

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
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AN INSTRUMENT FOR SEPARATING CONVECTION AND
RADIATION COMPONENTS OF HEAT TRANSFER

by

A.J.M. Heselden and M. A. Mallet

SUMMARY

An instrument is described which measures separately the convective and radiative components of heat transfer within a large flame. Its principle of operation is that the convective transfer to smooth surfaces, whether polished or blackened, exposed to a given flame is the same but heat transfer by radiation is proportional to surface absorptivity. Two gold-plated copper segments, one blackened on its receiving surface, are exposed simultaneously for a few seconds within a flame, and radiation and convection components are obtained from the rates of temperature rise of the segments and separately measured surface absorptivities. Although cooling corrections are necessary they can be simply made since the cooling rate varies linearly with temperature excess.

The instrument can be used satisfactorily in flames of alcohol, town gas and wood.

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1. Introduction

The rate at which a fire burns in a compartment is determined by the feedback of heat to the fuel bed, partly by radiation from the flame zone and walls, and partly, perhaps, by convection from the flame and any recirculating combustion products. The total feedback of heat has been measured in a small compartment by means of a calorimetric total heat-flux meter⁽¹⁾ but since there are grounds for believing that the relative magnitudes of the convection and radiation components of heat transfer vary with size of compartment, these must be known before the results can be applied to any other size of compartment. It was not possible to calculate the convection transfer because of the large uncertainties in the physical properties of the flame gases, and a second instrument to measure convection and radiation components separately has therefore been developed and is described in this report.

The instrument is primarily intended for use in fairly clean flames, such as those of town gas but it has been found possible to use it in flames from burning wood. This instrument was made the same size as the total heat-flux meter so that the convection transfer would be similar in both instruments and the results could be directly compared.

Other workers have measured convection transfer in large flames by two methods.

In the first convection transfer was obtained as the difference between two measurements, one with a total heat-flux meter and one with an instrument sensitive only to radiation, e.g. the ellipsoidal radiometer of the United Steel Companies⁽²⁾. Baulk and Thring have suggested a means of converting a total heat-flux meter into a radiometer by surrounding the receiver with an annular jet of air or nitrogen to prevent hot gases reaching the receiver⁽³⁾.

In the second method convection transfer was obtained from the total heat flows to two instruments whose receiving surfaces were at different temperatures, the gas temperature being also known, or whose surfaces were at the same temperature but were of different absorptivities⁽⁴⁾. It was thought that the last method, with two surfaces of different absorptivities, would be most suitable for the present measurements because the instrument would be relatively simple to construct.

2. Construction and operation

The instrument consists essentially of two receivers, one blackened and one polished, which are exposed simultaneously to a heat flux containing both convection and radiation transfer components. The convection transfer to each segment is virtually the same, but the radiation transfer is proportional to the absorptivity of the segment. From the rates of temperature rise of the segments, their absorptivities, and cooling coefficients, the radiation and convection components can be separately determined.

The receiver (Fig 1) consists of two nearly semi-circular segments of copper, plated with a layer of gold 0.05 mm thick. The front surface of one segment is blackened with matt black paint and carbon soot from a town gas flame. The segments are 6.0 mm thick and lie adjacent to each other along their diameters with a narrow air gap between them, forming a circular receiver 3.78 cm in diameter.

Two versions of the instrument were made, differing in the construction of the water jacket and supporting arm and in the air gaps around the segments. Details are given in Table 1. The first version (Fig 1) was used to measure heat fluxes in town gas flames in a small compartment. The second (Fig 2) had a similar receiver but the water jacket and water-cooled supporting arm were of leak tight construction enabling the instrument to be immersed in tanks of burning liquid fuel, with the liquid level about 1 cm below the plane of the receiver, or placed within burning wood cribs. In this version inlet water flowed first round the part of the jacket containing the segments and was returned along the annular supporting arm, cooling the arm and protecting the thermocouple and heater leads. Part of the return flow was by-passed through a hinge to cool the removable cap.

