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A TEST RIG FOR REPRODUCIBLE FIRES ON BANKS OF TUBES

by

G. W. V. Stark

SUMMARY

A method is described for the production of reproducible fires of oil pouring over an array of tubes (the tube rig), so that the tube rig is uniformly enveloped in flames. The effect of the oil (kerosine, gas oil or transformer oil) on the temperatures reached by the rig was small. An increase in the speed of the wind blowing on the tube rig reduced the temperature reached by the rig. The uniformity of envelopment in flame, and the temperature of the tube rig increased with increasing flow of burning oil. The uniformity of envelopment of the tube rig in flames was complete at rates of flow of oil about 3 gal/min, and the temperature of the tube rig became fairly constant at rates of flow greater than $4\frac{1}{2}$ gal/min.

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INTRODUCTION

A report has been published recently of an investigation of the extinction by water spray of fires of oil running over banks of steel tubes(1). It was a requirement for this investigation that, for a given set of conditions, the fires against which sprays were tested should be reproducible. The present note describes the test rig used and the measures adopted to ensure that fires on the rig were reproducible. The effect of the rate of flow of oil, oil properties, and wind conditions (a) on the temperature reached by the tube rig, and (b) on the total radiation from the tube rig and flames, are also discussed.

EXPERIMENTAL

Site and equipment

A diagram of the site and equipment is given in Fig.1. The radiation thermopiles R_1 and R_2 were used to measure the total radiation from fires on the tube rig.

The tube rig as used in the vertical and horizontal position is sketched in Figs.2 and 3 respectively. The five tubes marked X in Fig.2 were each equipped with two nichrome-steel thermocouples at 2 ft 9 in and 4 ft 3 in from the bottom of the tubes. The leads from the thermocouples passed through sealed conduit extending 1 ft up inside the steel tubes, so as to minimise the risk of water shorting the thermocouples (Fig.4). Any thermocouple could be connected to a recorder by means of a rotary switch, and the bottom thermocouple on the centre tube was permanently connected to a millivoltmeter. In the following account all quoted temperatures of the tube rig are the temperatures of the permanently connected thermocouple, unless stated otherwise.

Details of the construction of the vertical tube rig, and some notes on its use to obtain reproducible fires, are given in Appendix 1.

Method for obtaining reproducible fires

Several methods were tested before a satisfactory way was found of ensuring reproducible fires on the tube rig. In each method the oil was ignited by preheating the tube rig by fires of petrol in small trays at the base of the tube rig. The trays of burning petrol were left there for a short time after the oil had been turned on, and was pouring down the tubes, to act as an extended ignition source. It was found essential to shield the tube rig from the wind during the early stages of ignition, in order to ensure rapid and complete development of fire over the tube rig. A 10 ft square screen erected about 10 ft from the rig on the windward side was found unsatisfactory, as the wind, whose direction often fluctuated as much as 90° about the mean, could still reach the rig. A 6 ft square screen mounted against the tube rig on the leeward side of the tube rig was also unsatisfactory because, when the wind velocity was above about 3-5 ft/sec and, the flames were deflected downwards and around the lower portion of the screen, allowing the upper part of the tube rig to cool so that it did not support flames. The best results were obtained with the arrangement shown in Fig.5. A 6 ft square screen was mounted close to the tube rig on the windward long side of the tube rig; this was augmented by a smaller screen, erected for part of the pre-heating period on the short windward side of the tube rig, (Appendix 1). With the latter arrangement of screens, a satisfactorily uniform development of fire over the whole of the tube rig was obtained within 20 seconds of turning on the oil supply to the tube rig. Any failure of the fire to develop completely by that time was usually found to be due to some defect in the oil supply system.

Sufficient tests were performed under otherwise constant conditions to estimate the effects of variation in the wind on the fire. The majority of the tests were made with transformer oil ("Insulating Oil, Low Viscosity for Transformers and Switch Gear", British Standard 148) but tests were also made with kerosine and gas oil. The properties of the oils used are given in Table 1.

TABLE 1

Properties of Oils

Type	Flashpoint °C	Firepoint °C	Distillation	
			First drop °C	50 per cent °C
Transformer oil	167	180	220	350
Gas oil	91	98	190	270
Kerosine	58	61	158	198

The tests on the horizontal tube rig were made with transformer oil only for comparison with the results on the vertical tube rig. The effects of variation of the preburn time, oil flow ratio and oil properties above parameters on the fire on the tube rigs were estimated from measurements of tube temperature and total radiation from the fire, supplemented by observation. The temperature from the bottom thermocouple on the centre tube was taken to be representative of the temperature of the tube rig.

General procedure

The procedure for tests with each oil was the same, except for the preheating period, i.e. the period when petrol was burned at the base of the tube rig, prior to turning on the oil supply. This preheating period was 3 minutes for transformer oil and 2 minutes for kerosine and gas oil fires.

RESULTS

Effect of rate of flow of oil

The effect of the rate of flow of oil on the properties of the fire on the tube rig was examined with transformer oil fires on the vertical tube rig. Tests were made with the oil flowing at differing rates of flow, and in Figs.6 and 7 are given the relations found after two minutes burning between the rate of flow of transformer oil, and the temperature of the tube rig and total radiation respectively. The scatter in the results was considerable, being much larger for radiation than for temperature. The mean curves given in Figs.6 and 7 were obtained by grouping the results at intervals of about 1 gal/min rate of flow of oil. The extent of the scatter in the results for temperature of the tube rig is shown by the individual test points in Fig.6. Although the mean wind speed during individual tests ranged from 1.5 to 15.4 ft/sec., the mean values for the groups of results used to plot the curves had a much narrower range, 5.2 to 6.5 ft/sec, with an overall mean value of 5.8 ft/sec.

The curve, Fig.6, indicates that the mean temperature of the tube rig reached a fairly steady value at rates of flow of transformer oil above $4\frac{1}{2}$ gal/min. The total radiation Fig.7, which included not only the radiation from the tube rig and the flames on it, but also the radiation from the flames above the rig, increased uniformly as the rate of flow of oil increased from about 4 gal/min. The curve in Fig.7 shows a sharp inflexion upwards at about 2-3 gal/min rate of flow; this inflexion was also found for shorter burning times. The effect would appear to be allied to the observation that unless the rate of flow was above 3 gal/min, the tube rig was not completely involved in flames.

The values at zero time of burning of temperature and total radiation in Figs.6 and 7 are above ambient and zero respectively. This was because firstly, the tube rig was preheated by petrol fires and secondly, a small volume of the petrol flames escaped beyond the wind screens to be detected by the radiometers.

Effect of time of burning

The effect of the time for which oil was burning on the tube rig on the mean tube rig temperature and total radiation was examined from tests in which the rate of flow of oil was between 4.5 and 6.5 gal/min, with a mean value of about 5.5 gal/min. Tests were made with transformer oil, gas oil and kerosine on the vertical tube rig, and with transformer oil on the horizontal tube rig. The results obtained are shown in Figs. 8 and 9.

It was again found that the temperature of the tube rig at a given time varied less between tests than the total radiation. The mean curve relating temperature of the vertical tube rig to the time of burning of transformer oil is drawn in Fig.8, together with the curves of the 95 per cent confidence limits of the individual plotting points. The temperature of the tube rig increased regularly for the first two minutes, after which the rate of increase of temperature decreased as the time of burning increased. The maximum possible mean temperatures of the tube rig did not appear to have been reached after 4 minutes burning, the longest time of burning used.

The results of tests on the horizontal tube rig with transformer oil and tests on the vertical tube rig with kerosine and gas oil are also plotted in Figs. 8 and 9. The temperatures of the tube rig in these tests are related to the time of burning in the same way as for fires of transformer oil on the vertical tube rig. Thus the curves are similar, except for the initial temperature of the tube rig at the end of the preburn period, when the oil was turned on. The differences in initial temperature were associated with the different preburn and ambient conditions. The relations between time of burning and total radiation, however, show greater differences between the conditions of test. The mean radiation from transformer oil fires on the vertical tube rig reached a value of 0.1 cal cm^{-2} sec^{-1} at a distance of 17 ft from the tube rig in about 2 minutes, after which the rate of increase was small. Both gas oil and kerosine fires reached similar maxima but in times shorter than two minutes. The relation between the time to reach maximum total radiation and the fire point of the oil is plotted in Fig.10. The maximum level of total radiation from fires of transformer oil on the horizontal tube rig was significantly higher than the maximum for transformer oil fires on the vertical tube rig.

Effect of wind

The results of tests on fires of transformer oil on the vertical tube rig, in which the rate of flow of oil lay between 4.5 and 6.5 gal/min, were used to examine the effect of wind conditions on the temperature of the rig, and the total radiation from the flames and the rig. Insufficient tests were made with other oils, or on the horizontal rig, for curves to be plotted. The variation in the values at a given time of burning of tube temperature and total radiation prevented these values being used with confidence to study the effect of wind conditions on the development of the fire. The variations were due mainly to the differences in the preheating by the petrol fires, and to the differences in the times for which the wind shields were in place to ensure the development of a uniform fire over the tube rig. The rate of increase of tube temperature and total radiation, however, was not subject to such variation. In Figs. 11 and 12 the rate of increase, (in the period from 30 secs to 1 min. of burning time) of temperature and total radiation respectively are plotted against wind speed. These figures suggest that the rates of increase of temperature and total radiation pass through maxima, that for temperature occurring at about 3 ft/sec and that for radiation at 7 ft/sec. The results of tests with transformer oil fires on the horizontal tube rig indicated similar behaviour.

It was observed during tests that at windspeeds greater than about 1 ft/sec the flames were readily deflected, but that the individual tubes in the rigs were surrounded by flames up to wind speeds of 2-3 ft/sec. The flame envelope was about 10 in wider than the tube rig under still conditions. The brightness of these flames increased with increasing wind speed, and the length of the flames did not appear to vary much over this range of wind speeds. However, as the wind speed increased above 5 ft/sec, the increasing brightness was accompanied by a reduction in the volume of the flames which were also very thin on the windward side of the tubes, until at speeds greater than about 8 ft/sec, the flames ceased to surround the tubes all the time, but remained attached principally to the leeward side. This latter stage was accompanied by a reduction in the luminosity of the flames, and, as the wind speed increased to speeds above about 12 ft/sec, the flames became very short and often transparent.

Temperature distribution over the tube rig.

