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A CALORIMETER FOR MEASURING THE HEAT FLUX FROM EXPERIMENTAL FIRES

by

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SUMMARY

The calorimeter will be useful for measuring heat flux in the range 0.1 - 10 W/cm^2 from such sources as flammable liquid fires.

Shortcomings of existing methods are considered, and desirable characteristics for the new instrument are enumerated. Descriptions of the new calorimeter design and its advantages are given, together with its construction, performance under fire-test conditions, and its principal characteristics.

A further possible development is described which will permit the heat retained by the calorimeter to be determined in its two component parts - radiation and convection.

KEY WORDS: Calorimeter, Flammable liquid fires, Radiation, Convection.

Department of the Environment and Fire Offices' Committee
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INTRODUCTION

Measurement of the heat from petroleum fires was required to assist in the design of a model laboratory fire for assessing the extinction properties of foam liquids. The heat received by the foam blanket, from the portion of the fire not extinguished, is an important factor controlling the duration of the foam's effectiveness. We required to know how this varied with fire size in order that results on model laboratory fires could be used to predict results on larger fires.

Similar information is required to answer enquiries concerning the protective cooling necessary for petroleum storage tanks should an adjacent tank be on fire.

There are a number of reports[1-7] which provide data in this field. The total information, however, is meagre and in most cases has important limitations. The large majority of workers have confined measurements to radiant heat[1-12], the work of N Tay and R N Cox[13] being a notable exception. Few experimenters have made measurements less than one diameter from the fire; the radiometers used frequently limited the results because their angle of view did not include the entire fire. Some radiometers had protective windows[5] which introduced complications because their transmission is related to wavelength and data is not available on the spectral distribution of the radiation from large petroleum fires. Protective windows preclude the use of instruments on the downwind side of fires because the windows may be obscured by smoke deposits.

A frequently employed approach[1, 5, 6] has been to determine a flame temperature from narrow view radiometer readings and then to assign dimensions to the flame in order to calculate radiation at points closer or more distant than the radiometer position. The flame is usually assumed to be rectangular, 1 fire diameter wide and 1½ or 2 fire diameters high. Figures 1, 2 and 3 show views of experimental fires and illustrate how erroneous it may be to attribute a simple geometrical shape to the flame. The photographs also illustrate the very different aspects which the fire presents when viewed from an up-wind or down-wind position.

Experience with test fires 9 m x 9 m (29.5 ft x 29.5 ft) provides convincing evidence of the importance of convection as well as radiation. In the wind conditions commonly prevailing in tests, 2-7 m/s (6.5-23 ft/s), it is possible to approach within 1 diameter up-wind for short periods without protective clothing, while this could not be done on the down-wind side where the flames and smoke will sometimes sweep along close to the ground and herbage is burned for a distance of 2 diameters or more from the fire.

Only rarely are experimental fires conducted solely for measurement of their heat output, while larger numbers are planned as extinction tests. Foam is the principal agent used for extinction and will interfere with most radiometers if the wind carries foam flakes onto the instrument. Radiometer wires around the test site become covered with foam and are liable to damage during fire fighting. Another problem is that large test fires take some hours to prepare, and change in wind direction between commencing preparations and ignition are not infrequent, particularly in coastal areas. When this occurs the resiting of numerous radiometers with their connecting wires, which may be buried or covered for protection and in some designs cooling water lines also[9], imposes practical limitations on their use. Some radiometers and associated recording equipment are so expensive as to limit their use in substantial numbers, and some present complex calibration problems[10,11,12,13].

It was concluded that if a new instrument could be designed specially for this purpose with the appropriate characteristics it would materially accelerate progress.

PRINCIPAL CHARACTERISTICS REQUIRED

The principal characteristics required are:

1. Simple to construct and not so costly as to inhibit the use of between 10 and 50 of them
2. 2π steradians view angle
3. Operate in vertical or horizontal plane
4. Measure both radiant and convective heat - preferably separately
5. Can be exposed close to large fires, including down-wind in the smoke and hot gas area
6. Response to be independent of the wavelength distribution
7. No wires or cooling water lines
8. Must stand up well to fire test ground conditions where foam and water spray and hose lines are in use, and periods of rain may occur

9. Easily and quickly repositioned should the wind change
10. Minimum labour requirement to control a battery of instruments
11. Rapid response not required - suitable for use with exposure times of several minutes
12. Great accuracy of results not essential but a high level of confidence in the veracity of the measurement within the known limits of accuracy
13. Must be easily calibrated and maintain characteristics well during use.

A calorimeter has been constructed which incorporates most of these characteristics. Its design, characteristics and use in fire tests will now be described.

PRELIMINARY DESIGN CONSIDERATIONS

From among many possible designs, the most promising was a substantial block of metal whose temperature rise would be limited, so that loss of heat by re-radiation would be small, i.e. the calorimeter would act as its own heat sink. This proposal became attractive when it was coupled with the idea that a maximum thermometer, providing it was placed in the remote half of the disc, would register the maximum temperature attained following a finite exposure period, and permit the total heat pick-up to be determined. This principle designates the instrument as a calorimeter and not a radiometer.

The first step in the feasibility studies was to decide the range of heat flux which it was required to measure. The radiation received by an object with a 180° view of a petroleum fire has been reported to have widely different values[2,3,5,6,7], from 3 to 25 W/cm^2. A value of 3.25 W/cm^2, as found by H B Peterson et al[2] was selected as a reference basis because, although this is at the lower range of the reported values, it approximates to the heat reaching the fuel surface when this is calculated from the fuel burning rate, upon which more agreement exists. Assuming a flame height of 1 diameter and using the configuration factors of J H McGuire[14], the following radiation estimates were obtained (Table 1).

Table 1. Estimate of heat rates to be measured

Distance from fire front	Horizontal plane W/cm^2	Vertical plane W/cm^2
Close	1.56	3.15
½ diam	0.60	1.14
1 diam	0.23	0.61
1½ diam	0.095	0.35
2 diam	0.054	0.21

Another approach to decide the range of heat rates of practical interest was also used. Consider the ullage plates of a storage tank exposed to radiation from an adjacent tank fire. Neglecting convection cooling, but allowing for the ullage plate to radiate heat from its two surfaces, the rate of radiation from the fire which is necessary to raise the ullage plates to any particular temperature can be calculated. Two temperatures of practical interest were selected - 250°C and 350°C. These are typical of the auto-ignition temperatures of many liquid petroleum products[15,16,19,20]. These calculations gave 0.8 and 1.05 W/cm^2 as the radiation levels which could just raise the ullage plates to these auto-ignition temperatures.

In some tests the instrument may receive heat by convection from the hot combustion gases. A J Heselden et al[17] reported tests in which a steel column was surrounded by flames from a petrol fire and measured heat flux to the steel column up to 11.5 W/cm^2.

The new instrument should therefore be suitable for measuring heat rates of the order of 1 W/cm^2, the level of greatest practical interest in tank protection problems; up to 5 W/cm^2 which includes radiation very close to fires and which would apply to foam blankets and burning fuel surfaces; and in the range 10–20 W/cm^2 if placed in the hot combustion gases.

DEVELOPMENT OF DESIGN

A detailed study of various designs was then made, considering different materials of construction and dimensions for the receiver. It quickly became apparent that a disc was the most suitable shape and that it must be mounted in a protective case, from which it is effectively insulated, to minimize heat losses or gains from the unexposed face and sides of the disc. Calculations showed that careful design of the case, and of the method of supporting the disc in the case, is essential to achieve this objective. It was also found that the case would be best made from a heavy gauge of metal, in order that its temperature rise would be of the same order as that of the calorimeter disc, to minimize the temperature difference between case and disc and thus any heat loss or gain from disc to case. It is not possible to equate the temperature rise of disc and case because of changes in configuration factors and proportions of radiant and convective heat. These calculations also showed the value of a highly polished case with a low absorptivity, contrasting with a highly absorbent black face to the disc.

Figures 4 and 5 show the design finally adopted and Figs 6 - 8 show various views of the calorimeter. The recommended design details are described later.

Improvements in design resulting from trials

On one occasion when the instrument was used at 0.5 diam. down-wind in a stiff breeze, the annular aluminium cover suffered some damage from overheating. It was therefore decided to use chromium plated brass for the lid and annular cover.

A lid for the calorimeter was found to be essential. Besides protecting the disc from foam and water spray, it permitted the exposure time to be precisely controlled which improved accuracy. In what are primarily extinction tests a typical pattern is 15 s flame spread, 60 s preburn, 60 s extinction, and it is difficult to convert a full experiment exposure to an equivalent full flame period. It was also found necessary to fit the lid with a square hinge-pin and provide a set of rods so that the lid could be opened and closed from 20 m (65.6 ft) distance when tests were being made in down-wind positions.

A steel base plate 450 mm x 450 mm x 12 mm (17.7 in x 17.7 in x 0.5 in), to which the calorimeter could be fastened by two wing nuts, when being used in the vertical position, was found to be an advantage in rough fire-test ground conditions. The plate was unpolished to avoid reflection.

Design of the calorimeter lid involved several factors. While the lid is open, its inner surface will be exposed to radiation and its temperature will rise. If the lid is heavy gauge metal to minimise this rise there is a subsequent problem when the lid is closed after the exposure because the fire may burn for a considerable period and heat the lid from the outside. This problem was overcome by fitting a light gauge polished lining to the lid, separated from the heavier gauge top by a layer of insulation, and by ensuring that the lid rim is of substantial gauge and fitted neatly on the top of the case to permit heat received by the closed lid to be distributed throughout the entire casing.

CONSTRUCTIONAL DETAILS (see Figs 4 and 5)

The calorimeter consists of a circular disc of pure aluminium, 25 mm (1 in) thick and 150 mm (6 in) diam. The top surface is coated with lamp black, a finish which is readily renewed when necessary. The edge and base of the disc are highly polished. In the bottom half of the disc edge a thermometer pocket is drilled with a diameter which is a neat fit for a maximum thermometer[18]. This thermometer pocket extends to the centre of the disc. Also in the bottom half of the disc edge is a second pocket of smaller diameter to match a thermocouple. The entrance to this pocket is countersunk to assist insertion of the thermocouple.

