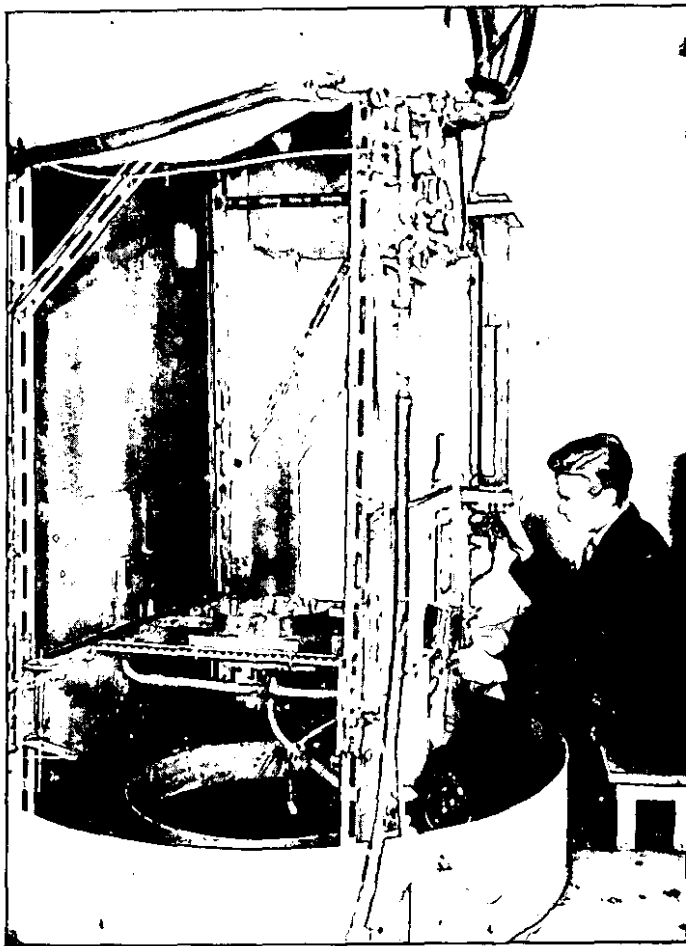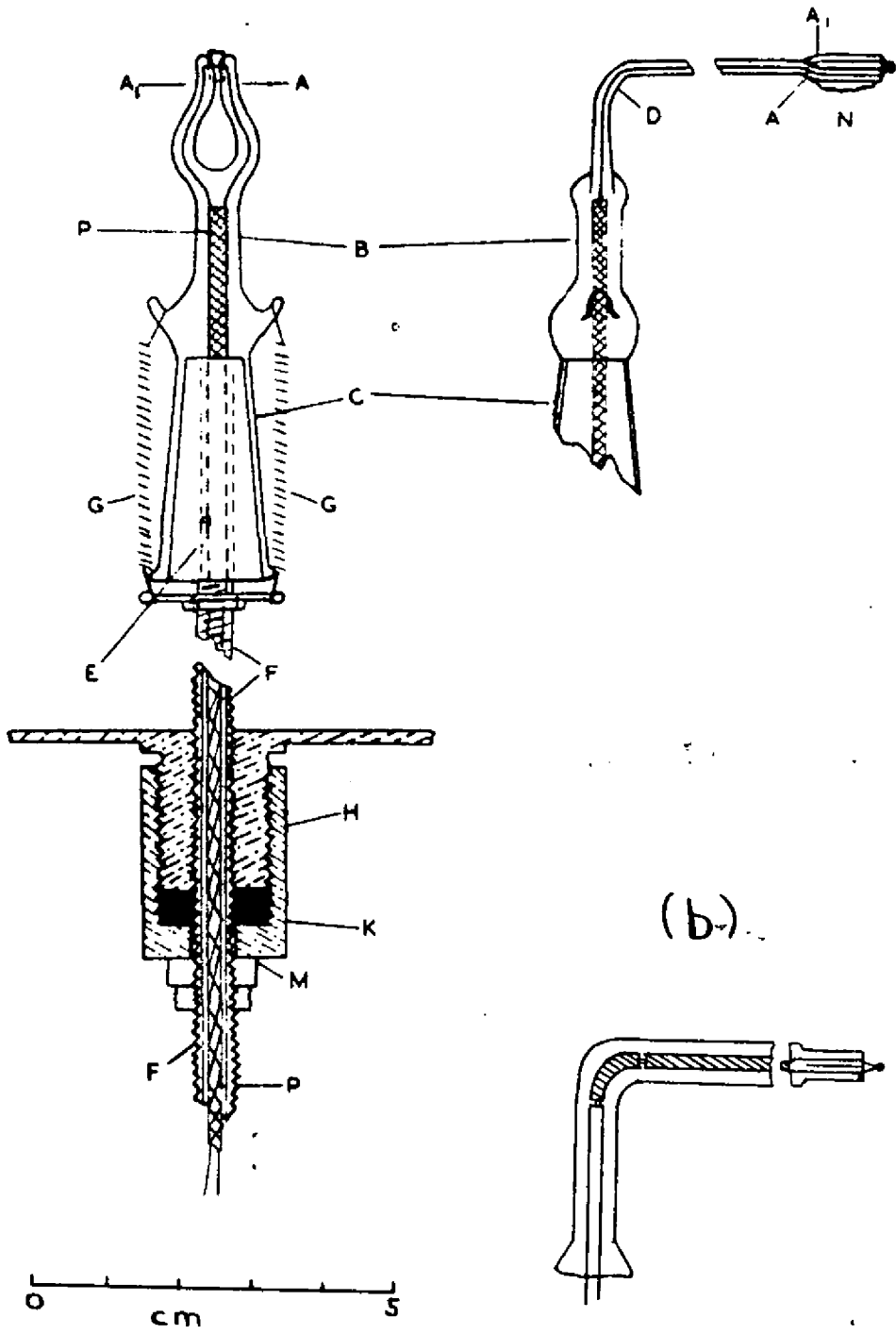FIG.1   DETAILS   OF   COMBUSTION   VESSEL.