The 10 thermocouples on the tube rig (Fig.2) were fitted so as to allow a survey of the distribution of temperature over the tube rig to be made during fire tests. Records of temperature were incomplete, because this work was part of the programme on the extinction of the fires by water sprays[1] and the tube rig suffered such distortion during extinction tests that thermocouple leads were often ruptured, the thermocouples in the outer positions being damaged most frequently. However, sufficient records were obtained to allow a general assessment of the effect of wind speed and direction on the distribution of temperature over the tube rig.

Maximum temperatures were more frequently recorded on the bottom than on the top thermocouples, the proportion remaining fairly constant from 2 to 8 ft/sec, wind speed, and increasing rapdily as the wind speed increased from the latter value. Wind speed also affected the position on the tube rig at which the maximum temperature was recorded. At wind speeds greater than about 9 ft/sec, the maximum temperature was recorded mainly on the outer four pairs of thermocouples; no maximum temperatures were recorded on the centre pair of thermocouples at wind speeds greater than 13 ft/sec. On the other hand, as wind speed decreased from 9 ft/sec, the proportion of maximum temperature readings recorded on the centre pair of thermocouples increased, no records being obtained of maxima on the outer pairs of thermocouples at wind speeds below 3 ft/sec.

The pair of thermocouples on which maximum temperature was recorded depended largely upon wind direction. In general, the maximum temperature was recorded either on the centre thermocouples, or on those on the leeward side of the rig. One particular exception was noted, when the wind was from the South West. Maximum temperature was then often recorded on the pair of thermocouples on the West. This was thought to be due to the practice of erecting the small wind screen on the North West short side of the bank when the direction of the wind was normal to the long sides of the tube rig. The flames from the petrol or oil, when these screens were erected, were drawn into the corner formed by the two screens. During the period before the screens were removed, maximum temperatures were recorded on these thermocouples closest to the corner so formed, and often a minute or so elapsed before the more common pattern of temperature distribution established itself.

DISCUSSION

The reproducible fire

The tests described herein show that the method used, while producing fire in which the tube rig was uniformly involved in flames, nevertheless results in some variation in the temperature of the tube rig and the total radiation from the fire for a given set of conditions. The variation of temperature was less than that of the total radiation. The important property for the assessment of the requirements for extinction of such a fire with water spray is the temperature of the tube rig(1). Total radiation is unsuitable for such an assessment, because the extinction process is essentially one of reducing the temperature of the oil on the tube rig below the fire point, not the flames. It was noted elsewhere(1) in this respect that the extinction of fires on the tube rig need not be accompanied by the cooling of the tube rig itself to a temperature below the fire point of the oil. Much of the observed variation in temperature of the tube rig was due to the range of wind conditions.

Heat transfer processes

The contribution of radiation, convection and conduction to the transfer of heat from burning transformer oil to the tube rig has been calculated (Appendix II). Calculated and experimentally determined rates of rise of temperature of the tube rig are given in Fig.13; curve A is calculated for an average flame thickness around each tube of 38 cm, curve B for an average flame thickness of 18 cm, and curve C is the mean temperature from a series of tests with transformer oil supplied at an average flow of 5.5 gal/min (48 lb/min). The larger flame thickness was based on an estimate of the flame thickness for low wind to still air conditions, say 0-1 ft/sec, and the smaller flame thickness is an estimate of the flame thickness for a low to medium wind speed, say about 3-5 ft/sec. Higher wind speeds would be expected to reduce the contribution of heat transfer due to radiation, because of dilution with air of the flames around the tubes producing a reduction in intensity.

The different shape of the experimental to the calculated curves in the first minute or so of burning is probably due to time taken for radiation to reach a maximum (Fig.9), as the calculated rise in temperature was made assuming that radiation from the flames was constant.

The similarity of the rates of increase of temperature of the tube rig, when kerosine, gas oil or transformer oil were supplied to the tube rig at the same rate of flow (Fig.8), suggests that the heat transfer is directly related to the heat supplied by the combustion of the oil and that flame temperatures and emissivities for the three oils are similar. The rates of heat release (heat of combustion) for the three fuels are nearly the same, namely 159000, 165000 and 169000 B.T.U./gallon for kerosine, gas oil and transformer oil respectively.

Only a small part of the heat available from the combustion of the fuel is used to raise the temperature of the tube rig and to vaporise the fuel supplied to the tube rig. Since the bulk of the heat supplied to the tube rig is radiant, the temperature of the tube rig would be expected to approach a maximum value when the rate of flow of fuel is such that the tube rig becomes completely enveloped in flames. Once the tube rig is completely enveloped in flames, the temperature of the tube rig at a given time would be expected to decrease as the rate of flow of oil increased, because some of the heat supplied by radiation and convection from the flames would be used in heating and vaporising the additional oil supply. At a certain high flow rate of oil, the oil passing over the tubes would not be heated to its fire point; under these conditions, extinction would occur.

The heat transfer to the tube rig at the beginning of a burning test is estimated as about 21000 B.T.U./min with transformer oil supplied at 5.5 gal/min (48 lb/min). The application of an additional 23 gal/min (202 lb/min) would remove all this heat without the liquid reaching the fire point. Such a flow rate was not reached in the present tests, where the maximum rate of flow of transformer oil was about 12 gal/min. The results presented in Fig.6 however, suggest that the condition of complete envelopment of the tube rig by flames, indicated by a levelling off of the heat transfer to the tube rig, was achieved at a flow rate of about 5 gal/min or more of oil. The levelling off could well be due to the additional heat from increasing radiation (Fig.7) offsetting heat lost by heating the increased supply of oil to its fire point. The increase in radiation as flow increases above 5 gal/min suggests that the thickness of the flame enveloping the tube rig increases with increasing oil flow.

The quicker approach to maximum radiation, shown by the more volatile fuels burning on the tube rig, Fig.9, leads to the expectation of a more rapid rise in temperature during the early stages of a fire on the tube rig. However, no marked differences were found between the rates of rise in temperature of the tube rig, for fires of the three oils, for burning times up to 1 min. The effect of a more rapid approach to maximum radiation, however, would be offset by the observed differences in flame distribution over the tube rig. With the more volatile fuels, the bulk of the flames were on the upper part of the tube rig, where the temperature was not measured, while the least volatile fuel, transformer oil, gave a more uniform distribution of flame over the tube rig.

The effect of wind

The effect of wind speed, as it increased, was firstly to deflect and intensify the flames then, as the speed increased further, to remove visible flames from the windward side of the tubes in the tube rig and finally, at the highest speed, to reduce the luminosity of the flames. The length of the flames decreased as wind speed increased.

It therefore appears that over an intermediate range of wind speeds combustion would be improved and heat transfer would be at a higher rate than at lower windspeeds. As wind speed increased above this intermediate range, the heat transfer would be reduced because of the reduction in the radiation from the flames to the tubes; the tubes would also be cooled more readily because of the exposure of their windward surfaces to the wind. The experiments showed that the rate of increase of radiation from the flames (Fig.12) increased with increasing wind speed up to about 7 ft/sec; the rate of increase of tube temperature (Fig.11) decreased as the wind speed increased from about 3 ft/sec.

The latter result suggests that at wind speeds between 3 ft/sec and 7 ft/sec the cooling effect of the wind on the tube rig was greater than any increased heat transfer by radiation from the flames. The effect of high wind speeds on a fire of oil on the tube rig can be examined by comparing the amount of air required for combustion and the amount of air, and consequently wind speed, passing through the tube rig.

At high wind speeds, when the flames are appreciably shortened, it would be reasonable to expect the bulk of the air for combustion to be supplied through the interstices of the tube rig. Considering the circumstances of wind from the prevailing direction, the air for combustion would be supplied through the long face of the tube rig. The combustion of 5.5 gal/min (48 lb/min) of transformer oil requires about 700 lb/min of air, and this quantity would be supplied by a wind speed of 7.4 ft/sec. Higher wind speeds than this would be expected to dilute the combustion products and reduce their temperature and the radiation from the flames.

CONCLUSIONS

The method of producing a fire of oil pouring over the tube rig, as described in Appendix I, is sufficiently reproducible for its use as a standard for testing extinguishing systems if the following conditions are fulfilled.

1. The tube rig is kept in good condition and shape by repair and rebuilding as necessary.

2. The oil distributing manifold and its orifices are kept clean.

3. The oil distributing baffle plates are correctly placed and free from major distortion.

4. The wind screens are placed in position and withdrawn as indicated.

5. Tests are conducted when the wind speed does not greatly exceed 7 ft/sec. However, tests at high wind speeds may be necessary to examine the capabilities of an extinction system.

An assurance that the above conditions have been fulfilled can be obtained by performing tests in replicate.

A simple assessment of the heat transfer and combustion process suggests that the rate of heating of the tube rig and the effect of wind on the fire can be reasonably explained.

REFERENCES

1. RASBASH, D. J. and STARK, G. W. V. F.R. Note No.303.

APPENDIX I

THE TUBE RIG FOR REPRODUCIBLE FIRES

1. General

The tube rig consisted of a framework of 21 tubes, 7 ft long, with loose fitting caps on the exposed ends, supported by three frames of light $1\frac{1}{2}$ in angle. The tubes were $1\frac{1}{2}$ in pipe conforming with B.S. 1387, Class B. They were erected vertically in 3 rows at 9 in $\pm \frac{1}{4}$ in centres, each consisting of 7 tubes at 9 in $\pm \frac{1}{4}$ in centres apart, forming a rectangular array. The overall dimensions of the tube rig, excluding the short cross members of the supporting frames, were 7 ft $\pm$ 1 in high x 4 ft 8 in $\pm$ 1 in long x 1 ft 8 in $\pm \frac{1}{2}$ in wide.

2. Supporting frames

The top two supporting frames were made from $1\frac{1}{2}$ in angle of 14 SWG slotted steel and consisted of three long members extending $1\frac{1}{2}$ in beyond the end tubes in the rows, braced at each end of the rig by a short member of the same angle, and braced across the middle of the frame by a strap not more than $1\frac{1}{2}$ in wide and $\frac{1}{8}$ in thick. The long members of the supporting frame were mounted with the flat surface uppermost on the inside of the rows of tubes, and the tubes were attached thereto by U-bolts made from $\frac{1}{4}$ in dia. steel rod; each junction of long frame member and tube was secured in this way. The bottom frame was of similar construction but was made from 3/16 in rolled $1\frac{1}{2}$ in angle. The bottoms of the supporting frames were 9 in $\pm \frac{1}{2}$ in, 3 ft 5 in $\pm \frac{1}{2}$ in and 6 ft 1 in $\pm \frac{1}{2}$ in respectively from the base of the array of tubes. Further details of the attachment of the top frame is given in Article 3 below.