The disc is mounted in a case 210 mm (8.3 in) outside diameter and 50 mm (2 in) overall height; the case is constructed of polished aluminium. The base is welded to the side while the annular top, which is made of chromium plated brass, 3 mm (0.12 in) thick, is securely fastened to the side by screws so that an effective heat conduction path exists between the annular top and the remainder of the case. The inside edge of the top annular cover is chamfered to minimize any transmission of heat from disc to case. There is a clearance of approximately 1.5 mm (0.06 in) between the chamfered edge of the cover and the disc. It is important that disc and cover do not touch. The top of the disc and the top of the annular cover are in one plane. The disc is supported in the case by 4 plastic pillars. These are made from 'Delanco', 30 mm (1.2 in) diam. and are secured to the case by screws through the base. The tops of the pillars are rebated to locate the disc laterally and are recessed to limit the contact area between disc and pillars. A stud on one pillar locates in a hole in the disc to position it, and ensure that the thermometer pocket aligns with the thermometer guide tube. Small angle clips, secured by screws on two of the pillars, attach the disc to the pillars to prevent it falling out when the calorimeter is in the vertical position. A guide tube in the case serves to allow the thermometer to be inserted through the fibre glass lagging with which the case is packed. This guide tube is of light gauge stainless steel, it is liberally perforated and stops 3 mm (0.12 in) from the disc to minimise conduction of heat from disc to case. On the outside of the case a guard tube of polished aluminium, with screw cap , protects the part of the thermometer projecting from the case. A hole is provided on the opposite side of the case through which a thermocouple can be thrust through the fibre glass lagging into the hole provided in the disc.

Four short legs are screwed to the base of the case to assist level seating of the instrument when used in the horizontal position. A stand is fixed to one side of the case to enable it to be used in the vertical position and by which it can be secured to a steel base plate 450 mm x 450 mm x 12 mm thick, by means of wing nuts, to two studs in the base plate.

The calorimeter is fitted with a hinged lid. The top of the lid is made from 3 mm brass and the edge,which is 12.5 mm (0.5 in) deep,from 5 mm (0.2 in) brass. The lid is lined with 0.5 mm (0.02 in) brass sheet which retains a 5 mm layer of asbestos or fibre glass lagging. The lid and lining are chromium plated and polished. The lid is fixed by a single hinge so that when closed the lid edge sits neatly on the annular cover, and when it is open and the calorimeter is in the vertical position it will tilt slightly backwards and so remain open. The ends of the hinge pin are square so that extension rods can be fitted on either side to open or close the lid when the calorimeter is placed downwind in the hot combustion gases and is unapproachable. Light gauge 12.5 mm diam. steel tube, in 1.5 m (4.9 ft) lengths, was used to construct the extension rods. This was found to be sufficiently flexible to require only 1 or 2 fire brick supports close to the calorimeter and could then be allowed to lie along the ground. Care is necessary in positioning the lid hinge on the casing to prevent it fouling the thermometer guard tube.

CALIBRATION

The calorimeter provides an absolute measure of the net heat retention during an exposure period, and calibration against a standard source of radiation is not necessary. The disc is removed and carefully weighed, togther with the small clips and screws which hold it to the supporting pillars. From this weight a calorimeter constant is calculated using the specific heat of aluminium and the disc diameter. A small correction is applied to allow for the mercury in the thermometer bulb. The instrument constructed had a constant of 0.11 W/cm^2 ^oC min.

If the instrument is exposed in a position where it is not receiving heat by convection from the hot combustion gases (but is losing heat by convection to the atmosphere), it will be shown later that, if the exposure time and wind velocity are within appropriate limits, the calorimeter will provide a measure of the radiant heat with an accuracy which is adequate for most purposes, and is probably superior in this respect to most other instruments. Strictly speaking, it is necessary to know the absorptivity of the lamp-blacked surface and although this has been reported at around 0.97 it is difficult to design experiments to measure this for the spectrum from each liquid fuel fire. Any correction for this factor has been omitted and radiation measurements are therefore those related to retention by a lamp-blacked surface.

The specific heat of the aluminium disc was taken from published data for pure aluminium and a refinement would be to determine this experimentally, perhaps using the electrical method described by D I Lawson and J H McGuire[9].

Corrections can be made to total heat retention measurements to obtain more accurate radiation values when the instrument is not in the zone of hot combustion gases. These are explained later.

A novel development of the new calorimeter which should enable the heat retention to be measured as its two components, radiation and loss or gain by convection, in any position, is discussed later.

METHOD OF OPERATION

The calorimeter has been used successfully on a number of test fires which were being conducted as extinction tests using foam.

The calorimeter was positioned at the selected point which was usually 1 diameter or less from the fire front. It was carefully orientated in either the vertical or horizontal position, as desired, and parallel to the fire front when in the vertical position. Extension rods were fitted to the lid when the calorimeter was too close to the fire to be approached. The lid was left open during the fire preparation period to permit the disc to approach close to ambient temperature, and it was shaded from the sun when this was necessary. A few minutes before ignition time the lid was closed and the steel float on the thermometer drawn down to the mercury level and the temperature noted. Care was necessary to ensure that the initial reading was the top of the mercury column and not the top of the steel float. Approximately 30 s after ignition, when full flame conditions had been established, the lid was opened and a stop-watch started. At the end of the preburn period, when foam application was about to start, the lid was closed and the watch stopped.

After extinction the maximum temperature was read at leisure and the lid was opened to permit the disc to cool to ambient temperature for a subsequent test.

A few tests have been made on 2 m^2 fires in which large burning periods were possible and the disc temperature was measured by a thermocouple. After these fires were extinguished the temperature of the disc was measured for a further period. This provided a measure of the cooling loss which could be used to make a correction to the radiation measurement for up-wind positions: but in the cases when this was done the correction was insignificant. When using the thermocouple the rate of temperature rise was obtained from the slope of the temperature curve rather than from two single observations. When using the thermometer only, it is also possible to obtain a cooling rate measurement in the post-extinction period, by reading the thermometer over an interval of around 10 minutes.

COOLING RATE EXPERIMENTS

The calorimeter was heated with an electric lamp and then allowed to cool, and the temperature was noted at intervals. In all tests the calorimeter was in the horizontal position. Cooling tests were made in 'still' air, in a laboratory free from severe draughts, and in a wind tunnel. When in the wind tunnel the calorimeter was horizontal with the air stream flowing horizontally across the disc.

From the temperature curves, cooling rates were calculated for various temperature differences between air and disc. These were expressed as a percentage per minute of the heat content of the disc above the air temperature, and are shown in Fig. 9. Also included in Fig. 9 is the loss by radiation calculated from the Stefan-Boltzmann law, assuming a base temperature of 20°C which was close to that pertaining in the tests. The other cooling curves of course also include this radiation loss.

Since the cooling rates in Fig. 9 are close to constant for each wind speed, we can relate the percentage loss by cooling to the wind velocity and this has been done in Fig. 10. The relationship is close to linear and conforms to the following formula:

$$l = 0.85 + 0.195\,v$$

l = heat loss per minute as a percentage of the acquired heat
v = wind velocity m/s

SPECIAL EXPERIMENTAL FIRES

Four experimental fires were conducted to obtain data on the calorimeter's performance. Kerosine fires, 1.4 m x 1.4 m (4.6 ft x 4.6 ft) were used and in each case the disc was in the vertical position in the centre of, and parallel to, one side of the fire. In tests Nos 1 and 2 the calorimeter was up-wind and in tests Nos 3 and 4 down-wind from the fire. In all four tests the disc temperature was followed by means of a thermocouple. In tests Nos 2, 3 and 4, the fire was extinguished with foam and the calorimeter was left exposed and unmoved for a period, and the cooling rate observed. Figures 11, 12, 13 and 14 give the results obtained.

TESTS ON OTHER FIRES

The calorimeter was used to obtain readings on 8 other fires. These were extinction tests and varied in size up to 457 m^2 (4919 sq ft) and included 3 different fuels. The results obtained, together with those from the 4 experimental fires, are summarised in Table 2 and were used to construct Fig. 15.

Table 2

Summary of fire test data

Test No.	Fuel	Fire area m^2	Calorimeter distance fire widths	Wind speed m/s	Exposure time min	Temp rise ^oC	Total heat retention W/cm^2
Calorimeter up-wind							
1	Kerosine	2	1.0	4.0	8	52	0.715
2	Kerosine	2	0.44	3.6	6	84	1.54
5	Kerosine	81	1.0	3.5	0.83	4.5	0.595
6	Kerosine	81	0.5	3.5	1.72	15	0.96
7	MIBK*	7.3	0.25	2.0	0.5	10	2.2
8	MIBK	7.3	0.25	7.5	1.0	11.6	1.28
9	MIBK	7.3	0.7	nil	1.6	16.7	1.15
10	Crude oil	457	0.31	3	0.54	7.25	1.46
11	Crude oil	457	0.21	2	0.65	6.7	1.14
12	Crude oil	457	0.096	1.25	0.82	12.2	1.65
Calorimeter down-wind							
3	Kerosine	2	1.0	1	2.5	45	1.98
4	Kerosine	2	0.5	4	4	320	8.8

*MIBK = methylisobutyl ketone

DISCUSSION

The calculated radiation loss (1 in Fig. 9) must have a slight curvature which must also be a component of the other curves in Fig. 9. It can be seen that the curvature is so small that linear relationships can be assumed over the range of temperature concerned.

The slight slopes on some of the lines in Fig. 9 are probably experimental deviations resulting from progressive small changes of the air temperature during the cooling tests, which each extended over a number of hours.

Below temperature differences of $10^{o}C$ the points on curves 2-6 in Fig. 9 become increasingly erratic, because the cooling curves then have small slopes which cannot be read accurately.