FIG.2. MOUNTING OF THE COMBUSTION VESSEL

FIG.3. DESIGN OF THERMOCOUPLES

COLUMN OF LUMINOUS FLAME

SEMI TRANSPARENT FILM

RIBS OF LUMINOUS FLAME

VAPOUR ZONE

SMALL GAP

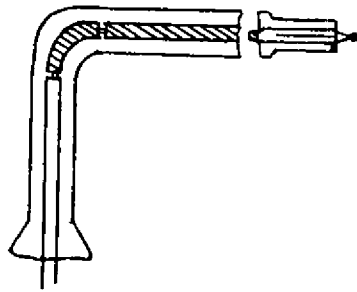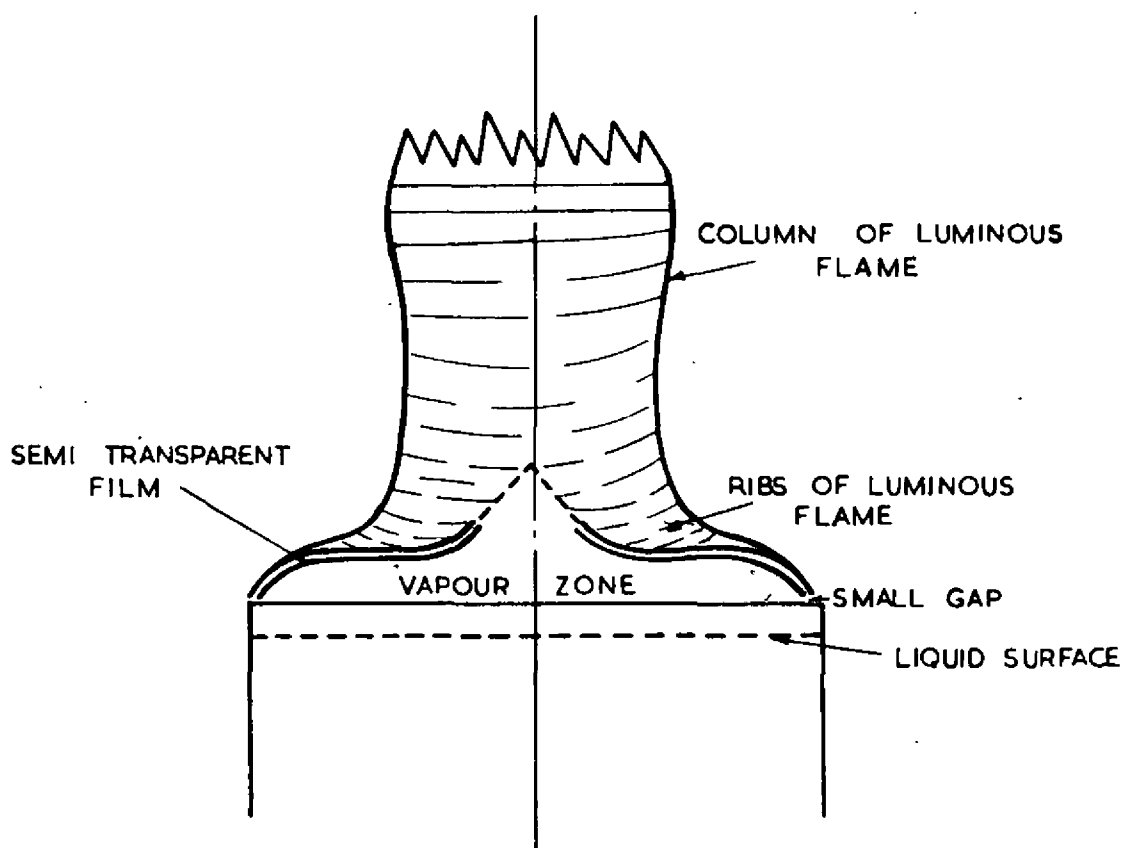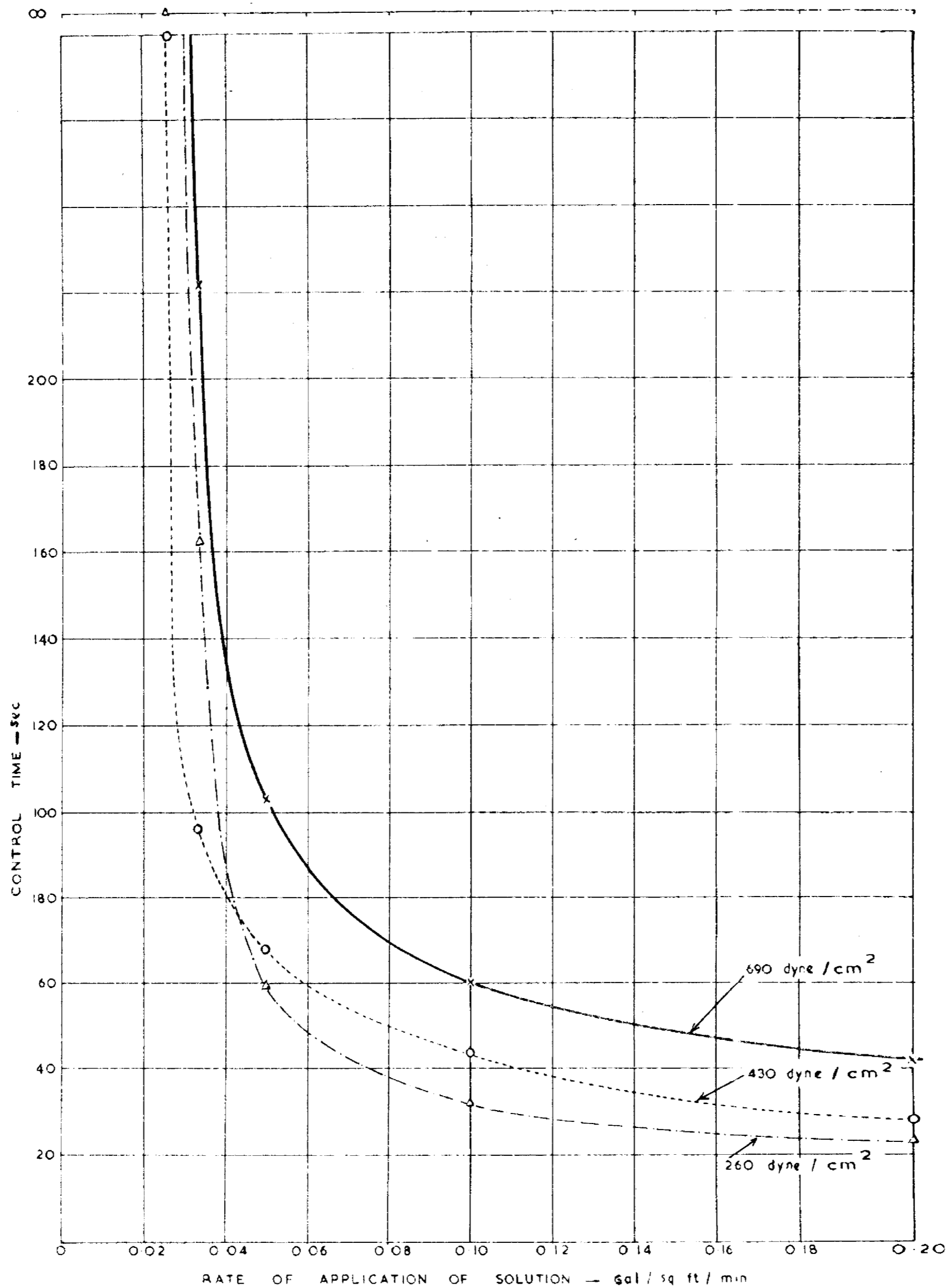LIQUID SURFACE