3. Oil distribution over the tube rig

Oil was delivered to the tube rig by a three-branch manifold of $\frac{1}{2}$ in dia., B.S. pipe, rigidly attached to the supporting frames of the tube rig, and arranged to run inside the array of tubes and above the top supporting frame. The oil was delivered from 1/16 in jets drilled in the manifold and directed at an angle of 30° downwards from the horizontal, at the middle line of each tube. To contain the oil within the confines of the tube rig, a 16 S.W.G. mild steel baffle plate, 5 ft long and 6 in high, was fixed above the top rail to each row of tubes, between it and the oil manifold. The bottom edge of the baffle plates was secured by clamping them between the tubes and the top frame; the top edge was secured to the tubes by one or two of the U-bolts described above. An even distribution of oil over the tubes was secured by placing small wedges of $\frac{1}{8}$ in x $\frac{1}{8}$ in section between the top supporting frame and the baffle plates, at the junction with each tube, and clamping them in place with the U-bolts securing the tubes to the frames.

The three oil distribution pipes of the manifold were mounted so that their centres were 1 in $\pm \frac{1}{2}$ in from the tubes and 1 in $\pm \frac{1}{2}$ in from the top surface of the supporting frame.

4. Oil supply. Metering

The rate of flow of oil delivered to the tube rig from the manifold was measured by a flowmeter. The total flow of oil for each test was measured by a sight gauge fitted to the oil-storage tank. The transformer oil used was clean, water-free, used insulating oil, low viscosity, for transformers and switch gear, British Standard 148; the kerosine and gas oil used were fresh oils.

5. Siting, drainage

The tube rig was erected with a long side normal to the prevailing wind and 30 ft or so from the nearest building on an open site. It stood in an 8 in deep tray, 8 ft x 12 ft, filled to about 6 in depth with pea gravel, and fitted with a filter and drain so that a pool of oil and water did not form during a test.

6. Development of a standard fire of transformer oil

The fire was ignited by burning petrol. A $\frac{1}{2}$ gallon was poured into each of two long trays, 5 ft x 6 in x 6 in resting on the gravel bed and against the long sides of the tube rig, and $\frac{1}{4}$ gallon was poured into a short tray, 2 ft x 6 in x 6 in resting on the gravel bed and against the short windward side of the tube rig.

A 6 ft square framed sheet steel screen was erected against the long tray on the windward side of the tube rig, resting on gravel and against the top of the tube rig. The petrol was then ignited and after burning for two minutes, a narrow screen, 2 ft 6 in wide and about 6 ft high was erected against the short petrol tray and the top of the tube rig. After 3 minutes total burning time of the petrol, the oil was turned on. When the fire had developed so that at least 9/10ths of the bank was involved in fire, the petrol trays and screens were removed quickly so as to be clear of the tube rig and gravel filled tray.

The fire was usually sufficiently developed for the screens to be removed 15-20 seconds after the oil had been turned on. If the tube rig was not at least 9/10ths involved in fire at the end of the desired time of oil-burning, (preburn time) the test was considered void, and the system was checked as given below.

7. Maintenance of oil manifold

The 1/16 in jets of the oil manifold tended to become blocked with deposits and so to restrict the flow of oil. This was detected by observation and by the provision of a pressure gauge in the oil supply line. Since it was essential for the development of fire uniformly over the tube rig that the oil flow should not be restricted, the flow of oil was checked before each test and the manifold and jets cleaned if any restriction had occurred.

8. Notes on the operation and maintenance of the tube rig

Each test on the tube rig produced a certain amount of distortion of the rig and the individual tubes. This distortion became more severe as the preburn time increased and as water was applied to the rig, because of the uneven heating and cooling. A given tube rig could, however, be used for many tests, by levering the rig into its correct shape and straightening or replacing distorted tubes before each test. The U-bolts and supporting frames were also checked frequently for tightness.

It was essential for the safe operation of the tube rig that water was not drawn up into the tubes, where it might boil explosively. This was avoided by placing the caps loosely on the tubes, but it was found that drilling a $\frac{1}{4}$ in hole immediately under the caps was as effective.

The correct assessment of the performance of a spray nozzle system depended upon the development of a standard fire. Provided the oil was delivered uniformly to the tube rig, and the wind screens were correctly erected and removed, the variation between fires of a given duration were small, as measured by the temperature reached by the tubes in a given time of burning. If the fire was observed to be non-uniform, or if the oil flow was not within the prescribed limits, the test was considered void, and the oil supply system thoroughly checked before repeating the test.

Unburned oil was recovered from the drainage system for re-use by storing it in tanks until it had clarified, and then decanting it from the separated water and sludge, and adding it in "make-up" quantities to fresh oil.

APPENDIX 2

CALCULATION OF TEMPERATURE OF THE TUBE RIG

The processes involved when the tube rig is heated by burning oil pouring over the tube rig are

(a) preheating of the oil in the oil manifold by convection and radiation from the flames

(b) heating and vaporising the oil discharged

(c) heating of the tube rig by convection and radiation from the flames

(d) the removal of heat from the tube rig by the colder, wet gravel in which it stands

(e) the removal of heat from the flames and the tube rig by wind

In the calculation of tube rig temperatures given below, the effect of wind (e) has not been considered, except in so far as it could influence flame size.

Heat transfer by radiation from the flames was obtained from

$$H = 1.73 \times 10^{-9} \frac{E_1 E_2}{E_1 + E_2 - E_1 E_2} (T_1^4 - T_2^4) \text{ Btu ft}^{-2} \text{ hr}^{-1}$$

where

α = emissivity coefficient = 0.3

T_1 = Flame temperature, 1880°F (1025°C)

T_2 = tube temperature, 225°F (107°C) at start of burning

E_1 = flame emissivity = $1 - \exp(-\alpha L)$ (1)

L = flame thickness cm.

E_2 = emissivity of steel tubes = 0.8

Heat transfer by forced convection from the flames was obtained from

$$N_u = 0.24 \ R_e^{0.6}$$

when

Nu = Nusselt Number = $\frac{Hd}{K\theta}$

d = tube diameter

K = thermal conductivity of flame gases

θ = $T_1 - T_2$

Re = Reynolds Number $\frac{Vd\rho}{\mu}$

V = flame velocity(1) = 23900 ft/hr

ρ = density of flame gases

μ = viscosity of flame gases, in consistent units.

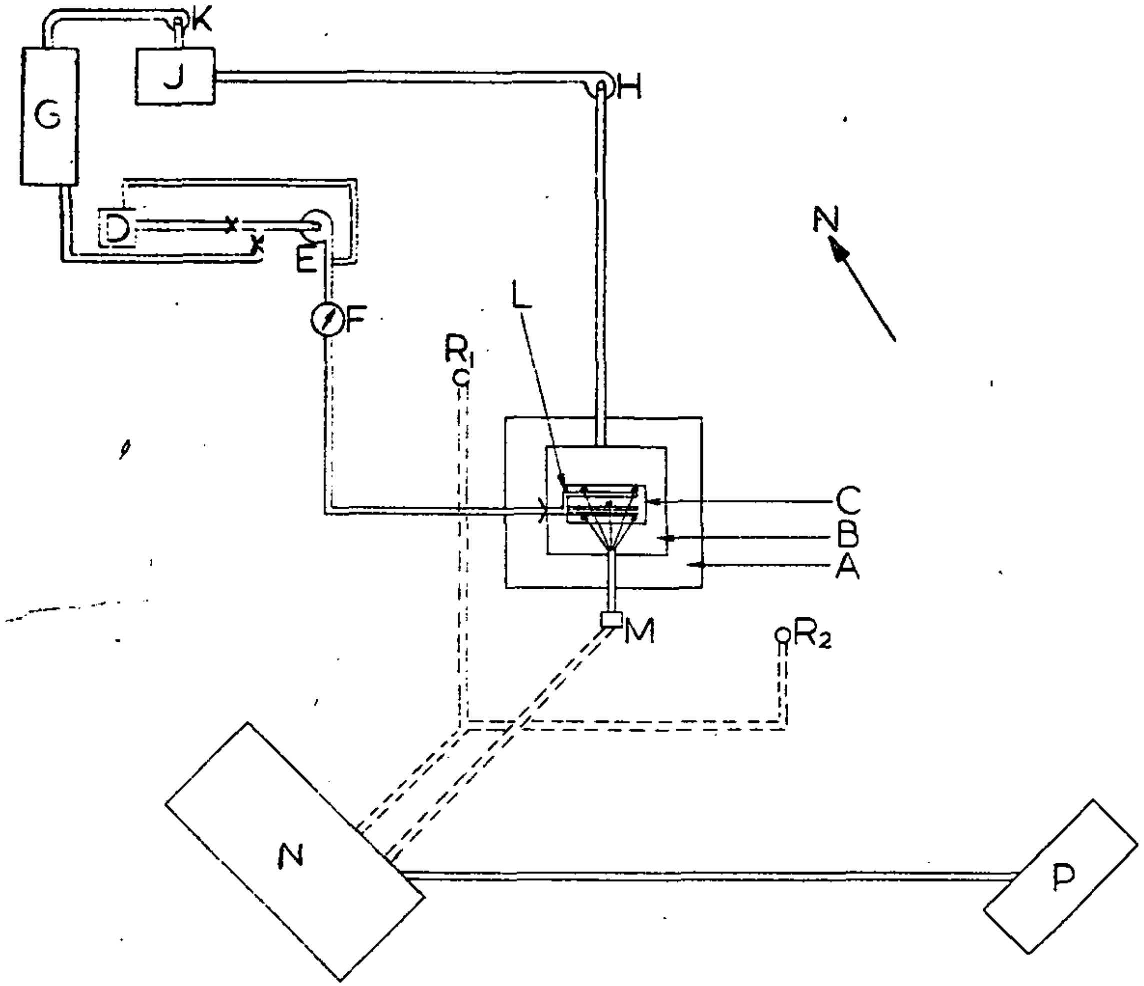
The flame gases were assumed to consist of the products of complete combustion of $C_n H_{2n}$. Relevant properties of gases and the oil were taken from Spiers "Technical Data on Fuel" and Fishenden & Saunders "Introduction to Heat Transfer".

Heat transfer by conduction from the rig to tbe wet gravel was calculated, making the assumption that conduction occurred over a 1 in. length of tube between the flame heated portion and the portion in wet gravel. This was the approximate depth of the dry gravel at the surface of the gravel bed. The temperature of the wet gravel, which was found to be heated to about 140°F at the end of some tests, was assumed to have a mean value of 85°F throughout a test.