At zero temperature difference the ordinate becomes indeterminate, but in the case of the radiation curve (1 in Fig. 9), a value for the intercept on the y axis at zero temperature can be obtained from equation (1).

$$y = \frac{5.725 \times 10^{-12} \left[T^4 - (T - dT)^4\right] \times 100}{0.11\ dT} \text{ per cent} \qquad \ldots\ldots (1)$$

T = air temperature ^{o}K

T + dT = disc temperature ^{o}K

Expanding (1) by the binomial theorem and neglecting terms with powers of dT we obtain equation (2) which has a finite value for y .

$$y = \frac{5.725 \times 10^{-12} \times 4T^3 \times 100}{0.11} \text{ per cent} \qquad \ldots\ldots (2)$$

$$y = 0.52 \text{ per cent when } T = 293^{o}K$$

Figures 11, 13 and 14 show that when the calorimeter is exposed to a fire the temperature rise also approximates closely to a linear relationship with time, up to periods of 8 min and $75^{o}C$ (Fig. 11) and 4 min and $350^{o}C$ (Fig. 14). This linear relationship will not, however, persist when the calorimeter is receiving heat by convection from combustion gases which are not at a much higher temperature than the disc, as they were in tests Nos 3 and 4 shown in Figs 13 and 14.

When the calorimeter is in an up-wind position a cooling loss correction can be made if it is required to know the radiant heat being received by the disc, rather than the net rate of heat retention by the disc. With an exposure time of 3 min the correction will vary from 2.5 per cent in still air conditions to 4.8 per cent at a wind velocity of 6.7 m/s (15 mph); only rarely will fire tests be made in higher wind speeds. These calculations are based upon the cooling tests in which the wind was blowing parallel to the disc face. In test No.2 (Figs 11 and 12) the radiometer was up-wind and its cooling was determined <u>in situ</u> immediately after the fire test: i.e. the radiometer was in the vertical position with its back to the wind. The wind velocity was

3.6 m/s (11.8 ft/s), and from Fig. 10 the cooling loss would be 1.55 per cent per minute ≡ 9.3 per cent during the six minutes exposure, if the wind had been across the face of the radiometer. The observed loss, from Fig. 12, was only 1.2 per cent per minute ≡ 7.2 per cent during the 6 minutes exposure period, because the wind was on the back of the calorimeter.

In this test No. 2 the temperature rise was 84°C in 6 minutes. An exposure time of 2 min would have given a temperature rise of 28°C, which is sufficiently large to be read correctly ± 1 per cent, and if a 2 minute interval had been used the addition to allow for cooling loss would have been only 2.4 per cent.

An appropriate choice of exposure time should therefore be made so that the temperature rise is sufficient to be read with an adequate accuracy without extending the exposure time unduly. The exposure time must not be reduced too low or the time measurement will introduce significant errors. Although the stop-watch is accurate to fractions of a second there is a human reaction time in opening and closing the instrument lid: ½ minute was considered an adequate minimum exposure time. Two other restrictions should also be observed; the radiometer disc should not exceed 350°C because the aluminium may be damaged, and the rate of temperature rise should not exceed 100°C per min until experimental evidence is obtained to prove that higher rates are permissible.

Taking all these points into consideration the test data obtained indicates that, if an astute choice of exposure time is made, the calorimeter will operate well over the following ranges:

In still air with 5 per cent cooling loss 0.4 – 10 W/cm^2
" " " " 10 " " " " 0.2 – 10 W/cm^2

At wind speed 6.7 m/s (15 mph) and 5 per cent cooling loss 1.0 – 10 W/cm^2
" " " " " " " " 10 " " " " 0.5 – 10 W/cm^2

The instrument therefore exceeds the requirements of Table 1 at the higher heat flux levels but barely meets the lowest level requirements.

This, however, only applies to upwind measurements which will be essentially radiation measurements with an acceptable level of veracity without applying a cooling correction, and the range could be extended at the lower levels by an _in situ_ cooling rate measurement.

In many investigations, however, the net heat retention by the disc, in stated wind conditions, will be a much more useful measurement, particularly in down-wind locations where both radiation and convection supply heat to the disc. This is particularly true for tank protection studies – the disc can be regarded as a section of the tank. In down-wind situations the heat acquisition from convection will depend upon the disc temperature. Two disc temperatures are of interest. A temperature of 80–100°C which will apply to tanks which are being cooled by water spray, and a temperature of 200°C which would be below the auto-ignition temperature of petroleum products and would apply to tanks not being cooled by water. If a thermocouple is used in the calorimeter the precise data required will be obtained, but in many cases where the rates of heat input are sufficiently high, and particularly if concerned with the 80–100°C disc temperature range, the temperature curves will not depart significantly from linear with time and the simpler maximum thermometer procedure will be adequate, as it was in tests Nos 1, 2 and 3 up to 80°C, and test No. 4 up to 350°C. When it is only required to obtain a net heat retention measurement, the restrictions on exposure time at the lower radiation levels no longer apply and the full range of values in Table 1 can be measured without problems.

In the 8 practical tests (Table 2 and Fig. 15) the calorimeter behaved well in spite of difficult test ground conditions. Since these tests were made during extinction trials, or either preburn or burn-off periods, it was not possible to select exposure times and they all tended to be much too short, resulting in low temperature rises and limitation of the accuracy by the thermometer reading. Nevertheless, Fig. 15 shows that the up-wind measurements provide a surprisingly consistent pattern considering the large differences in fire sizes from 2 m^2 to 457 m^2, and the use of three different fuels. Some of the displacements have logical explanations. Points 7 and 8 were both for MIBK fires at 0.25 fire widths distance. MIBK fires burn very brightly, with little smoke and a large flame area, and emit high radiation. This is shown by point 7, but point 8 was a repeat with a much higher wind velocity which bent the flames horizontally and so presented a much smaller solid angle of flame to the disc. Point 9 which is also above the curve was also on MIBK fire in low wind conditions. The other two points appreciably above the curve (Nos 1 and 2) are for the smallest 2 m^2 fires which, because of their small size, are not so air-starved as the larger fires and burn with proportionately large flame areas.

The up-wind curve intercepts the fire front ordinate at 1.9 W/cm^2; because the radiometer was standing vertically on the ground only π steradians would be viewed by the disc in the direction of the fire. This value must therefore be doubled = 3.8 W/cm^2 to obtain the radiation to the fuel bed or to a radiometer having a full field view of the fire. As stated earlier in the design considerations, H B Peterson et al[2] obtained a reading of 3.25 W/cm^2 and this approximates to the heat reaching the fuel surface which can be calculated from published burning rates. This is quite good agreement considering the limitations pertaining to these measurements. It would be expected that this new calorimeter would give a higher reading than H B Peterson obtained because its π view angle included all the fire and smoke pall, whereas with a narrower view radiometer used by Peterson some of the smoke cloud may have been omitted.

The tests reported in Table 2 and Fig. 15 are adequate proof that the radiation close to petroleum fire is of the order of 3-4 W/cm^2 and not up to several times this value as calculated by interpolation of measurements 1 or more fire diameters distance.

Only two tests have been made in down-wind positions and the dotted curve on Fig. 15 indicates that the heat flux down-wind is very much higher than in up-wind positions. This has important implications for tank protection problems and further experiments may produce results of great practical value if it is found that down-wind measurements from a single curve, or more probably a band of curves depending on wind velocity, but not dependent upon fire diameter.

A useful improvement to the calorimeter would be to replace the lamp black with a more permanent black paint or electrodeposit. The instrument has one disadvantage; several hours are necessary for the disc to return to ambient temperature, but this is a minor problem in large tests which are usually well spaced.

TWIN-SET CALORIMETER

Figure 16 depicts a proposal in which two calorimeter discs are mounted in the same case. Disc A is a standard disc as already described. Disc B is of identical diameter but only half the thickness and will therefore have half the thermal capacity. Only part of disc B is lamp-blacked, the other portion being polished. By conducting exposure tests using a radiant heat source on a completely blacked disc, and on a completely polished disc, it will be possible to determine the percentage area of disc B which must be lamp-blacked to make the calorimeter constants (W/cm^2 ^oC min) for the two discs identical in respect of radiant heat. Therefore, if the twin set is exposed to radiant heat both discs will increase in temperature at the same rate. If, however, the discs are exposed to convective heat, disc B will increase in temperature at twice the rate of disc A, having the same surface area and only half the thermal capacity, the convective heat transfer being independent of the colour, whether black or polished. If the twin set is exposed to a mixed heat flux the temperatures of the discs will rise at different rates and the total heat retention can be calculated and subdivided into its radiation and convection components.

$$q_t = \frac{k_a \times t_a}{m} \quad W/cm^2$$

$$q_c = 2 \times \frac{k_b \times (t_b - t_a)}{m} \quad W/cm^2$$

$$q_r = q_t - q_c \quad W/cm^2$$

k_a = constant for disc A $W/cm^2\ ^oC$ min

k_b = " " disc B $W/cm^2\ ^oC$ min

k_b = $0.5\ k_a$

t_a = temperature rise of disc A ^oC

t_b = " " " disc B ^oC

m = exposure time min

q_t = total heat retention W/cm^2

q_c = convective heat retention W/cm^2

q_r = radiative heat retention W/cm^2

This proposal has not been tested experimentally, and it promises to provide information which is difficult to obtain by other experimental means.

CONCLUSIONS

1. A calorimeter has been designed for measuring the heat flux from experimental fires. It measures the average heat flux over a period of several minutes.
2. It is simple to construct and to use, and is not expensive.
3. It is robust and has been used successfully under practical fire test conditions with liquid fuel fires up to 457 m^2 area, which were extinguished with foam.
4. It can be used without electric wire or water line connections across the test site, and this reduces the chances of mechanical damage occurring, and permits rapid repositioning to accommodate changes in wind direction.

5. No reference source is required for calibration and its characteristics remain constant.

6. Its response is independent of wavelength and knowledge of the radiation spectrum of the fire is not required.

7. It has a full 180° view angle and will therefore receive and measure the heat flux received by a plane surface, such as a storage tank or foam blanket, in either the vertical or horizontal position.