Table 1

Air spaces around segments

Instrument	Gap between segment edge and water jacket mm	Gap between segments mm	Gap between rear of segment and water jacket mm
Mark 1	0.1	0.1	2
Mark 2	0.35	0.5	3

The receiver is surrounded by a water-cooled jacket, separated by a narrow air gap at the edge and an air gap 2-3 mm at the rear of the segments. The segments are supported on nylon bushes to minimize conduction of heat to the jacket from the segments. A 40 s.w.g. chromel-alumel thermocouple was inserted into a hole in the rear of each segment and held in place with an epoxy-resin cement so that the junction lay about halfway through the thickness of the segment. An electric heater, consisting of 36 s.w.g. Nichrome was attached with an epoxy-resin cement to the rear of each block. Some 10 cm of wire was in contact with the block.

In use the instrument, mounted on the end of a probe, is rapidly positioned in a flame and a closely fitting cover over the front face of the segments is removed. The output from each thermocouple is amplified and registered on a pen recorder. After some 10-15 s exposure the cover is replaced and the instrument withdrawn.

The rise in temperature of the segments is an insufficient indication of heat absorption on the front face since part of this heat is lost to the water-cooled jacket, and there is an interchange of heat between the segments. However, Section 3 shows that these effects can be accurately allowed for.

3. Determination of the cooling coefficients

The rate of heat loss from the segments was found by calculation to be predominantly by conduction to the water jacket, partly through the air gaps and partly through the nylon supports, so that the heat loss and heat exchange between segments are proportional to temperature differences. The rate of temperature rise of the segments will therefore be given by the expressions:-

$$Q \frac{d\theta_1}{dt} = A (a_1 I_R + I_C) - h (\theta_1) + g (\theta_2 - \theta_1) \quad \dots\dots (1)$$

$$Q \frac{d\theta_2}{dt} = A (a_2 I_R + I_C) - h (\theta_2) - g (\theta_2 - \theta_1) \quad \dots\dots (2)$$

where Q = thermal capacity of one segment (cal deg C^{-1})

θ = temperature rise of segment above its initial steady temperature (deg C)

t = time (s)

A = area of the front face of one segment (cm^2)

a = absorptivity of the front face of the segment

I_R = intensity of radiation incident on the front face of the segment ($\text{cal cm}^{-2}\text{s}^{-1}$).

I_0 = rate of convection transfer to the front face of the segment ($\text{cal cm}^{-2}\text{s}^{-1}$)

h = heat loss coefficient for one segment ($\text{cal s}^{-1}\text{deg C}^{-1}$)

g = coefficient of heat exchange between segments ($\text{cal s}^{-1}\text{deg C}^{-1}$)

Suffixes 1 and 2 refer to the polished and blackened segments respectively.

It is convenient to put

$$H = A (a I_R + I_0) \quad \dots\dots (3)$$

and to write $\dot{\theta}$ for $\frac{d\theta}{dt}$.

h , g , a_1 and a_2 were found by exposing the instrument to known intensities of radiation measured with one of the J.F.R.O. secondary standard thermocouples⁽⁵⁾. The source of radiation was a gas-fired radiant panel running at some 800°C .

Adding and subtracting equations (1) and (2):-

$$Q (\dot{\theta}_1 + \dot{\theta}_2) = (H_1 + H_2) - h (\theta_1 + \theta_2) \quad \dots\dots (4)$$

$$Q (\dot{\theta}_2 - \dot{\theta}_1) = (H_2 - H_1) - (h + 2g) (\theta_2 - \theta_1) \quad \dots\dots (5)$$

where $\dot{\theta}_1$, $\dot{\theta}_2$, θ_1 and θ_2 are all values for the same instant. Plotting $\dot{\theta}_1 + \dot{\theta}_2$ against $\theta_1 + \theta_2$ yields a line of slope h/Q , which gives h , since Q can be obtained from the mass of the segment, and plotting $\dot{\theta}_2 - \dot{\theta}_1$ against $\theta_2 - \theta_1$ yields a line of slope $(h + 2g)/Q$ which gives g , since h is known. It is sufficiently accurate to obtain an estimate of $\dot{\theta}_1 + \dot{\theta}_2$ and $\dot{\theta}_2 - \dot{\theta}_1$ by differences (Appendix I).