The total heat transfer to the tube rig was obtained by summing the four contributions for the area of the tube rig, 100 ft^2, namely heat supplied by radiation and convection, and heat lost in vaporising the oil issuing from the manifold and heating the wet gravel. The values for flame thicknesses of 18 and 38 cm are plotted in Fig.14 against the temperature of the tube rig. From this heat transfer, the rate of rise of temperature of the tube rig was calculated, and is plotted in Fig.13, in which curve A is the calculated temperature for 38 cm flame thickness, curve B the calculated temperature for 18 cm flame thickness, and curve C the average measured temperature from experiments on the vertical tube rig with transformer oil supplied at a mean rate of 5.5 gal/min.

REFERENCE

(1) RASBASH, D. J., ROGOWSKI, Z. W. and STARK, G. W. V. "Properties of fires of Liquids" Fuel 35 No.1 Jan. 1956.



CODE

A = Concrete raft
B = Gravel filled trays
C = Tube rig, standing in B
D = 60 gall oil feed tank fitted with sight gauge
E = Centrifugal oil pump
F = Flowmeter
G = 1000 gall transformer oil storage tank
H = Drainage pump, gravel trays
J = Oil separating tanks
K = Transformer oil pump
L = Oil distribution manifold
M = Thermocouple cold junction
N = Control hut
P = Weather station
R = Wide angle radiation thermopiles
X = Control valves

FIG. 1. SITE AND EQUIPMENT — SCHEMATIC DIAGRAM

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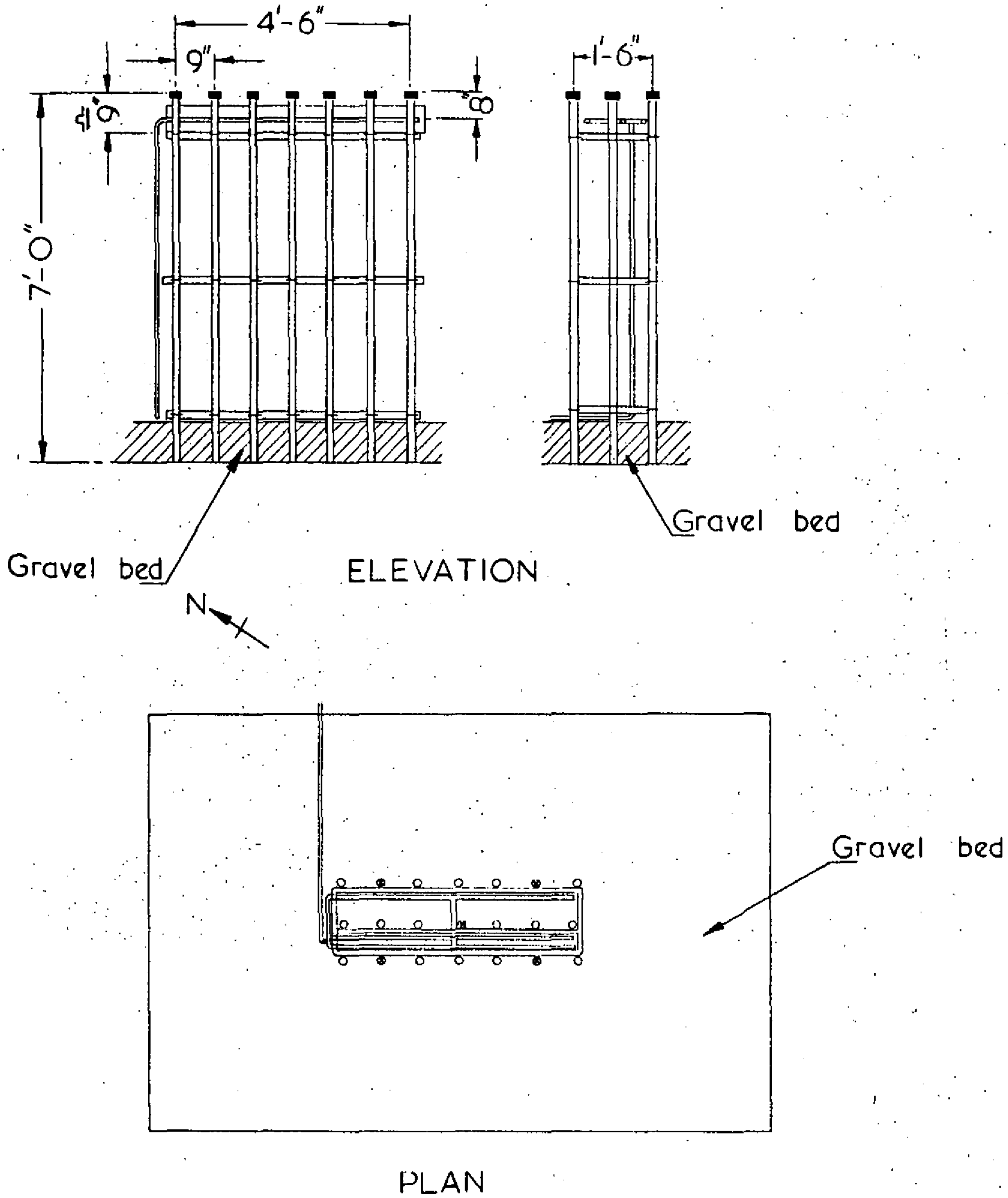