8. It responds to both radiant and convective heat and its operation is not interfered with by smoke, and it can therefore be used in a down-wind direction from the fire.

9. Without making any corrections for cooling losses during the exposure period, the calorimeter will measure radiant heat (i.e. when in up-wind positions) as follows:

   <u>In still air</u>

   Not less than 95 per cent of the radiant heat over the range 0.4 – 10 W/cm^2
   " " " 90 " " " " " " " " " 0.2 – 10 W/cm^2

   <u>In wind speed 6.7 m/s (15 mph)</u>

   Not less than 95 per cent of the radiant heat over the range 1.0 – 10 W/cm^2
   " " " 90 " " " " " " " " " 0.5 – 10 W/cm^2

   Greater accuracy is obtainable by applying a cooling loss correction related to wind speed and exposure period, and this is not a complex procedure.

10. If only net heat retention measurements are required, the range of operation can be extended to lower values.

11. Measurements on a number of liquid fuel test fires, of widely varying sizes, have shown that the radiation to a vertical surface close to the fire is in the range 3-4 W/cm^2. Although the tests were of limited accuracy because of the circumstances of the tests which had other primary objectives, they are a useful addition to knowledge in this field.

12. Two tests with the calorimeter situated down-wind in the combustion product zone illustrate the preponderant significance of convective heat flux. This is a subject upon which available knowledge is limited and this new calorimeter could be used effectively in this field of study.

13. A calorimeter twin-set, the design of which is described, would enable mixed heat fluxes to be measured in their components of radiation and convection. This is difficult to accomplish by other methods.