h and g have also been obtained from the cooling curves, with the radiation out off. Putting $H_1 = H_2 = 0$ in equations (4) and (5) and integrating gives:-

$$\theta_1 + \theta_2 = \theta_0 e^{-\frac{ht}{Q}} \quad \dots\dots (6)$$

$$\theta_2 - \theta_1 = \theta_0' e^{-\frac{(h + 2g)t}{Q}} \quad \dots\dots (7)$$

h and g were thus found from the slopes of the lines obtained by plotting $\theta_1 + \theta_2$ and $\theta_2 - \theta_1$ against t on log-linear paper. $\theta_1 + \theta_2$ and $\theta_2 - \theta_1$ for

a typical run are plotted in Fig 3 against t. The straightness of the lines obtained is evidently confirmation of the proportionality of the rate of heat loss to excess temperature, i.e. of the constancy of h and g. h (but not g) could also be found with both segments blackened or left polished so that θ_1 and θ_2 would be equal and the heat exchange between the segments zero.

Table 2 gives means and 95 per cent confidence limits for the mean for h and g found for both versions of the instrument from a number of determinations by both heating and cooling curves.

Table 2

Experimental and calculated values of cooling coefficients

Instrument	h cal s ⁻¹ deg C ⁻¹		g cal s ⁻¹ deg C ⁻¹	
	Experimental	Calculated	Experimental	Calculated
Mark 1	0.03 ± 0.004	0.02	0.015 ± 0.002	0.015
Mark 2	0.012 ± 0.003	0.008	0.004 ± 0.001	0.003

The values calculated for h and g, taking into account conduction loss to the water jacket through the air gaps and nylon supports and radiation and convection loss are also given in Table 2 and in view of the approximations made in the calculation these are in reasonable agreement with the values found by experiment.

4. Determination of absorptivities

The absorptivities were initially obtained from equations (4) and (5) and Appendix I gives a sample calculation. When $\theta_1 = \theta_2 = 0$, the intercepts of equations (4) and (5) on the $\dot{\theta}_1 + \dot{\theta}_2$ and $(\dot{\theta}_2 - \dot{\theta}_1)$ axis are respectively $\frac{H_1 + H_2}{Q}$ and $\frac{H_1 - H_2}{Q}$, and a_1 and a_2 can be found since A , I_R and Q are known. A simpler method had to be employed when the instrument was actually in use (Section 5.1).

The mean of a number of determinations gave absorptivity values for Mark 2 of 0.08 and 0.93 for a_1 and a_2 , with standard deviations for one measurement of 0.01 and 0.04 respectively. 0.93 is near the value normally taken for candle soot on black paint (0.95) for radiation from sources at about 800°C. The corresponding values for Mark 1 were 0.06 and 0.94. The value for the polished segment is higher than published values for gold (0.02 to 0.03(6)) but this may be because a small amount of soot remained in depressions in the surface when it was cleaned. The absorptivity was readily reduced to a constant value by cleaning with petrol after each exposure in a flame.

* θ_0 and θ_0' are values of $\theta_1 + \theta_2$ and $\theta_2 - \theta_1$ at a suitable time during the cooling period when t is taken as 0.

5. Operation in practice

5.1 Abbreviation of calculations

For routine use in flames a more rapid method for computing the results must be used. Further, although the time scale of the recorders can be accurately synchronised, the time of the start of the exposure is not always well defined. The simplest method for determining I_C and I_R is to read temperature rises at two times t and $t + S$ where S is a known time interval. It can be shown from equations (4) and (5) that:-

$$H_1 + H_2 = \frac{h \left[(\theta_1 + \theta_2) e^{-\frac{hS}{Q}} - (\theta'_1 + \theta'_2) \right]}{\left[e^{-\frac{hS}{Q}} - 1 \right]} \dots\dots\dots (8)$$