FIG. 2. VERTICAL TUBE RIG

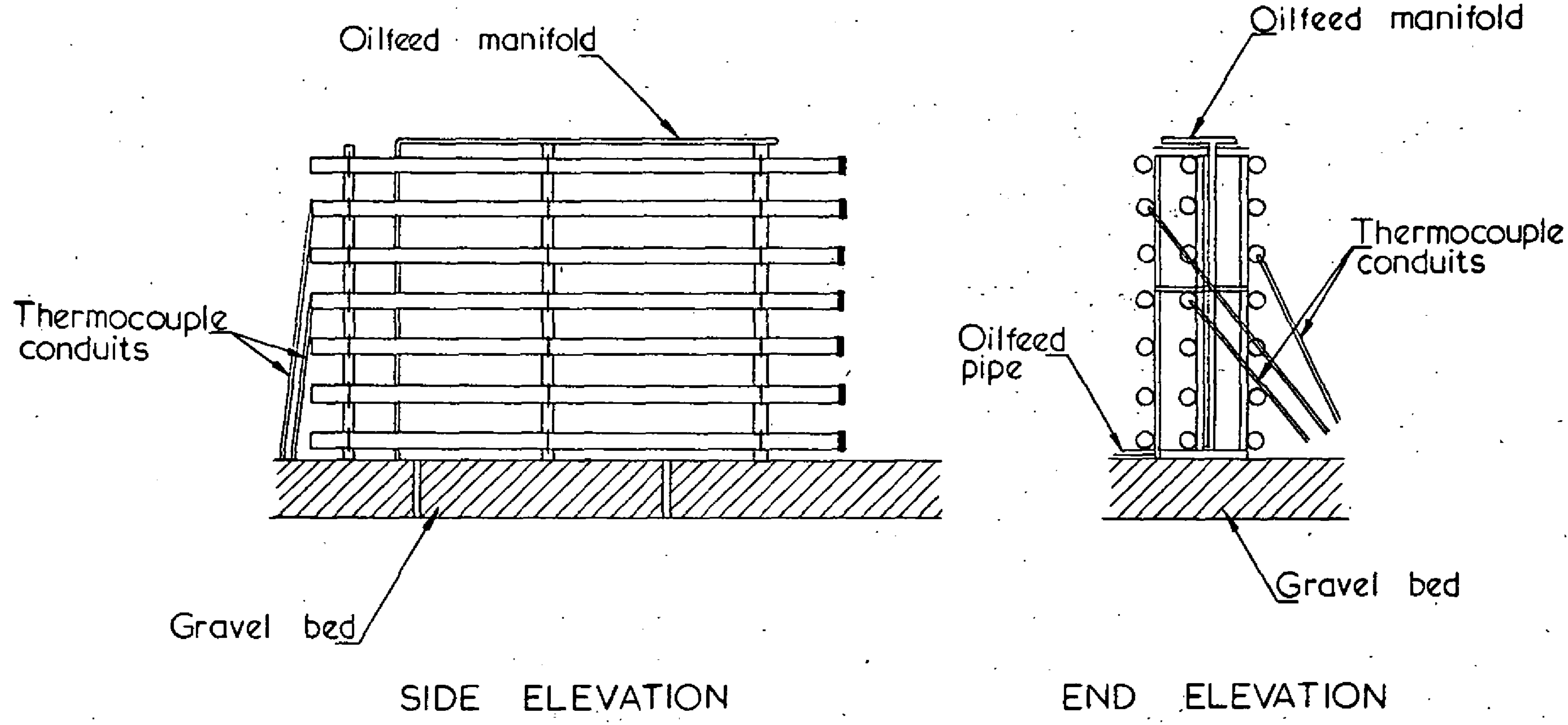

FIG. 3. HORIZONTAL TUBE RIG

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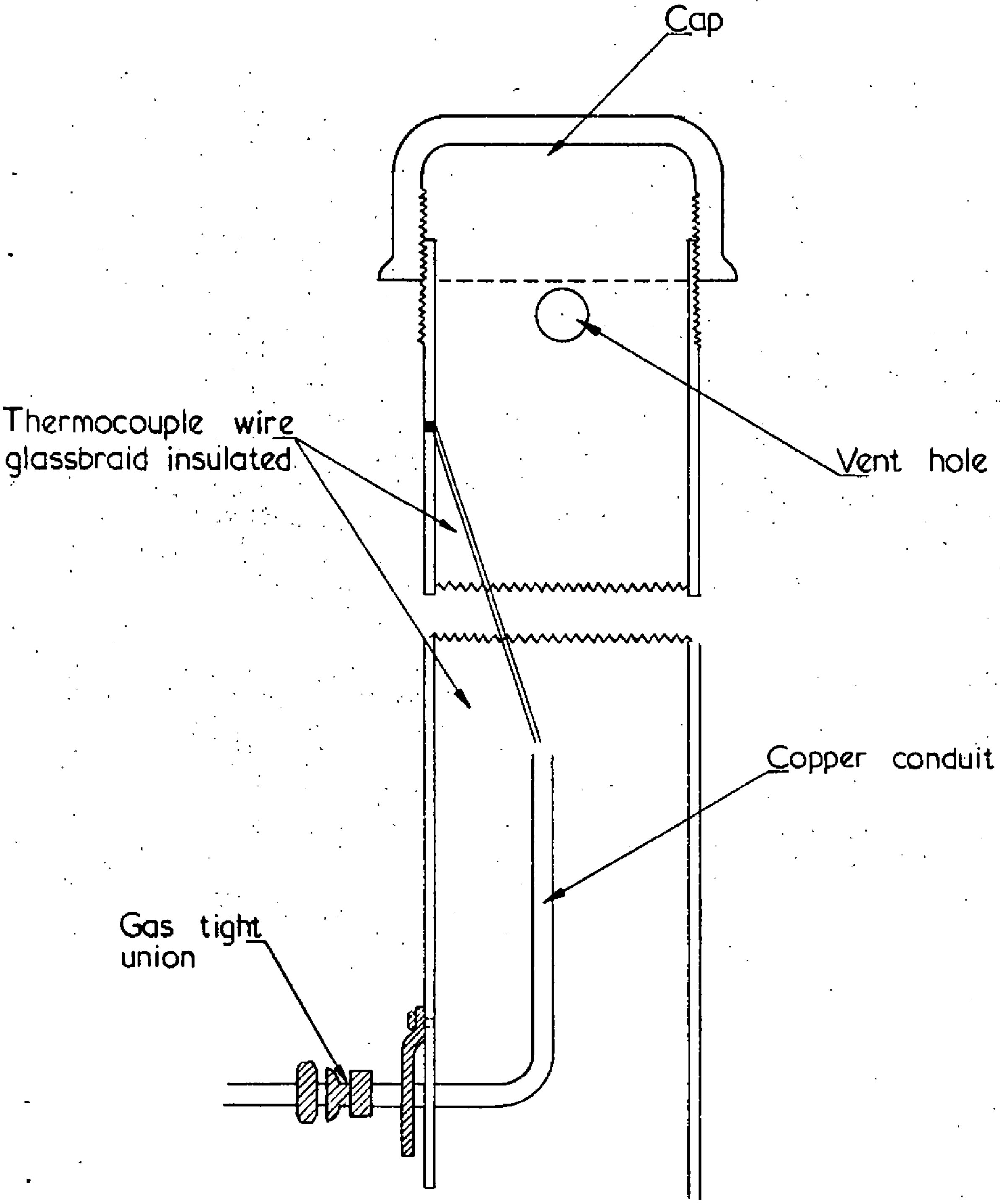
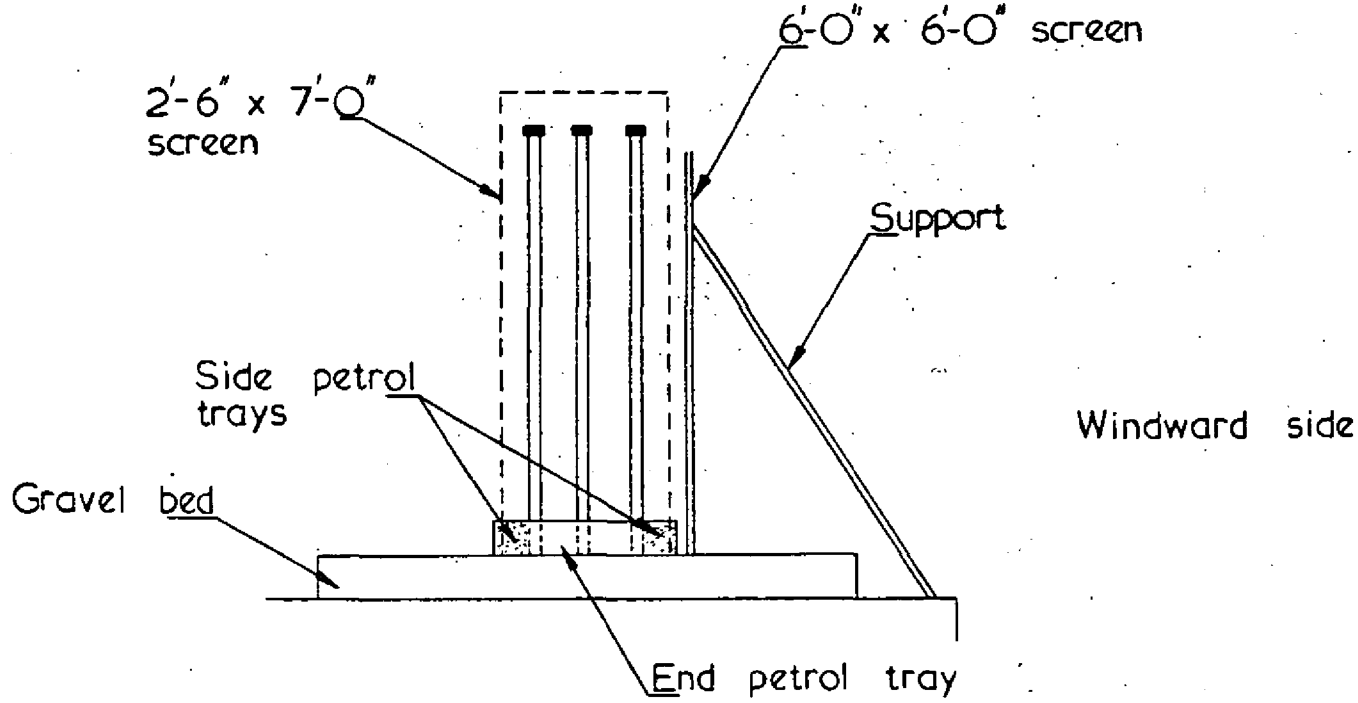


FIG. 4. PROTECTION OF THERMOCOUPLE LEADS



N.W. ELEVATION – WIND IN W. QUADRANT

FIG. 5. IGNITION OF FIRE ON TUBE RIG
STANDARD ARRANGEMENT OF SCREENS

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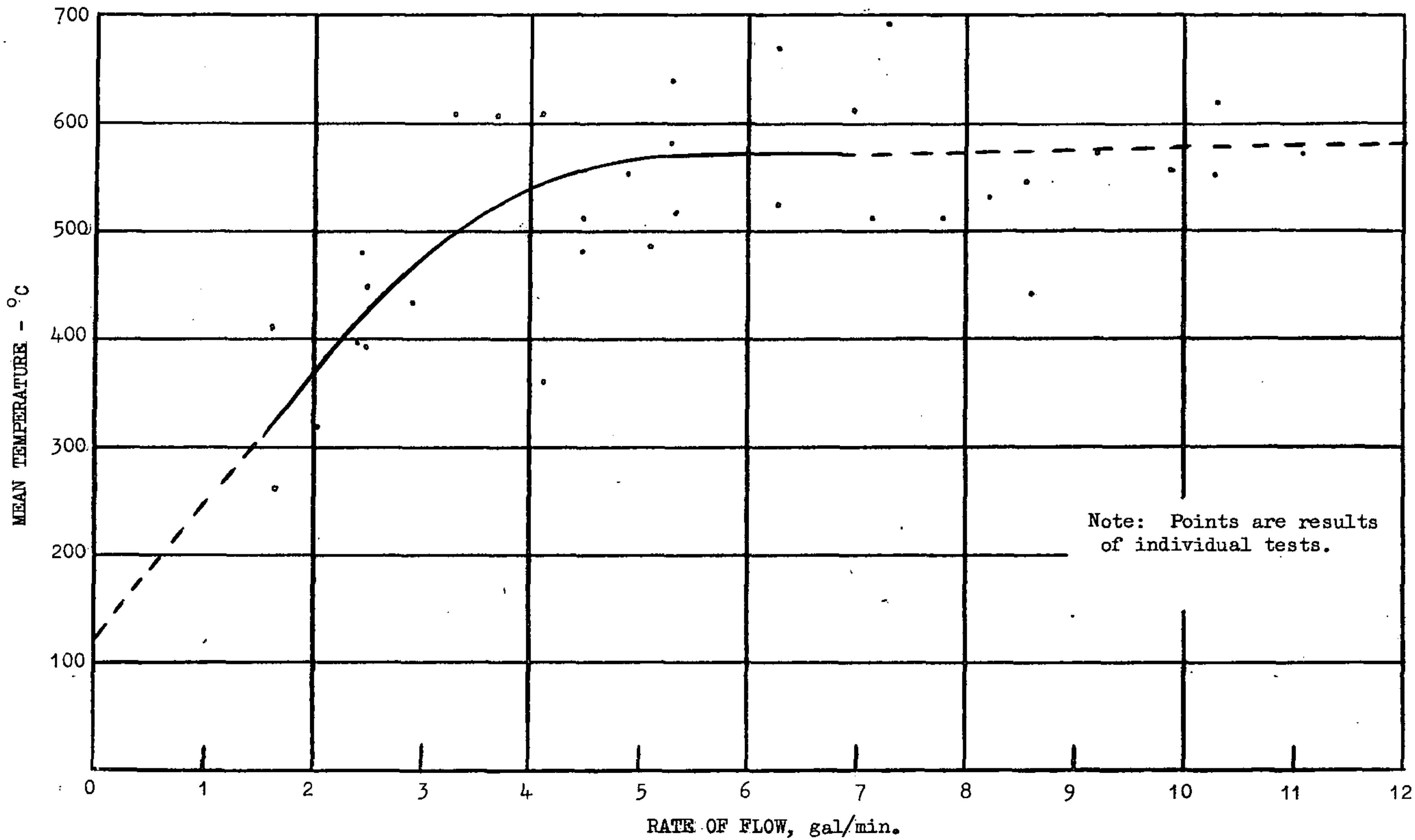

FIG. 6. INCREASE OF TEMPERATURE OF TUBE RIG WITH RATE OF FLOW OF OIL

Transformer oil fires on vertical tube rig.
2 min. burning time.