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FIG. 1 81 m^2 KEROSINE FIRE

FIG. 2 81 m^2 KEROSINE FIRE

FIG. 3 7.3 m^2 M.I.B.K. FIRE

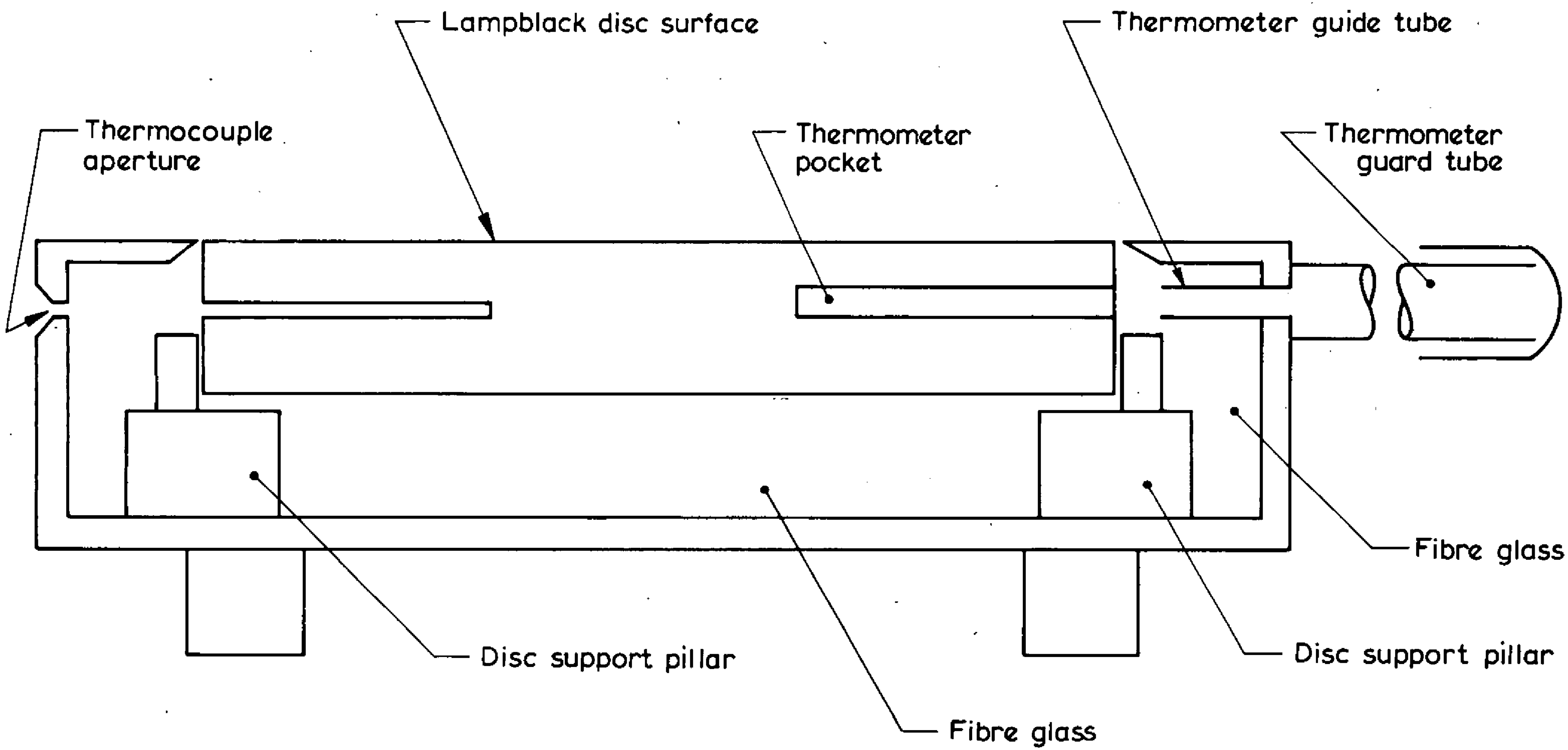


Figure 4 Diagram of calorimeter

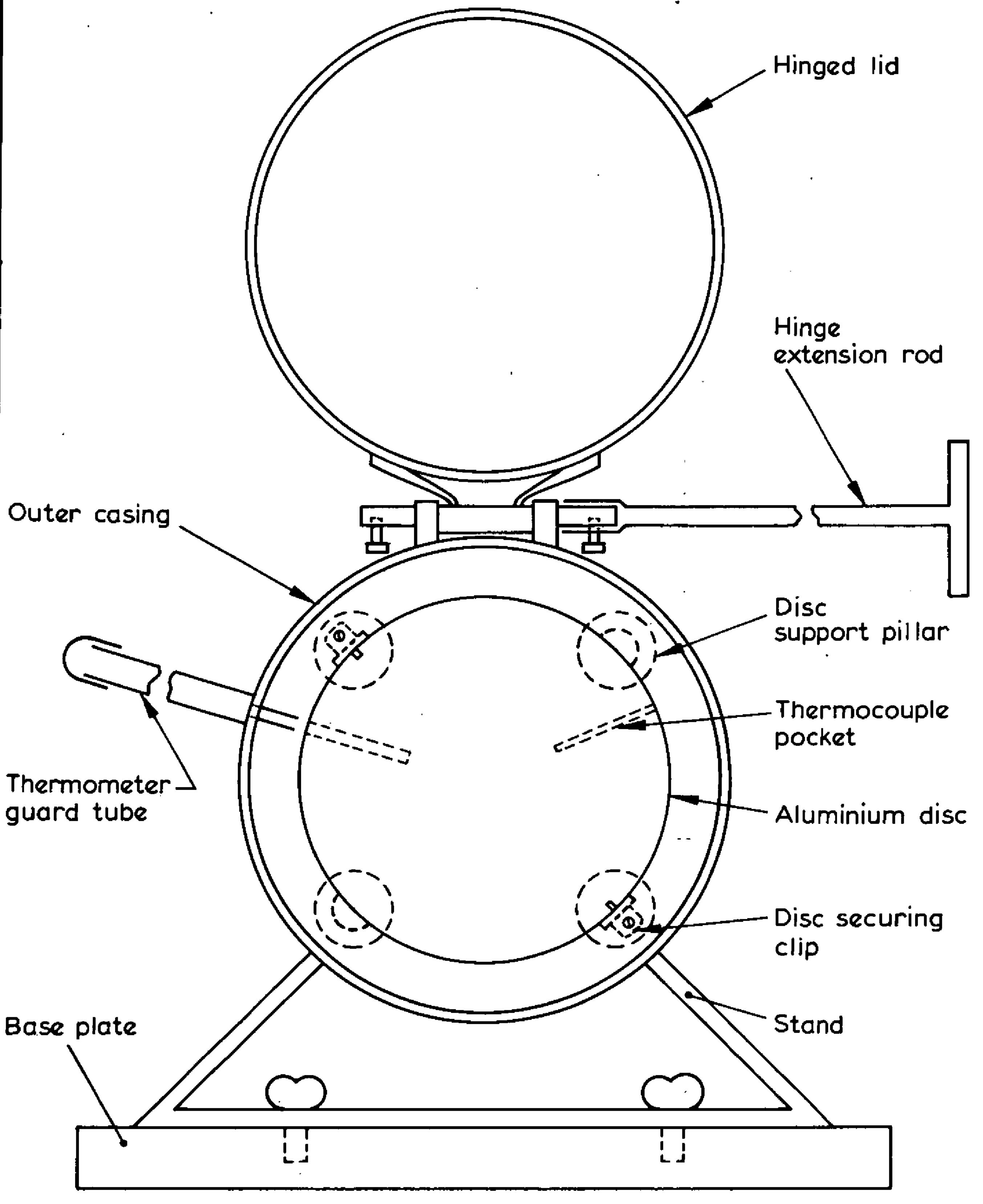


Figure 5 Diagram of calorimeter

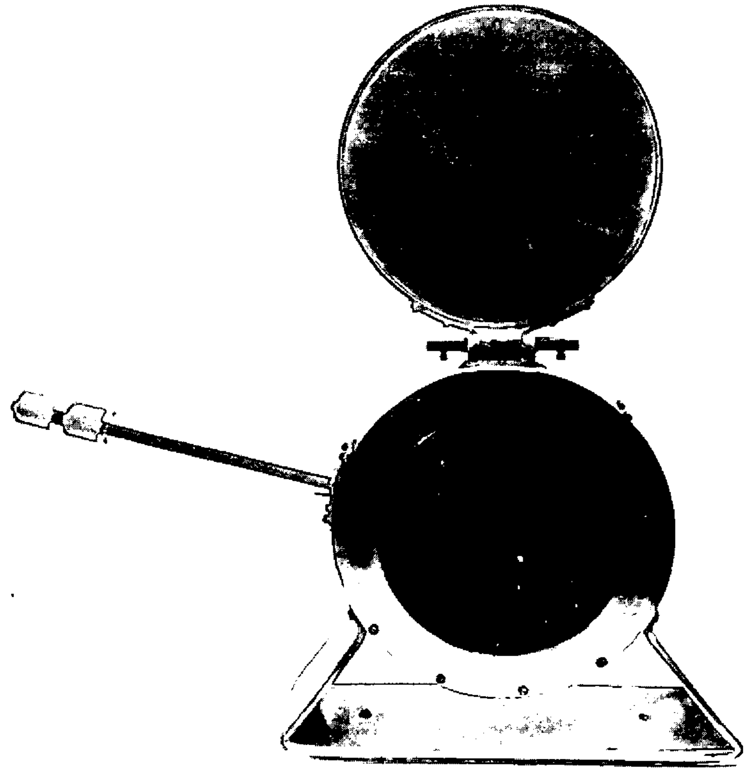


FIG. 6 CALORIMETER ASSEMBLED

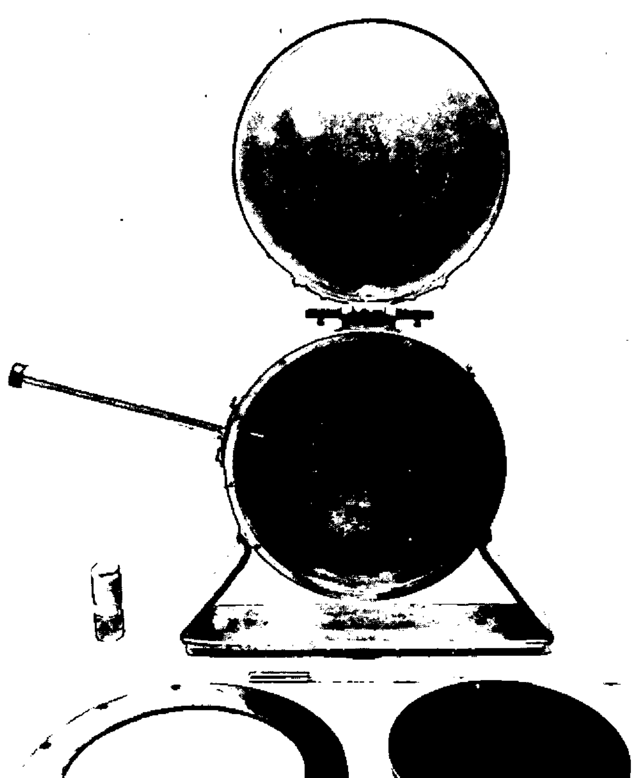


FIG. 7 CALORIMETER DISSEMBLED

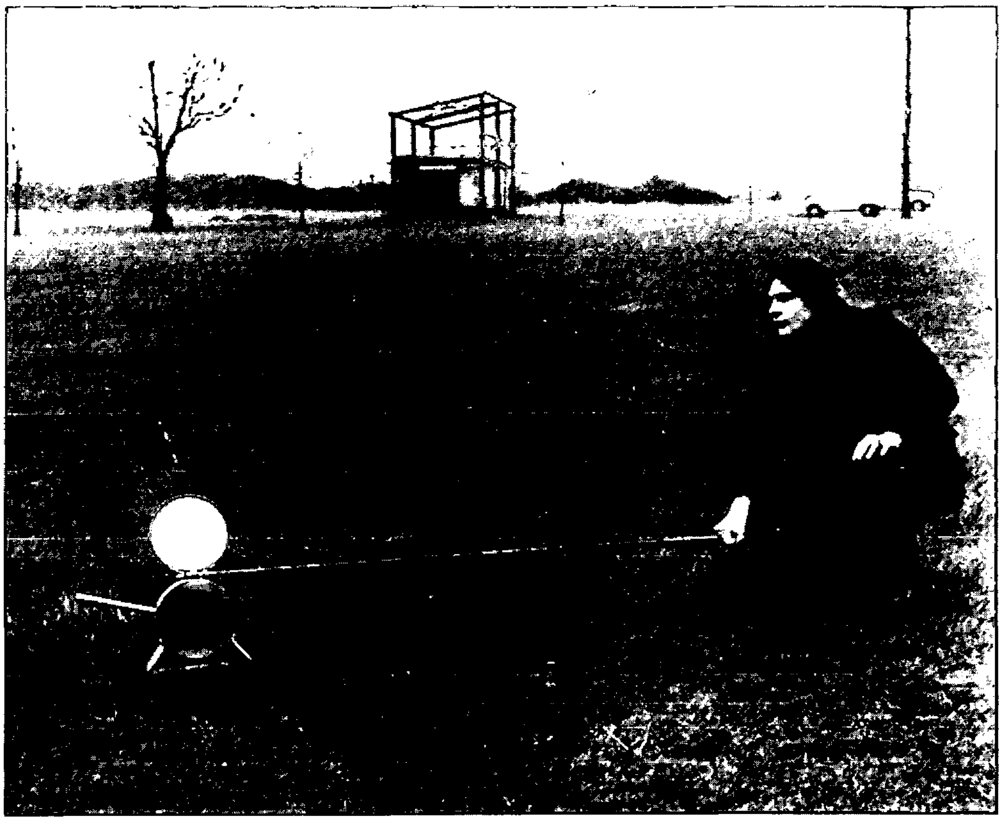
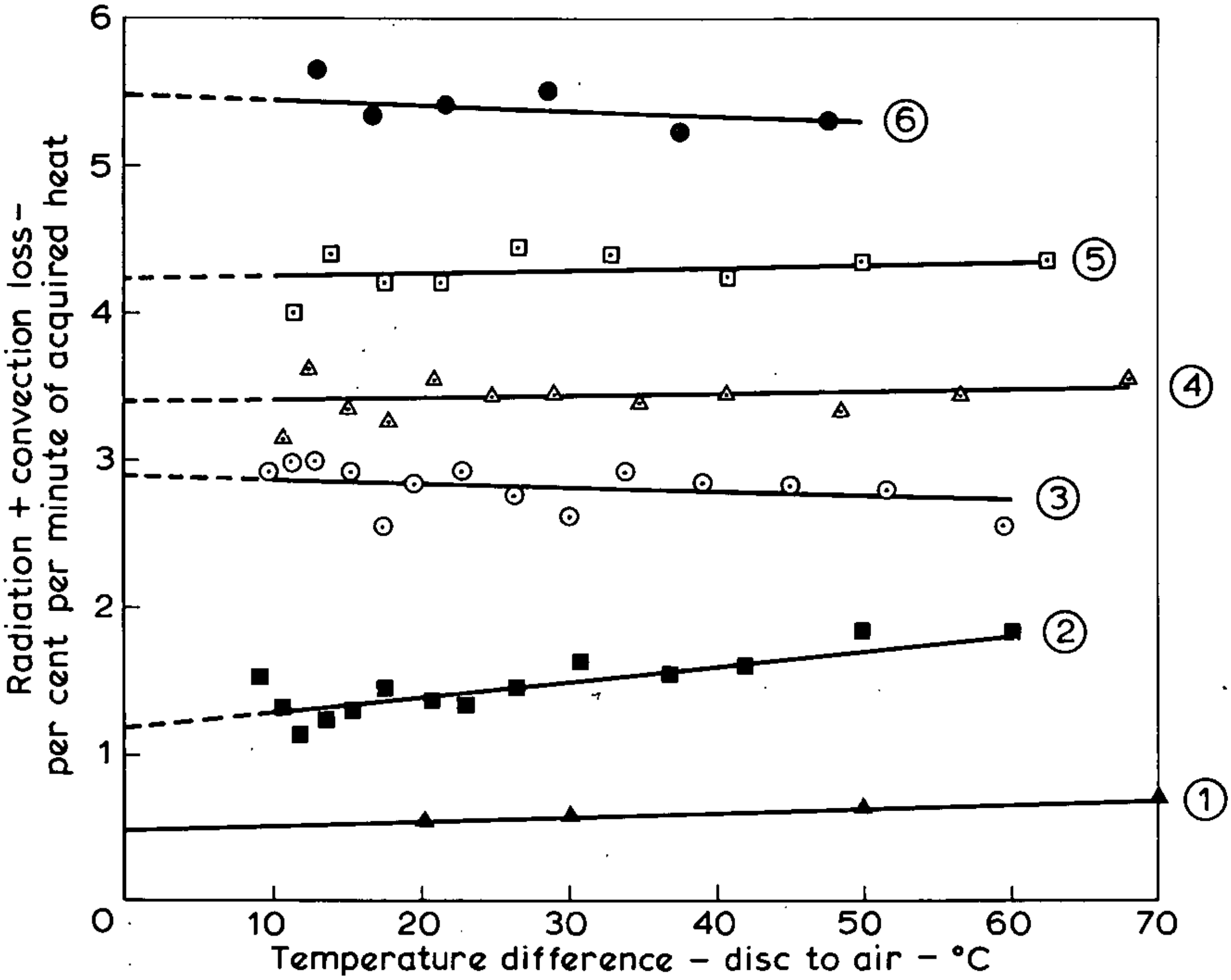


FIG. 8 CALORIMETER BEING USED WITH EXTENSION ROD



① Radiation only from Stefan – Boltzman law – above 20°C - emissivity = 1

② Radiation + convection – still air

③ Radiation + convection – wind speed – 2·25 m/s (5 m p h) (4·35 knots)