$$H_2 - H_1 = \frac{(h + 2g) \left[(\theta_2 - \theta_1) e^{-\frac{(h + 2g)S}{Q}} - (\theta'_2 - \theta'_1) \right]}{\left[e^{-\frac{(h + 2g)S}{Q}} - 1 \right]} \dots\dots\dots (9)$$

where θ_1 and θ_2 are the temperature rises at time t and θ'_1 and θ'_2 are the temperature rises at time $(t + S)$. Equations (8) and (9) do not contain t . Provided a standard value for S is taken, say 7.5 or 10s, equations (8) and (9) are rapidly solved for H_1 and H_2 , and then I_R and I_C can be found from equation 3.

It is often necessary to measure the absorptivity of the polished segment during experiments in which the instrument is exposed in flames and some sooting up occurs. This must be determined by exposure to radiation. The start of the exposure is then well defined, and it is only necessary to take one temperature reading, at a subsequent time (t_1). Then:-

$$H_1 + H_2 = A I_R (a_1 + a_2) = \frac{h (\theta_1 + \theta_2)}{1 - e^{-\frac{ht_1}{Q}}} = C \dots\dots\dots (10)$$

$$H_2 - H_1 = A I_R (a_2 - a_1) = \frac{(h + 2g)(\theta_2 - \theta_1)}{1 - e^{-\frac{(h + 2g)t_1}{Q}}} = D \dots\dots\dots (11)$$

so that
$$a_1 = \frac{C - D}{2 A I_R} \dots\dots\dots (12)$$

and
$$\frac{a_1}{a_2} = \frac{C - D}{C + D} \dots\dots\dots (13)$$

If I_R is known, a_1 can be found from (12), and if I_R is unknown a_1 can be found from (13) since a_2 is unlikely to vary significantly from 0.93.

It is not worth trying to simplify equations (8), (9), (10) and (11) further because the exponential series does not converge very rapidly with these values of h , g and Q and values of t , large enough to enable readings to be taken from the recorder chart with sufficient accuracy.

5.2 Elimination of condensation of water

It was found, as had been expected, that immediately the segments were exposed in a flame condensation of water occurred on the segments, increasing the absorptivity of the polished segment. To overcome this the segments were maintained above the dew point of the gases by means of the electric heaters attached to the rear of the segments. The dewpoint of combustion products from stoichiometric combustion of town gas is in the region of 61°C (7) and the temperature of the segments was therefore held well above this, at about 90°C , by an A.C. current fed from a Variac through both heaters in series.

The thermocouple outputs at this temperature (some 3 mV with cold junctions at room temperature) were reduced to values suitable for the amplifier used by introducing in opposition an e.m.f. which could be varied. The deflection due to exposure in the flame was thus arranged to occupy a large proportion of the recorder chart.

Owing to their elevated temperature the net heat transfer to the segments was reduced, but this effect was not very large, since the temperature of the flame into which the meter was placed was usually high. In any case quite a rough measure of flame temperature sufficed to enable a correction to be applied.

It was found that the values of h and g were apparently unaffected by the increased segment temperature. An increase of some 10 per cent in h and g might be expected in view of the increase in thermal conductivity of air with temperature, but as can be seen from Table 2 an increase of this order would be hard to detect.

5.3 Effect of sooting of polished segment

During exposure in a flame soot is gradually deposited on the polished segment and the absorptivity and hence the radiation absorption increases. It is assumed that during an exposure the absorptivity changes linearly with time, provided the absorptivity is initially low. Allowance for this change can be made by putting

$$a_1 = (a_1)_0 (1 + \gamma t), \quad \dots\dots (14)$$

in equations (4) and (5) where γ is a constant obtained by measuring the absorptivity before and after exposure in the flame for a known time. Solving, we have

$$(\theta_1 + \theta_2) \text{ Corrected} = (\theta_1 + \theta_2) \text{ Measured} \frac{-A (a_1)_0 \gamma I_R t^2}{2Q} \quad \dots\dots (15)$$

$$(\theta_2 - \theta_1) \text{ Corrected} = (\theta_2 - \theta_1) \text{ Measured} \frac{+A (a_1)_0 \gamma I_R t^2}{2Q} \quad \dots\dots (16)$$

A value for I_R sufficiently accurate to insert in the correction term can be obtained from equations (10) and (11).