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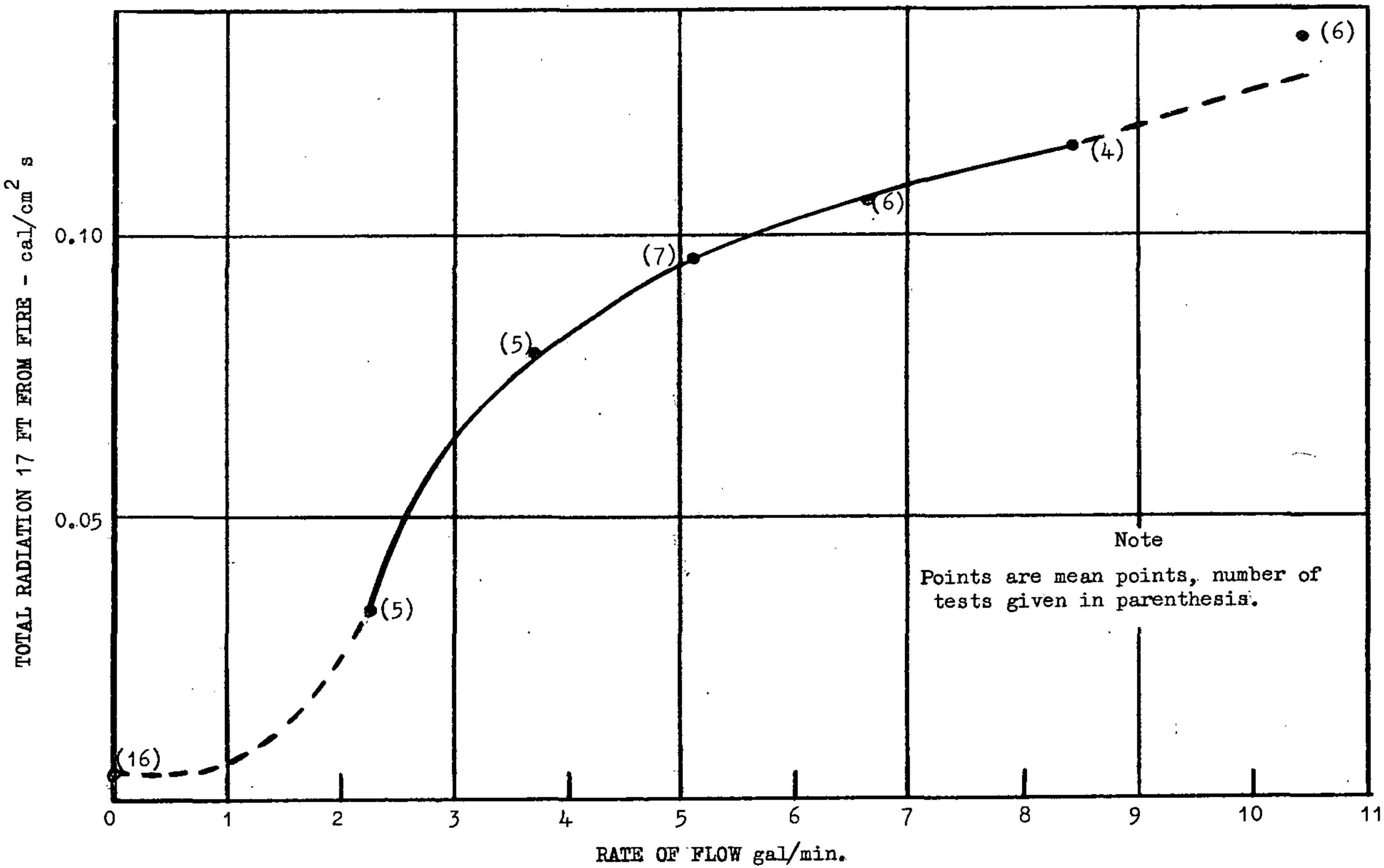

FIG. 7. INCREASE OF TOTAL RADIATION WITH RATE OF FLOW OF OIL

Transformer oil fires on vertical tube rig.
2 min. burning time.

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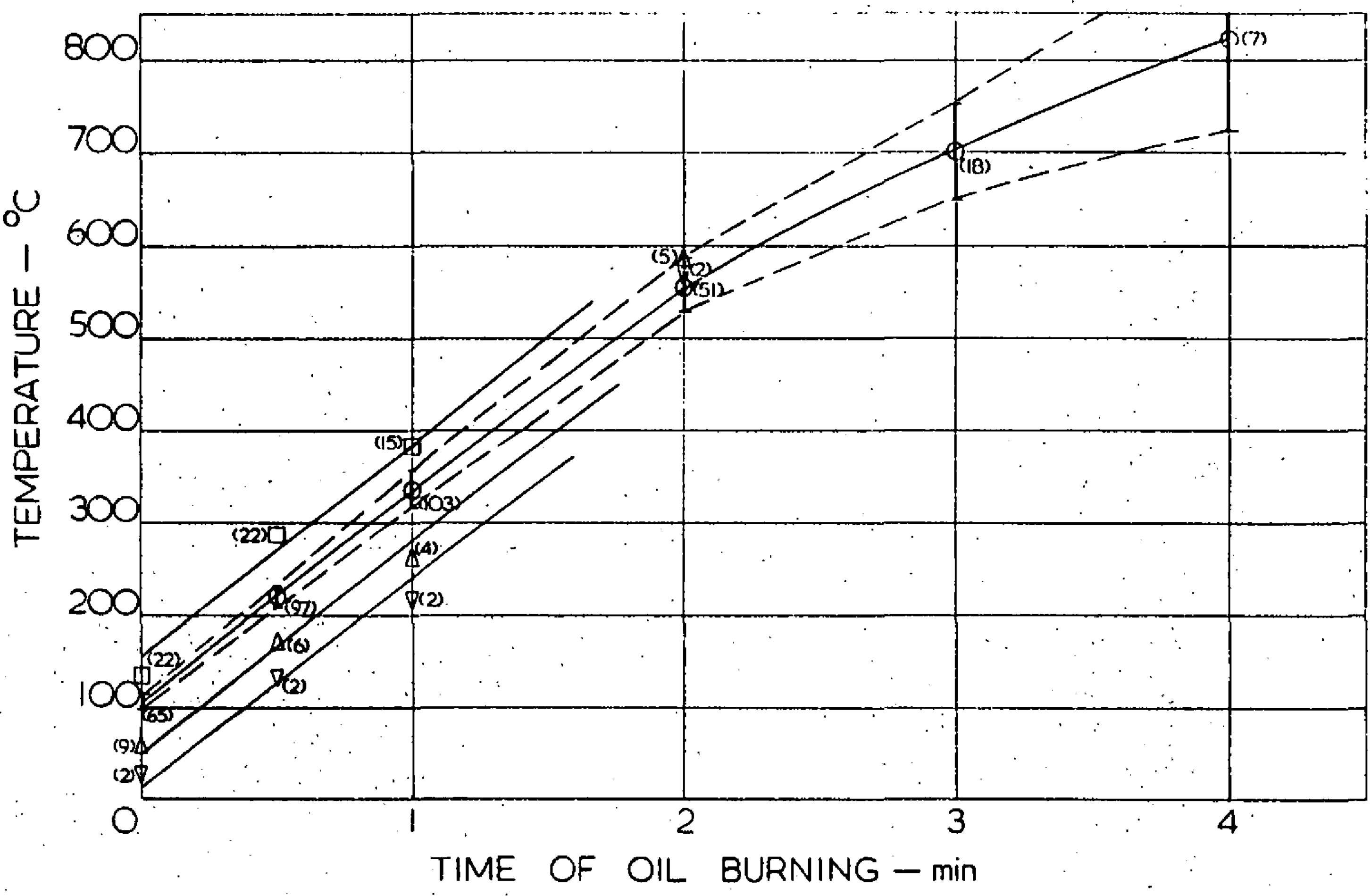
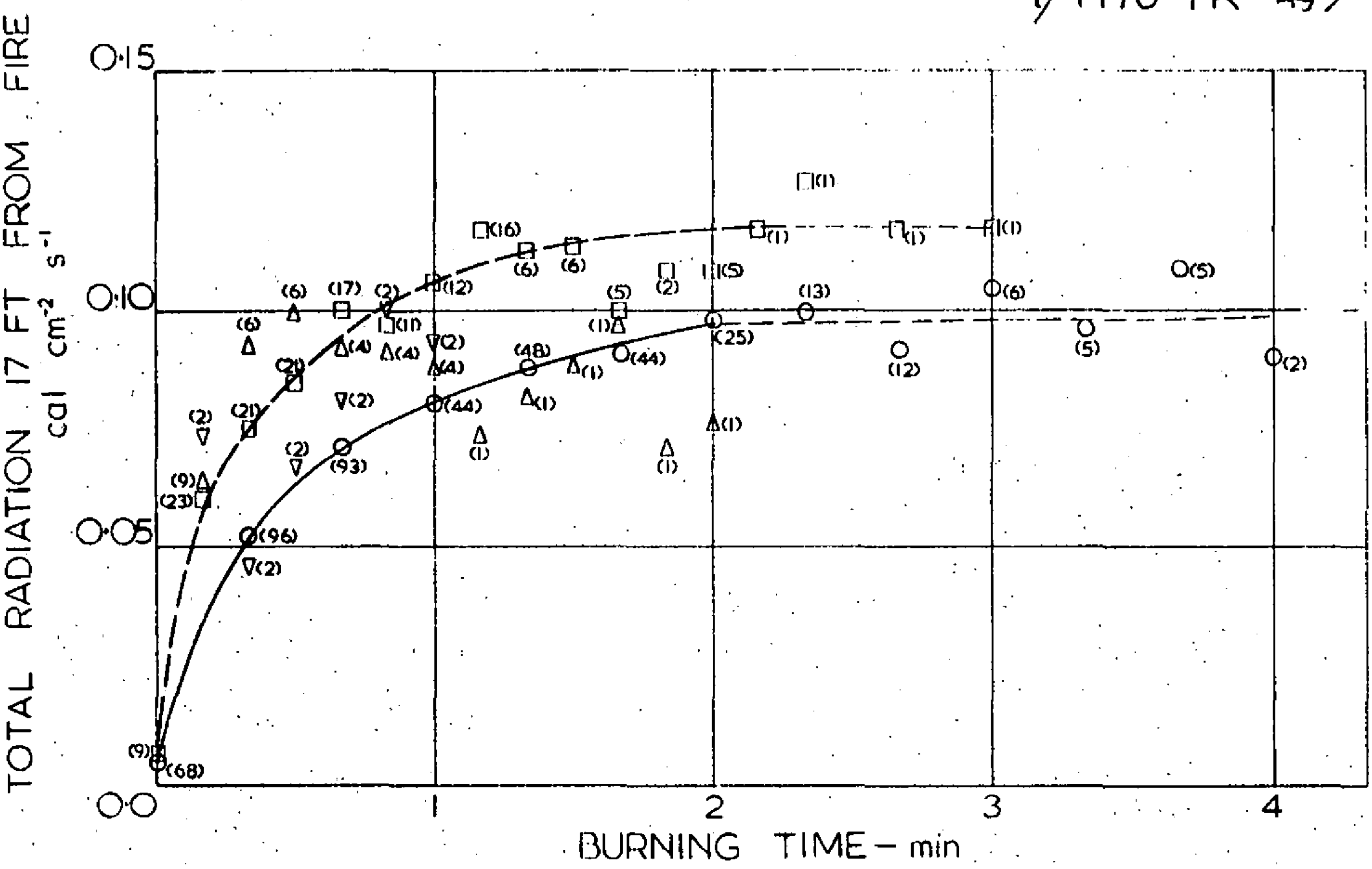