④ Radiation + convection – wind speed – 4·5 m/s (10 m p h) (8·7 knots)

⑤ Radiation + convection – wind speed – 6·7 m/s (15 m p h) (13 knots)

⑥ Radiation + convection – wind speed – 9·0 m/s (20 m ph) (17·5 knots)

Figure 9 Calorimeter cooling rates at various wind speeds parallel to face of disc

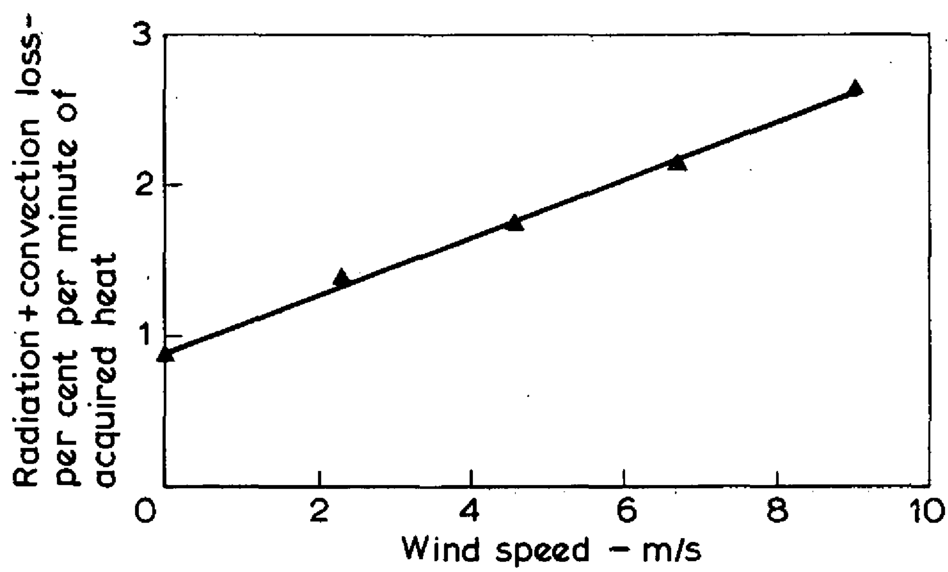
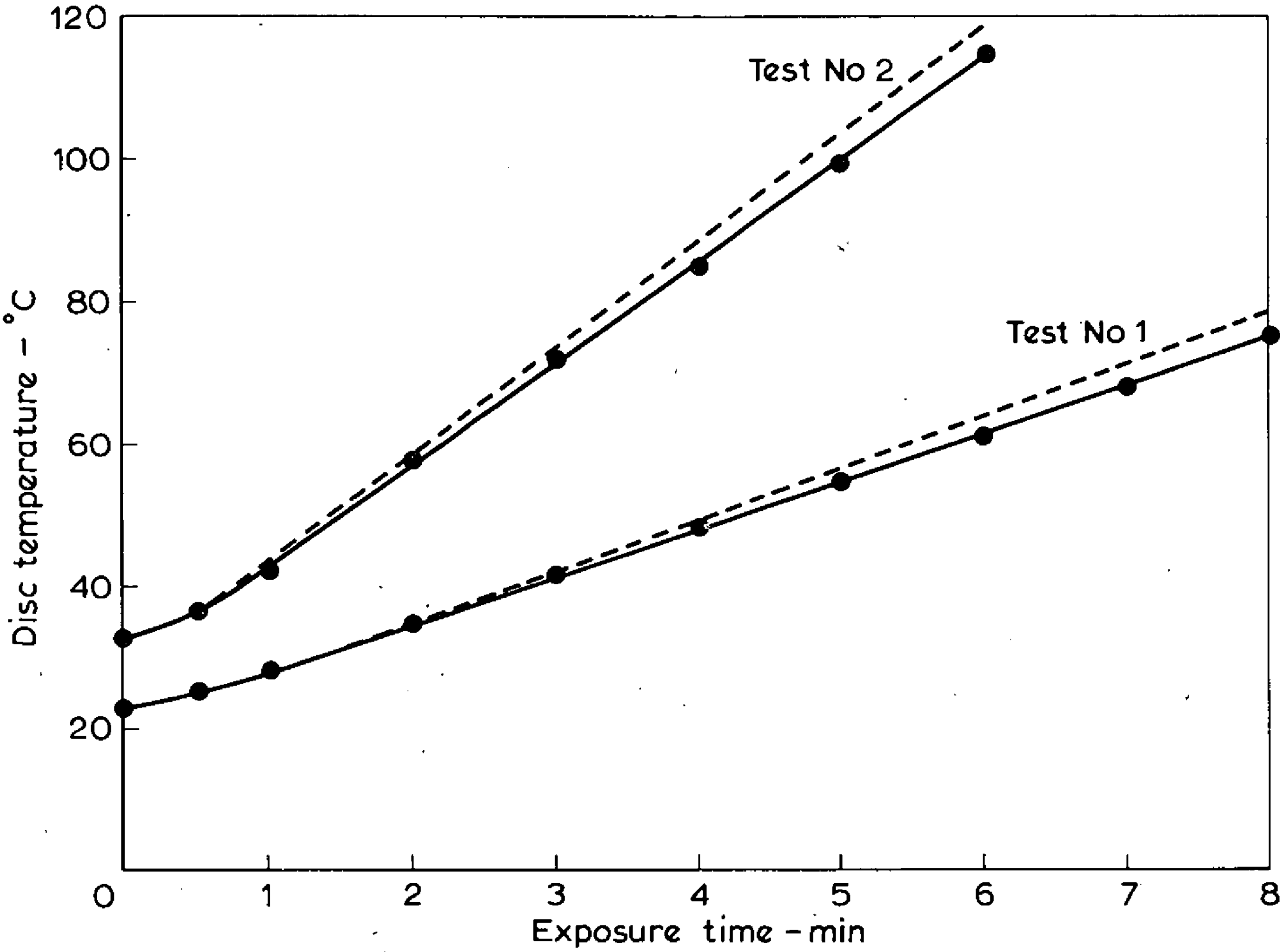


Figure 10 Radiation + convection loss at various wind speeds across the disc



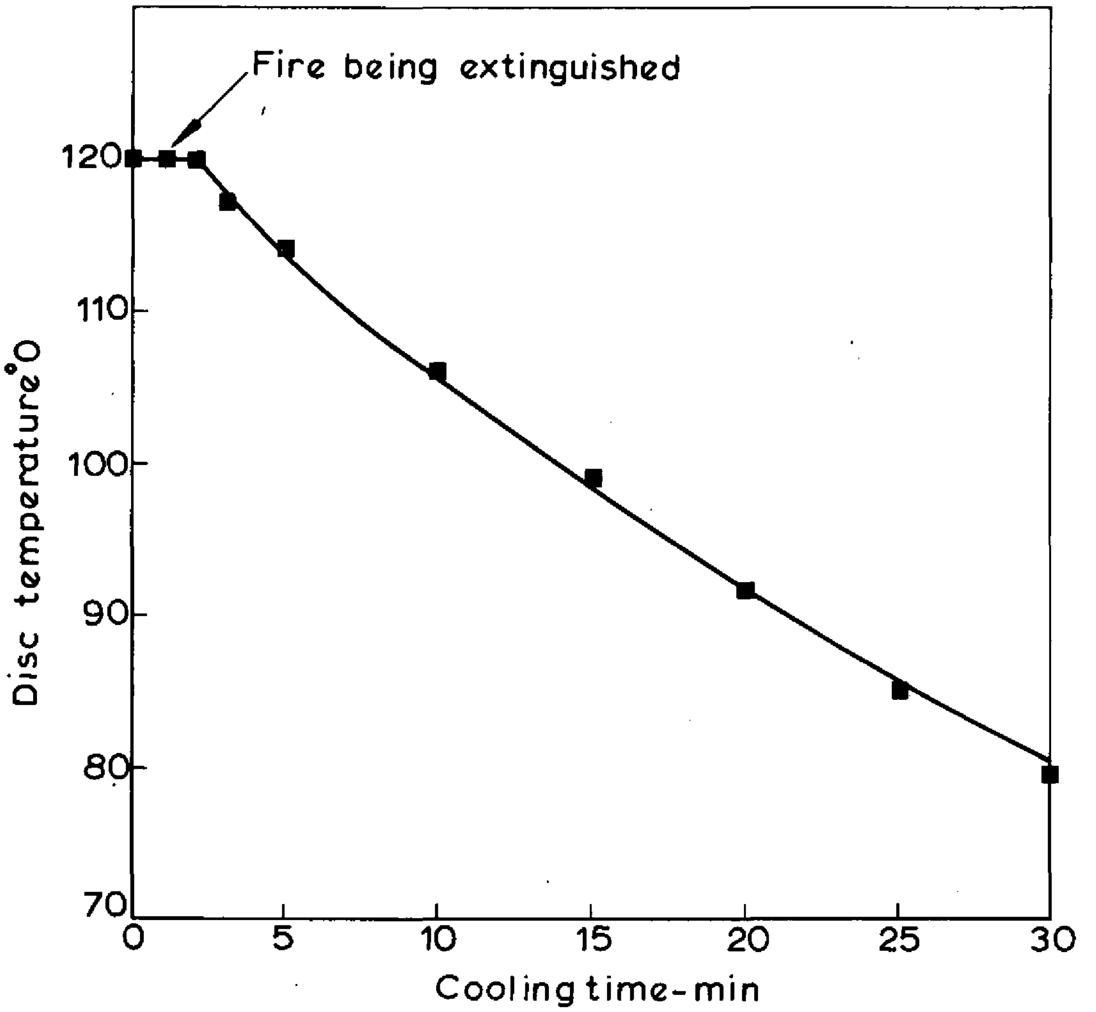
Calorimeter vertical and upwind from fire

	Test No.1	Test No 2
Distance from fire point	1 x Width	0·44x Width
Wind speed m/s	4·0	3·6
Ambient temperature -°C	22	29