Table 3 lists values of absorptivity of the polished segment of Mark 1, measured after exposures of 10s in a town gas flame in the compartment described previously(8), with corresponding values of γ .

Table 3

Values obtained for γ in a town gas flame

Town gas flow g/s	Increase in absorptivity (a_1) in 10s exposure*	γ s ⁻¹
21	0.025	0.0025
12	0.045	0.0045
4.5	0.13	0.013

*Initial absorptivity 0.06

The sooting up of the segments of Mark 2 was very slow at the base of ethyl alcohol (industrial methylated spirit) flames burning in a 92-cm diameter tray, the absorptivity changing by only 0.04 after a total exposure, in 10s units, of 4 min. In wood flames the sooting was more rapid but was still sufficiently small to enable accurate readings to be made; changes in absorptivity of up to 0.09 in 10s occurred, giving values of γ of up to 0.009.

6. Performance with convection flux

No means was available for calibrating the instrument in a known convection flux, but it has been possible to compare the measurement of a combined radiation and convection flux with the sum of the separate fluxes. The instrument was set up on a slide which could be positively positioned near a gas-fired radiant panel running at about 800°C or drawn back and screened. ^{the instrument} An electric firelighter(9) was placed on one side of the panel and the hot air blast trained on the receiver of the instrument. The first reading made was of the convection transfer from the air blast after the firelighter had attained thermal equilibrium. The radiant panel was then lit and allowed to reach a steady temperature and a second reading made. The electric firelighter was then turned off and a third reading made with the radiant panel alone.

The agreement shown in Table 4, between the measured total heat flux and the sum of the separate fluxes is satisfactory. An attempt was made to increase the radiation and convection fluxes, but it was not found possible with the available apparatus without bringing the air blast so close to the panel that it was deflected, and the convection flux changed, by the plume of combustion products from the front of the panel.

Table 4

Convection and radiation fluxes separately and combined

Condition	Component	Measured heat flux cal cm ⁻² s ⁻¹	
		Polished segment	Blackened segment
Panel cold, hot air blast on	I _C	0.18 [†]	0.20 [†]
Panel hot, hot air blast off	I _R	0.06	0.72*
Sum	I _C + I _R	0.24	0.92
Panel hot, hot air blast on	I _{Combined}	0.23	0.89

[†]The agreement between these values was to some extent fortuitous since the hot air blast was only aligned on to the receiver by eye.

*This corresponds to a radiation flux to a black body absorber of $0.72/0.93 = 0.77$ cal cm⁻²s⁻¹. The radiant flux measured with a Moll thermopile⁽⁵⁾ was 0.81 cal cm⁻²s⁻¹.

7. Accuracy

The accuracy of the instrument is difficult to assess and may depend on the relative proportion of radiation and convection components and on the steadiness of the heat fluxes measured. However the normal exposure time of 10s is sufficient long for the effect of the more rapid fluctuations e.g. those in turbulent eddies⁽¹⁰⁾ to be unimportant.

7.1. Error in heat flux measurement due to error in cooling constants

In the short time of exposure the heat losses are relatively small and the calculated convection and radiation heat fluxes are not sensitive to the values of h and g employed. Table 5 shows that if no account at all is taken of heat loss and heat exchange between segments the error of the Mark 2 instrument will not exceed 4 per cent, with 10s exposures.

Table 5

Effect of errors in h and g

Actual heat transfer cal cm ⁻² s ⁻¹		Error introduced by assuming h = g = 0 (true values 0.012 and 0.004 cal s ⁻¹ deg C ⁻¹ respectively) cal cm ⁻² s ⁻¹	
I _R	I _C	Radiation	Convection
0	0.1	0	- 0.002
0	0.5	0	- 0.01
0.1	0	- 0.004	+ 0.001
1.0	0	- 0.04	+ 0.01
1.0	0.5	- 0.03	0.00
0.1	0.1	- 0.004	- 0.002

The errors of the Mark 1 instrument are potentially greater since h and g are larger, but nevertheless h and g only have to be known to an accuracy of 30 per cent to give heat transfer measurements accurate to some 4 per cent.