Symbol	Oil	Mean rate of flow gal/min	Tube rig
▵	Kerosine	5·5	Vertical
▿	Gas oil	5·0	Vertical
○	Transformer oil	5·5	Vertical
□	Transformer oil	5·5	Horizontal

Figures in parenthesis are nos of tests for the mean points

Dashed curves = 95 per cent confidence curves for transformer oil on vertical tube rig

FIG. 8. INCREASE OF TUBE RIG TEMPERATURE WITH TIME OF BURNING



Symbol	Oil	Mean rate of flow gal/min	Tube rig
△	Kerosine	5·5	Vertical
▽	Gas	5·0	Vertical
○	Transformer	5·5	Vertical
□	Transformer	5·5	Horizontal

Figures in parenthesis are number of tests for the mean point

Solid curve = Transformer oil on vertical tube rig

Dash curve = Transformer oil on horizontal tube rig

FIG. 9. INCREASE OF TOTAL RADIATION WITH TIME OF BURNING

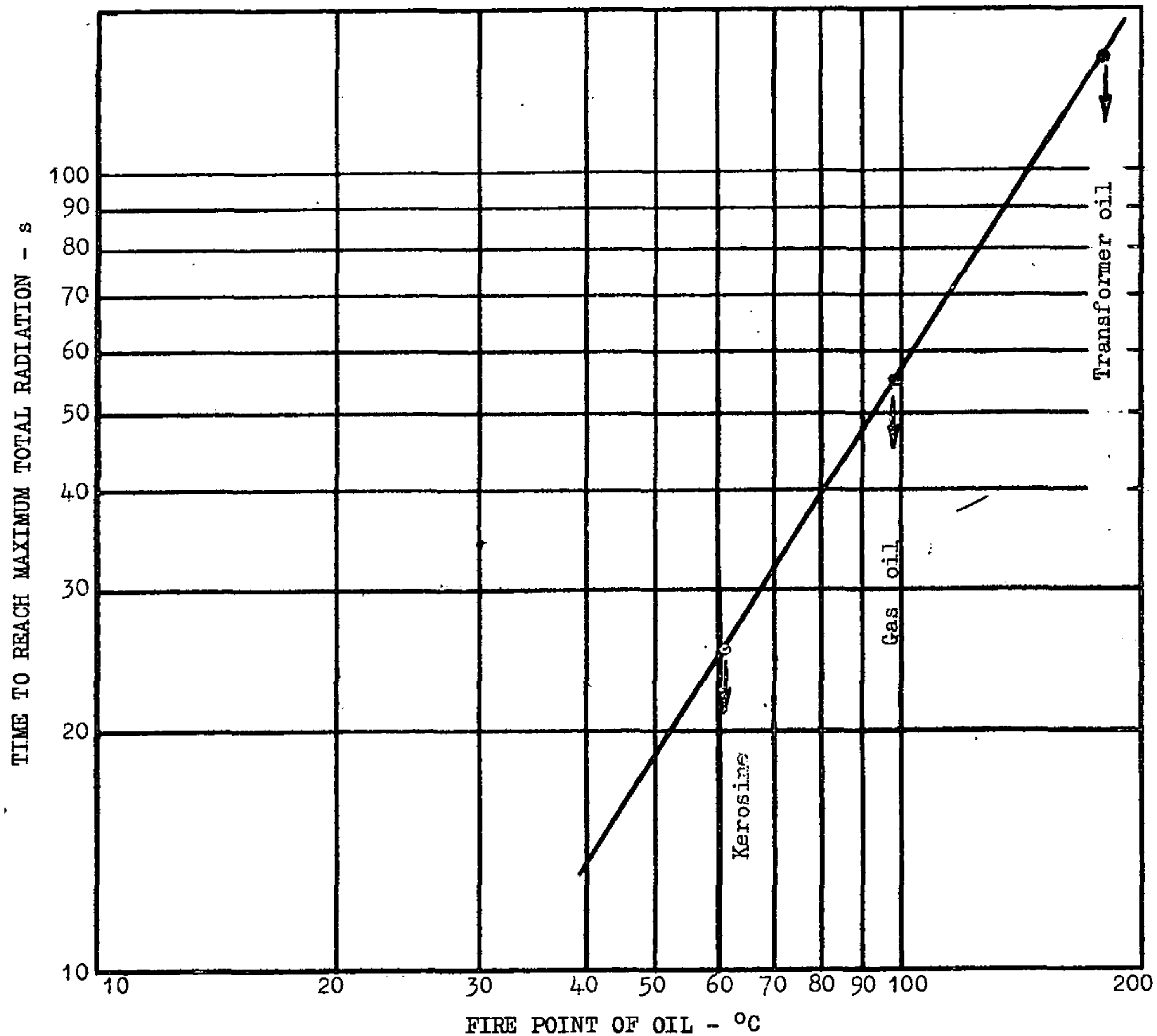


FIG. 10. RELATION BETWEEN FIRE POINT AND MAXIMUM RADIATION
Vertical Tube Rig

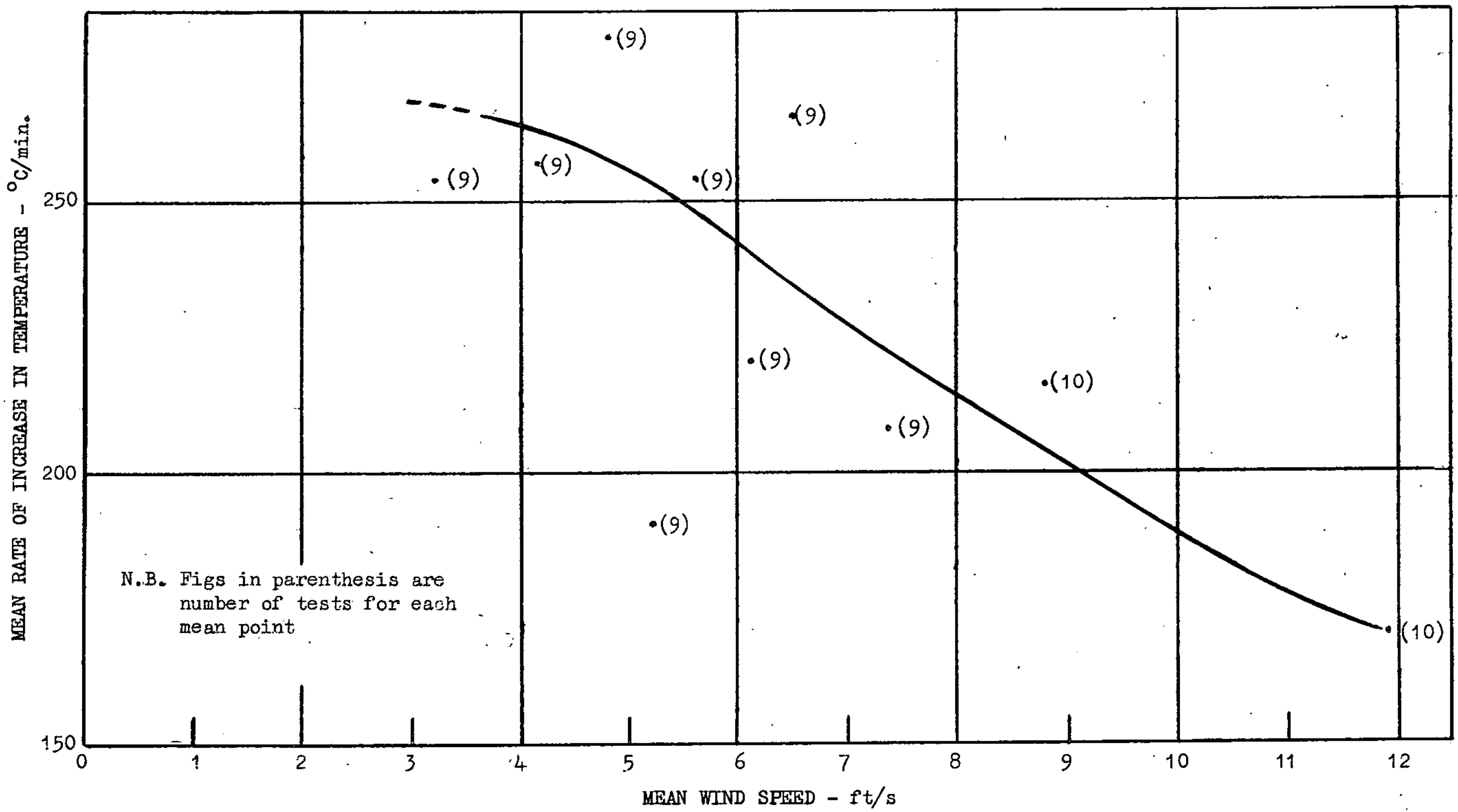


FIG. 11. EFFECT OF WIND SPEED ON HEATING OF TUBE RIG.

Rate of heating from 0.5-1 min. burning time
Transformer oil, 5.5 gal/min. on vertical tube rig.