——— Observed results

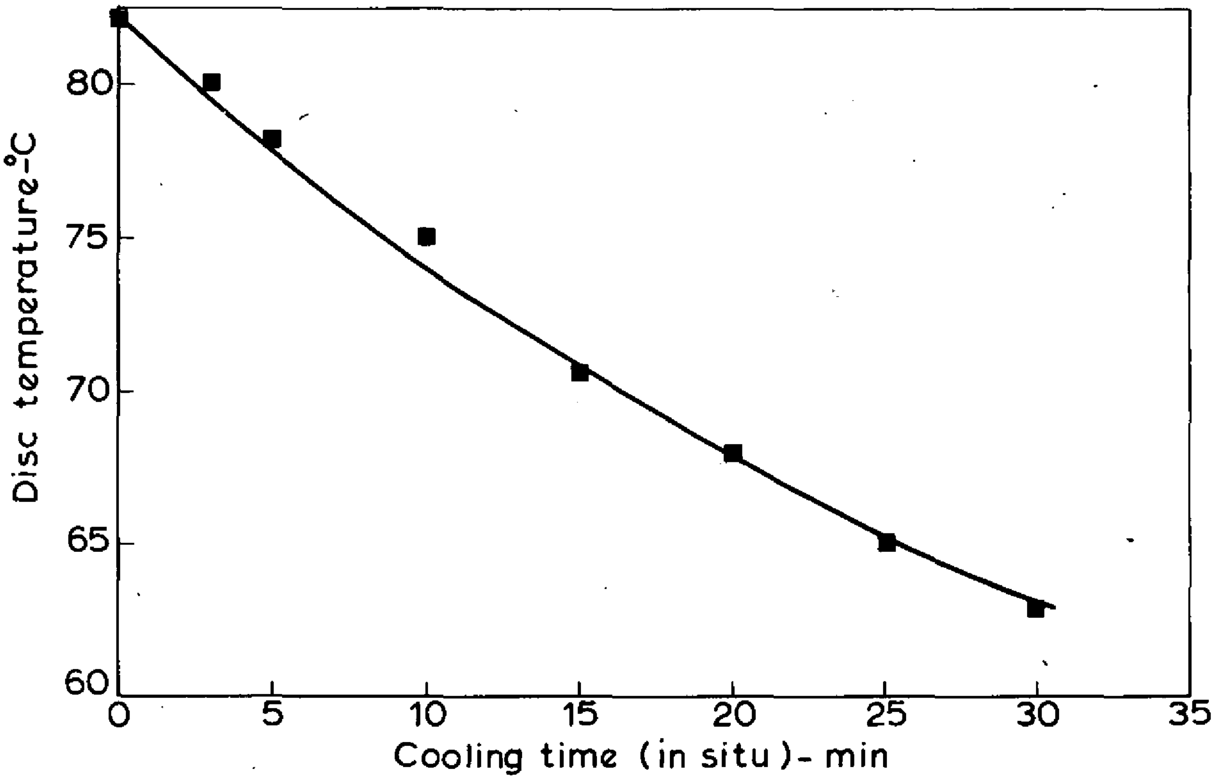
- - - - Corrected for cooling loss

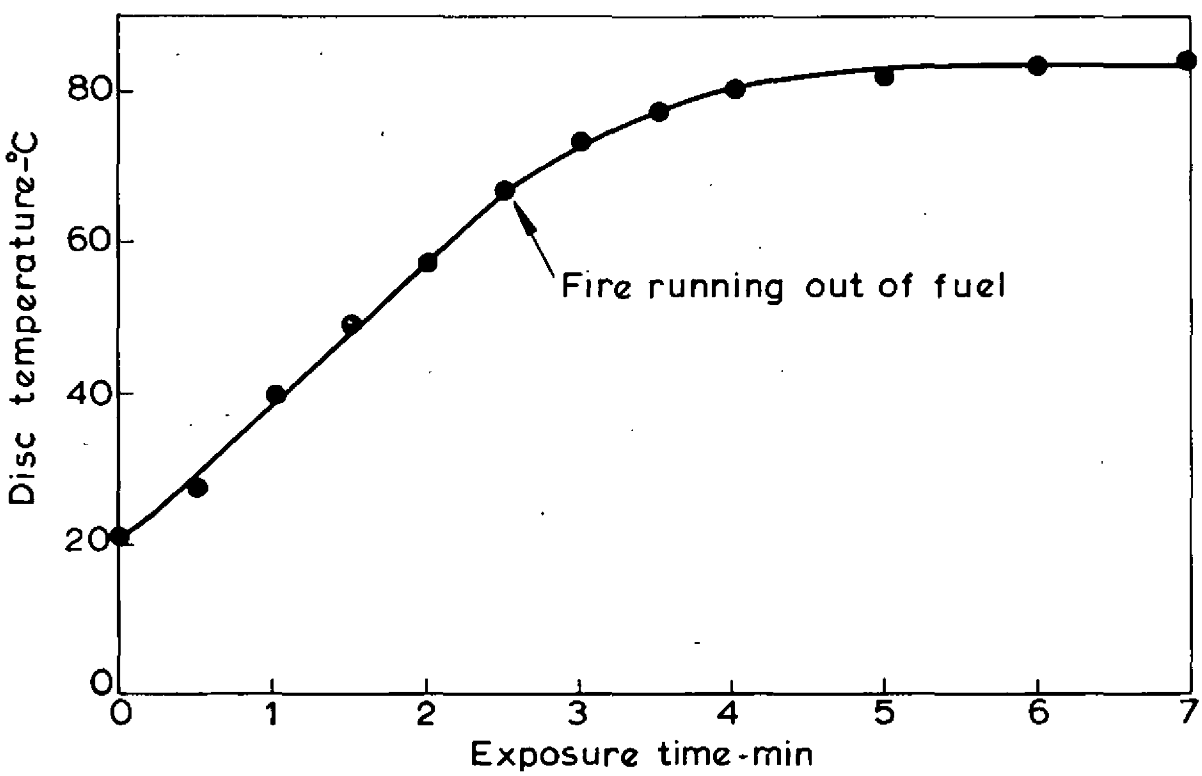
Figure 11 Tests using kerosine fires 1·4m x 1·4m with thermocouple



Wind speed 3·6 m/s
Ambient temp 29°C
Position vertical with back to wind

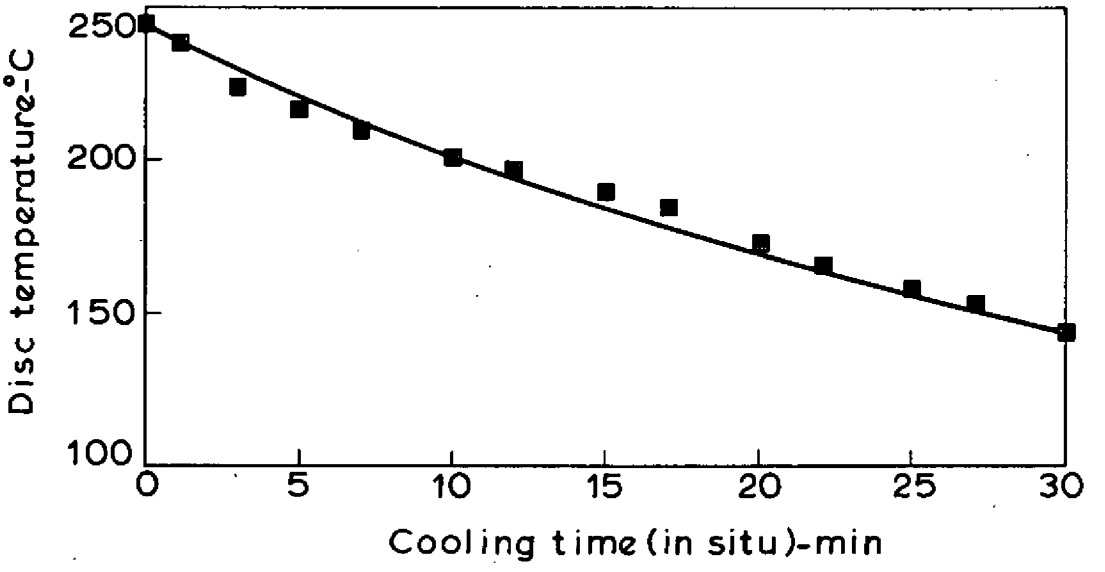
Figure 12 Calorimeter cooling rate – in situ following test No 2

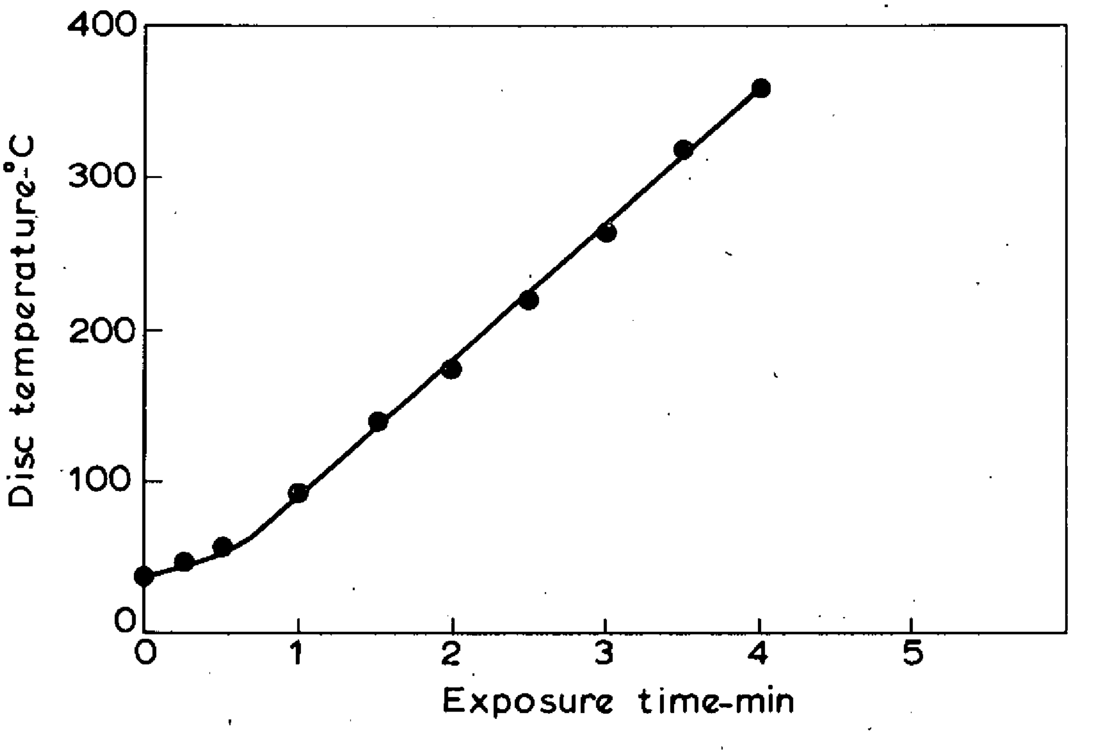




Calorimeter vertical and downwind from fire
Distance from fire front - 1 fire width
Wind speed - 1 m/s
Ambient temperature - 31 °C