FIG.4.   STRUCTURE OF THE FLAME

FIG.11. EFFECT OF RATE OF APPLICATION OF SOLUTION ON CONTROL TIME FOR THREE VALUES OF CRITICAL SHEARING STRESS. COMPOUND A. 25" DIAMETER TRAY. EXPANSION FACTOR = 7.5 EXCEPT FOR 430 dyne /cm² CURVE WHICH IS MEAN OF FOUR VALUES (SEE FIG.10)

Direction of increasing time

The upward motion of the flames
is followed by measuring the
position of the flame top in
consecutive photographs.
From the difference in position
in two consecutive photographs
the upward velocity at the
height of measurement may be
calculated

Film speed— 32 frames /sec
Each division= 5 cm

FIG. 5. MOTION OF THE FLAMES
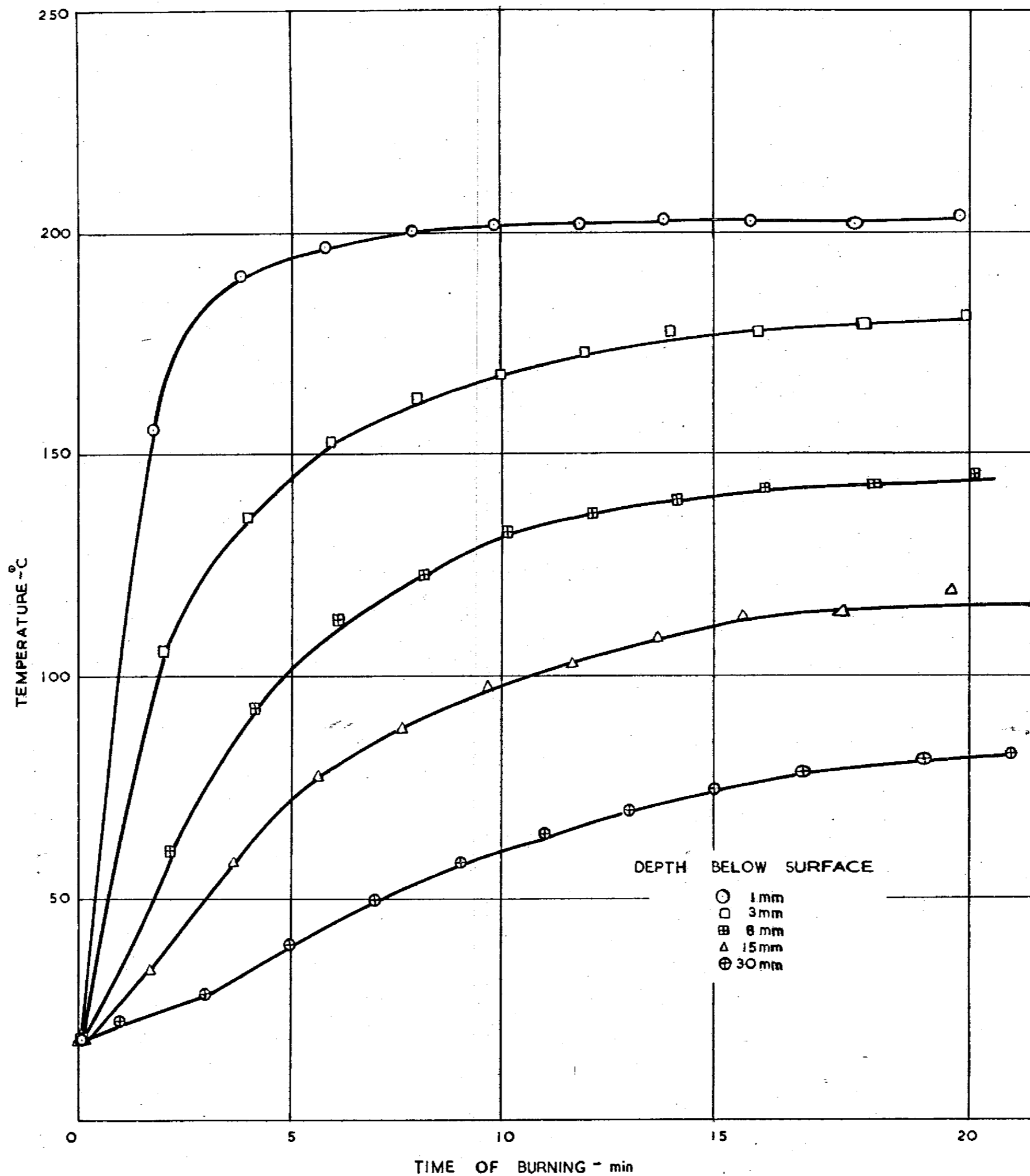
FIG. 6.   TEMPERATURE   BELOW   THE   SURFACE   OF   BURNING   KEROSINE
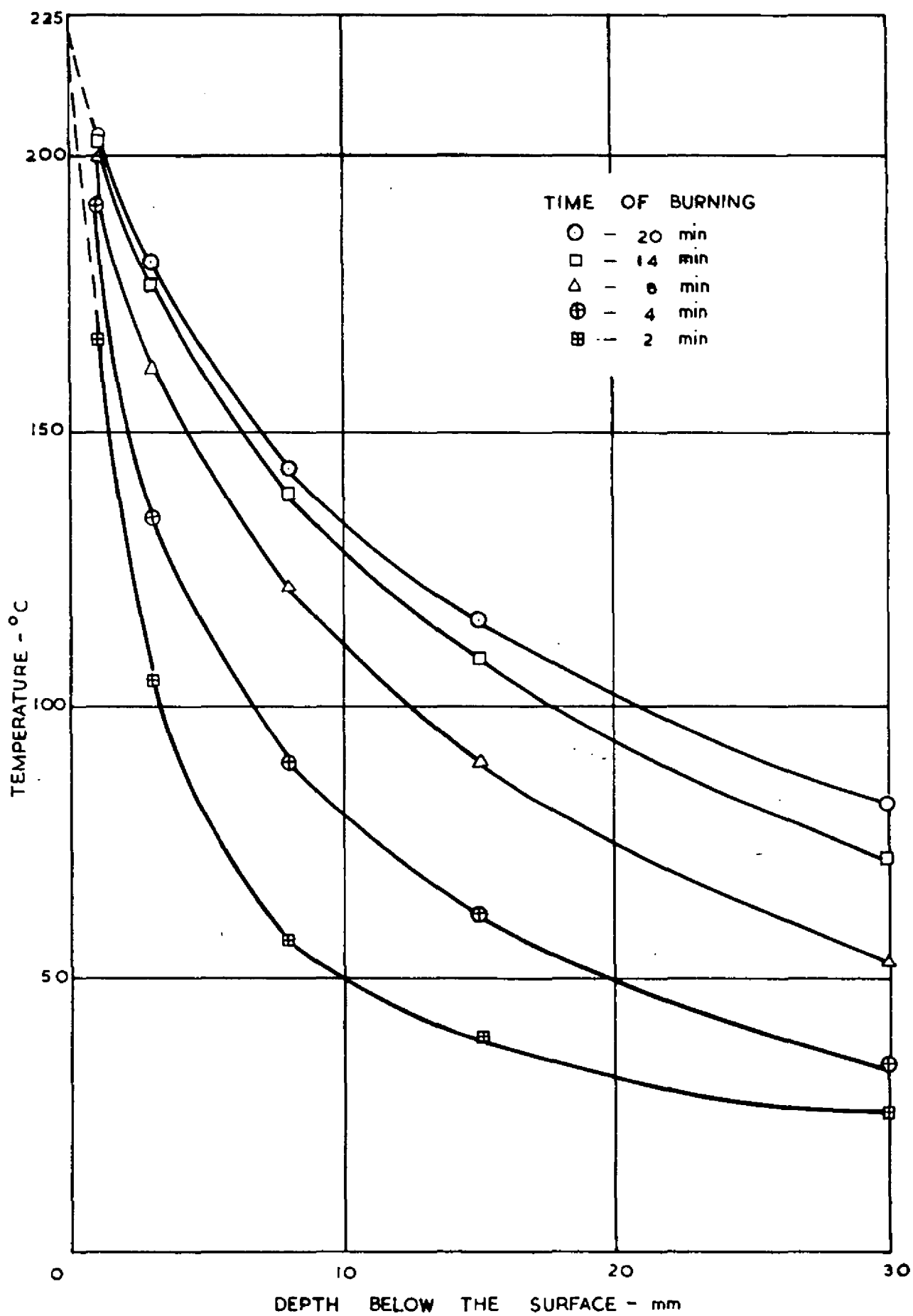(VARIATION   OF   TEMPERATURE   WITH   TIME   OF   BURNING)

FIG. 7.
TEMPERATURE BELOW THE SURFACE OF BURNING KEROSINE.
(VARIATION OF TEMPERATURE WITH DEPTH BELOW
THE SURFACE)