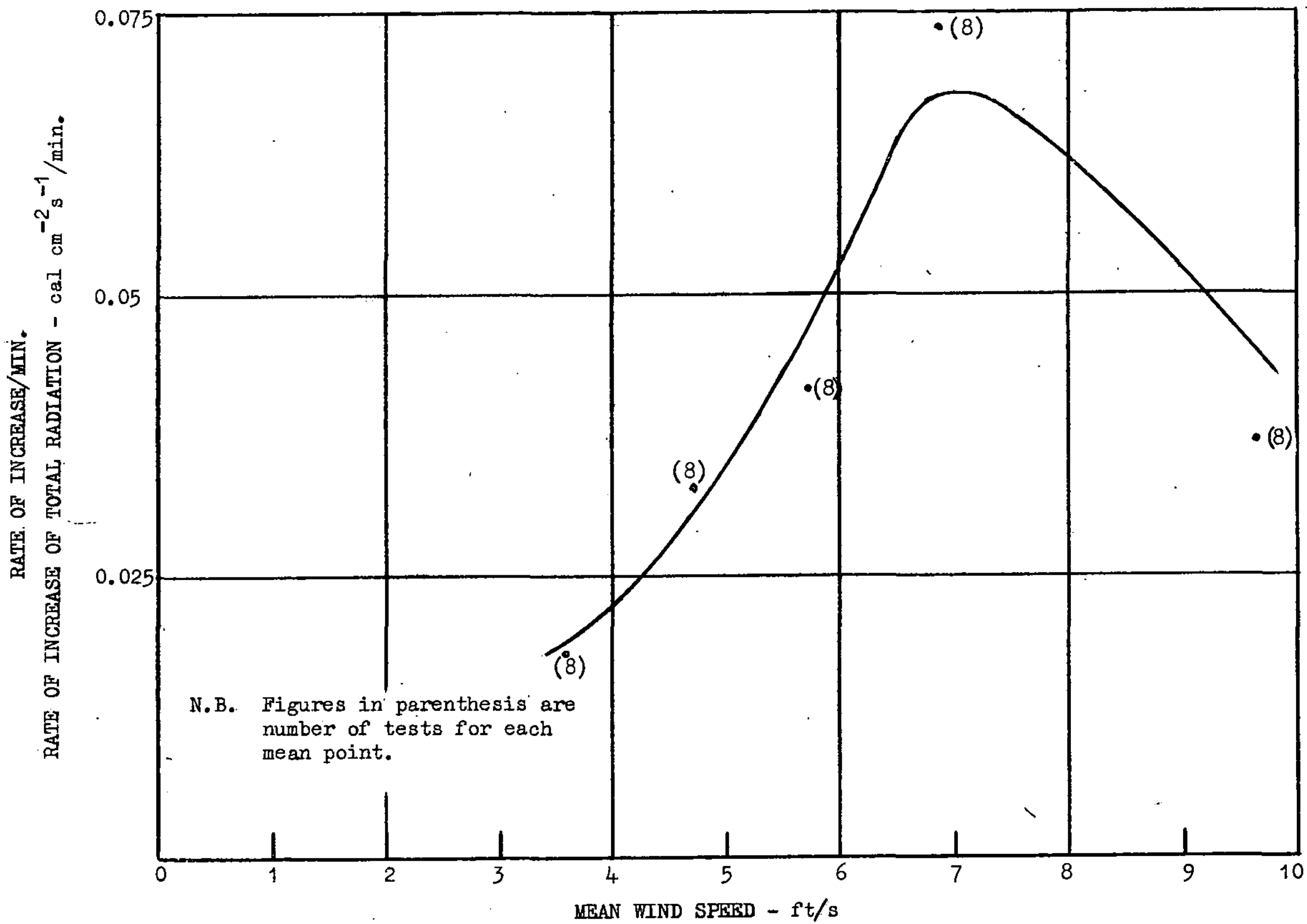


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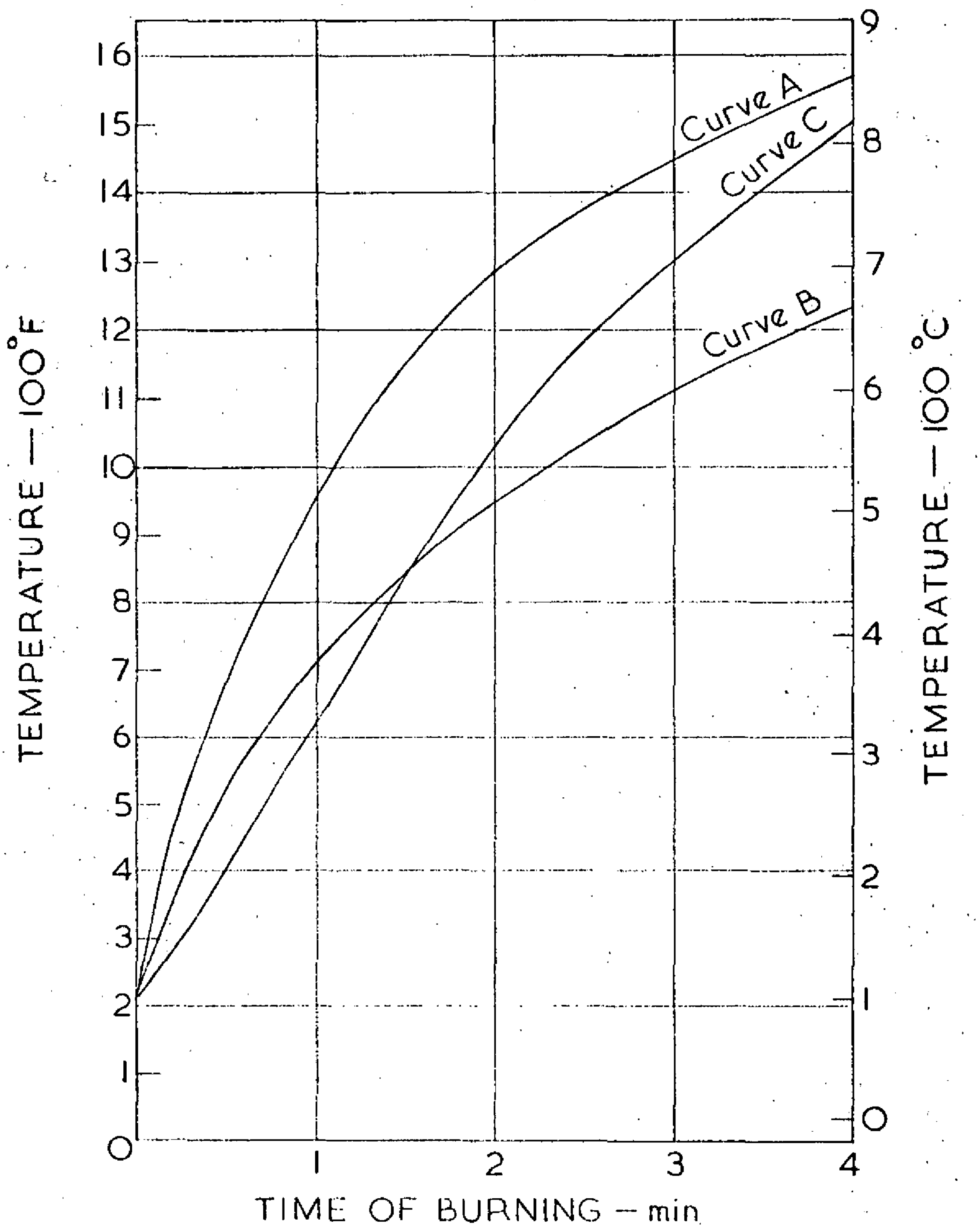
FIG. 12. EFFECT OF WIND SPEED ON TOTAL RADIATION

Rate of increase, from 0.5-1 min. burning time.
Transformer oil 5.5 gal/min. in vertical tube rig.

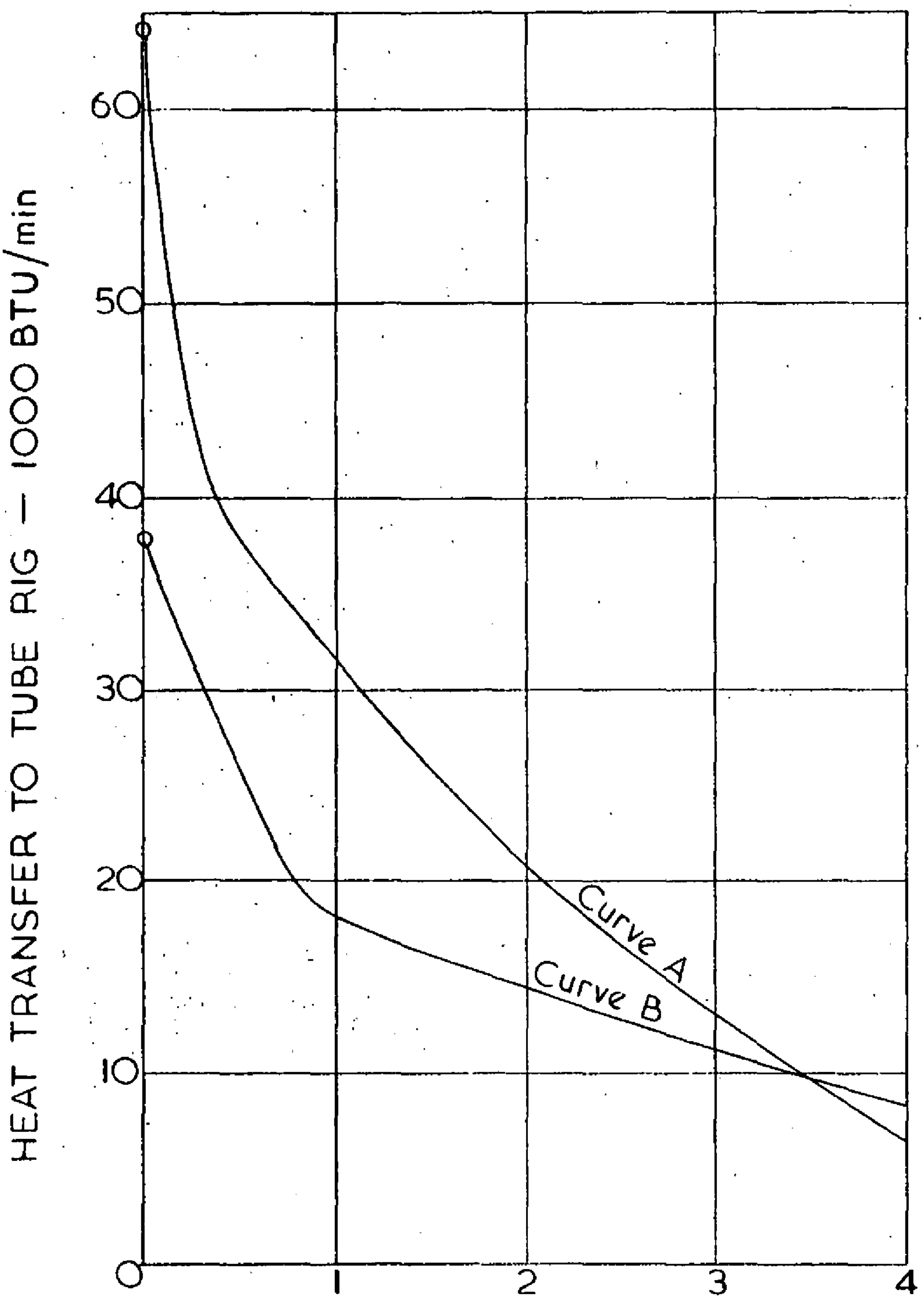


Curve A Calculated 38 cm flame

Curve B Calculated 18 cm flame

Curve C Experiment

FIG.13. RATE OF RISE OF TUBE RIG TEMPERATURE
(Experimental and calculated values)



Curve A Calculated 38 cm flame

Curve B Calculated 18 cm flame

FIG. 14 CALCULATED HEAT TRANSFER TO TUBE RIG