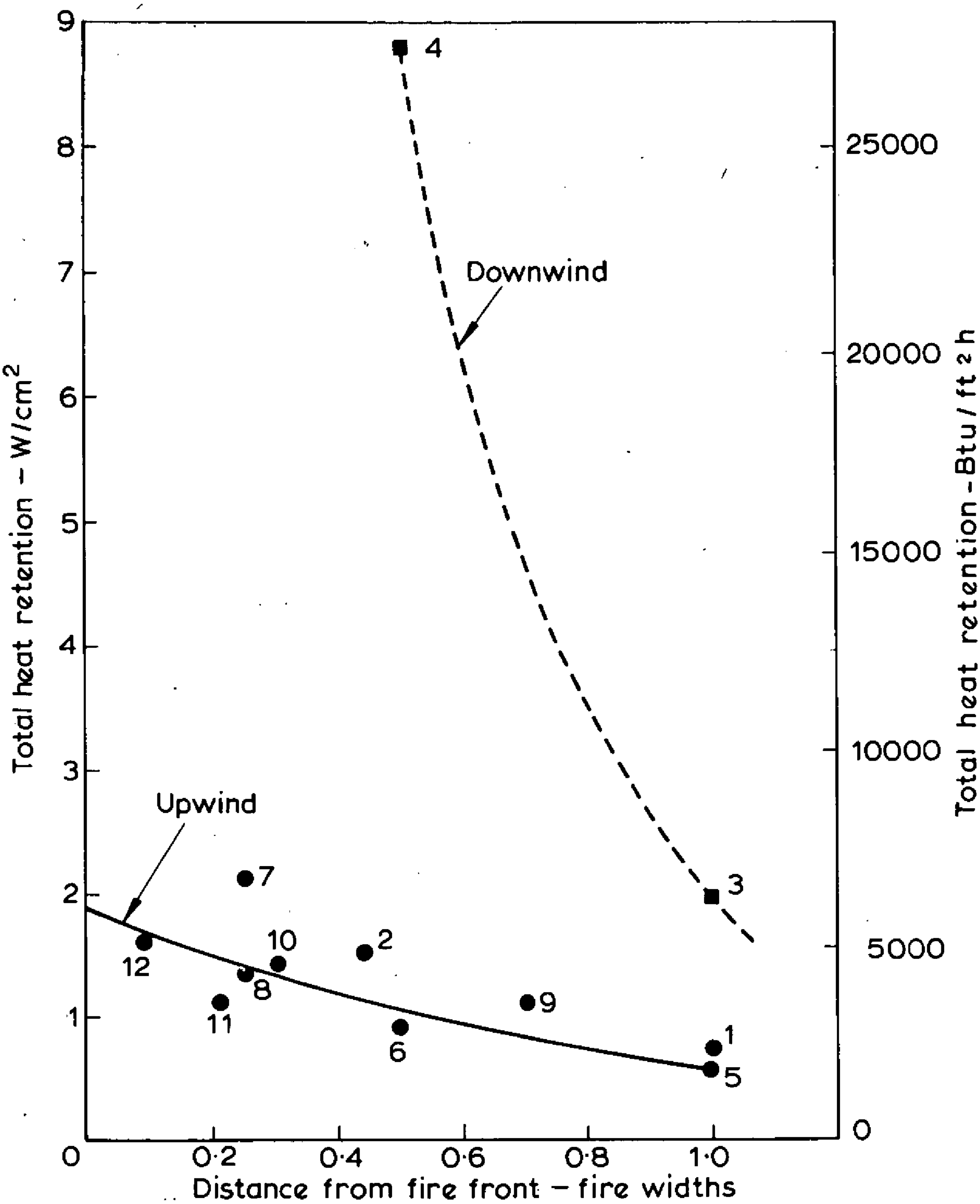
Figure 13 Test No 3 - kerosine fire 1·4m x 1·4m - with thermocouple





Calorimeter vertical and down wind from fire
Distance from fire front = 0·5 fire width
Wind speed - 4 m/s
Ambient temperature 27°C

Figure 14 Test No 4 - kerosine fire 1·4m x 1·4m - with thermocouple



Point No	Location	Fuel	Fire Area – m^2	Wind speed m/s
1	Up-wind	Kerosine	2	4
2	Up-wind	Kerosine	2	3·6
5	Up-wind	Kerosine	81	3·5
6	Up-wind	Kerosine	81	3·5
7	Up-wind	M I B K	7·3	2·0
8	Up-wind	M I B K	7·3	7·5
9	Up-wind	M I B K	7·3	nil
10	Up-wind	Crude oil	457	3
11	Up-wind	Crude oil	457	2
12	Up-wind	Crude oil	457	1·25
3	Downwind	Kerosine	2	1
4	Downwind	Kerosine	2	4

Position – vertical at centre fire front

Figure 15 Calorimeter measurements on various experimental fires

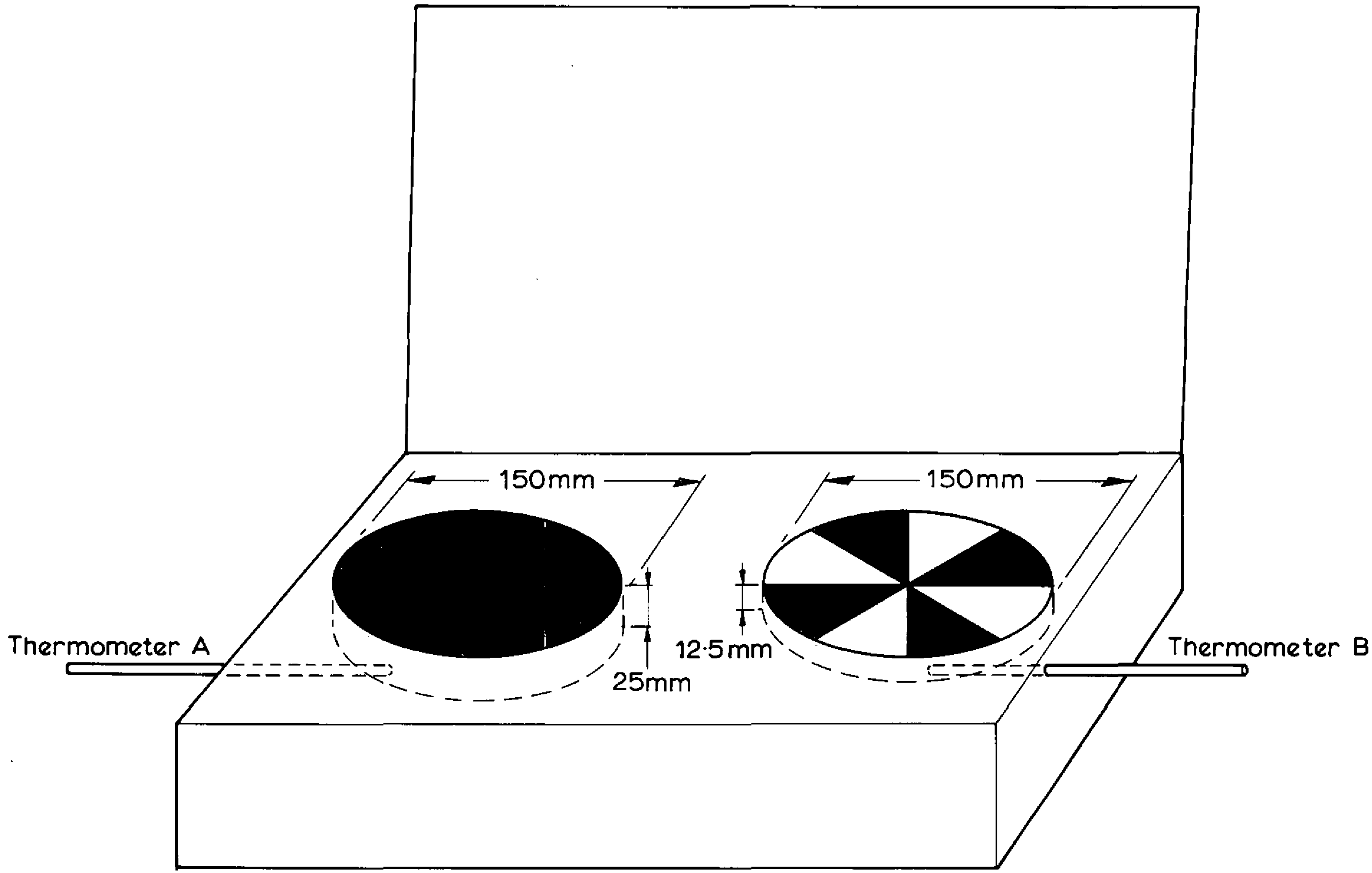


Figure 16 Twin-set calorimeter to differentiate radiant and convective heat

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