7.2 Error in heat flux measurement due to error in absorptivity

Error in the absorptivities of the receiving surfaces is more important than error in the cooling coefficients and Table 6 shows what errors would be made in the measured heat transfer components with the Mark 2 instrument if the actual values of a₁ and a₂ were 0.08 and 0.93 respectively, but other values had been employed in calculating the components from the temperature rises. Errors of 0.04 in one or other of a₁ and a₂ can cause errors in the measured components of up to 5 per cent, and errors of 0.04 in both a₁ and a₂ can cause errors of up to 10 per cent.

Table 6

Effect of errors in a_1 and a_2

Actual heat transfer cal cm ⁻² s ⁻¹		Error if true values of a_1 and a_2 are 0.08 and 0.93 respectively and the following values are assumed							
		$a_1 = 0.12$ $a_2 = 0.93$		$a_1 = 0.08$ $a_2 = 0.97$		$a_1 = 0.12$ $a_2 = 0.97$		$a_1 = 0.12$ $a_2 = 0.89$	
I_R	I_G	R	C	R	C	R	C	R	C
0	0.1	0	0	0	0	0	0	0	0
0	0.5	0	0	0	0	0	0	0	0
0.1	0	+ 0.005	- 0.005	- 0.005	0.000	0.000	- 0.004	+ 0.010	- 0.005
1.0	0	+ 0.05	- 0.05	- 0.05	0.00	0.00	- 0.04	+ 0.10	- 0.05
1.0	0.5	+ 0.05	- 0.05	- 0.05	0.00	0.00	- 0.04	+ 0.10	- 0.05
0.1	0.1	+ 0.005	- 0.005	- 0.005	0.000	0.000	- 0.004	+ 0.010	- 0.005

R = Error in radiation component cal cm⁻²s⁻¹C = Error in convection component cal cm⁻²s⁻¹

7.3 Repeatability of readings

Repeated readings with the Mark 2 instrument at the base of the flames from a 92-cm diameter tray of burning alcohol had standard deviations for the readings of the convection component of about $0.05 \text{ cal cm}^{-2}\text{s}^{-1}$ (in an average convection flux of about $0.2 \text{ cal cm}^{-2}\text{s}^{-1}$) and for the readings of the radiation component of about $0.1 \text{ cal cm}^{-2}\text{s}^{-1}$ (in an average radiation flux of about $0.7 \text{ cal cm}^{-2}\text{s}^{-1}$). The accuracy of the instrument is likely to be better than this, since these variations include any of the flame itself. Section 6 shows that under some conditions the instrument can be accurate to at least 5 per cent, which is more than sufficient in most applications in fire research.

8. Range of use

The useful range of the instrument is limited by the accuracy with which the readings can be read from the recorder chart and to some extent by the temperature which the nylon supports will withstand. The output from the thermocouple on the blackened segment should not be allowed to exceed about 1 mV (corresponding to a temperature rise of 24 deg C, or a maximum temperature of about 120°C); this is full scale deflection with the amplifier and recorder system employed. The standard exposure time of 10 s corresponds to a 1 in movement of chart paper at the highest chart speed of the recorders available and outputs can be read off at particular times with adequate accuracy.

Total heat flows up to $1.2 \text{ cal cm}^{-2}\text{s}^{-1}$, corresponding to a 24 deg C temperature rise in 10 s, can therefore be measured with fair accuracy but although the instrument can in principle be used at higher intensities provided the limit of 24 deg C rise is not exceeded, the accuracy will be lower for higher heat flows because the exposure time must be made shorter.

9. Conclusions

- (1) The instrument can be used to separate convective and radiative components of heat transfer in wood, alcohol and town gas flames, and could probably be used in flames of other materials, provided the flames are no more sooty than those of wood.
- (2) It is more complicated to set up and use than the total heat-flux meter and this together with the number of corrections necessary in calculating results makes it unsuitable for routine use.
- (3) The instrument is most accurate when measuring total heat flows less than $1.2 \text{ cal cm}^{-2}\text{s}^{-1}$, though higher heat flows could probably be measured provided a lower accuracy could be accepted.

10. Acknowledgements

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Appendix I

Sample calculations of method for obtaining h and g

The gradients of θ_1 and θ_2 are obtained from the values read off the recorded traces at fixed time intervals. The calculations for an experiment with $I = 0.105 \text{ cal cm}^{-2} \text{ s}^{-1}$ are as follows:-

t s	θ_2^* μV	θ_1^* μV	$\dot{\theta}_2$ $\mu\text{V/s}$	$\dot{\theta}_1$ $\mu\text{V/s}$	$\dot{\theta}_2 - \dot{\theta}_1$ $\mu\text{V/s}$	$\dot{\theta}_1 + \dot{\theta}_2$ $\mu\text{V/s}$	$\theta_2 - \theta_1$ μV	$\theta_1 + \theta_2$ μV
0	0	0						
20	155	10	7.1	0.8	6.3	7.9	145	165
40	283	31	6.2	0.9	5.3	7.1	252	314
60	402	47	5.5	0.8	4.7	6.3	355	449
80	505	62	5.0	1.0	4.0	6.0	443	567
100	603	88	4.5	1.0	3.5	5.5	515	691
120	685	103	3.9	0.9	3.0	4.8	582	788
140	757	124	3.5	1.0	2.5	4.5	633	881
160	824	144						

For example, $\dot{\theta}_2$ at $t = 20$ s is taken as $\frac{283 - 0}{40} = 7.1 \mu\text{V/s}$.

$\dot{\theta}_2 - \dot{\theta}_1$ is then plotted against $\theta_2 - \theta_1$, and $\dot{\theta}_1 + \dot{\theta}_2$ against $\theta_1 + \theta_2$ (Fig 4), and the gradients of the straight lines through the points measured.

From equations (4) and (5) and Fig (4)

$$h/Q = 0.0044$$

$$(h + 2g)/Q = 0.0074$$

*After correction for recorder error

Since $Q = 2.72 \text{ cal deg C}^{-1}$

$$\frac{h}{g} = \frac{0.012 \text{ cal s}^{-1} \text{ deg C}^{-1}}{0.004 \text{ cal s}^{-1} \text{ deg C}^{-1}}$$

The absorptivities can be obtained from the intercepts of the lines in Fig 4 on the $\theta_1 + \theta_2$ and $\theta_2 - \theta_1$ axis. Since the thermo-electric power of the thermocouples is 41 micro volt/deg C:-

$$\left(\frac{H_1 + H_2}{Q} \right) = \frac{8.5}{41} \dots\dots\dots (17)$$

$$\left(\frac{H_2 - H_1}{Q} \right) = \frac{7.3}{41} \dots\dots\dots (18)$$

$Q = 2.72 \text{ cal deg C}^{-1}$, $I = 0.105 \text{ cal cm}^{-2} \text{ s}^{-1}$, and therefore from equations (3), (17) and (18):

$$\frac{a_1}{a_2} = \frac{0.071}{0.94}$$

h and g can be obtained from the slopes of the lines of Fig 3. These lines were obtained from the period when the segments were cooling, after the exposure, giving the values plotted in Fig 4.

$$\frac{h}{Q} = 2.303 \times \left(\frac{10.3}{25.2 \times 200} \right) = 0.00471$$

$$\frac{h + 2g}{Q} = 2.303 \left(\frac{15.9}{25.2 \times 200} \right) = 0.00725$$

Since $Q = 2.72 \text{ cal deg C}^{-1}$

$$\frac{h}{g} = \frac{0.013 \text{ cal s}^{-1} \text{ deg C}^{-1}}{0.0035 \text{ cal s}^{-1} \text{ deg C}^{-1}}$$

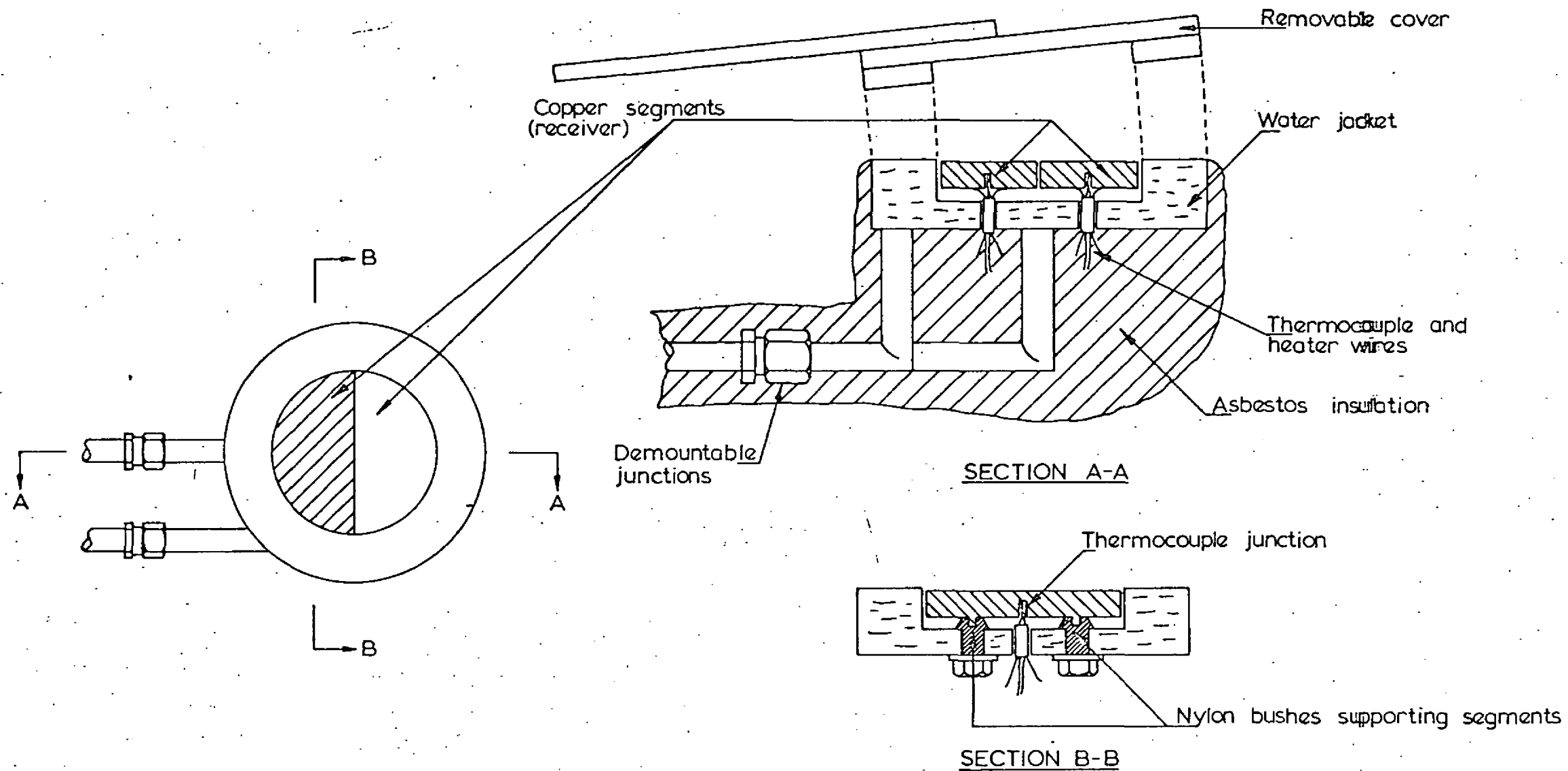


FIG. 1. SCHEMATIC DIAGRAMS OF THE MARK 1 INSTRUMENT

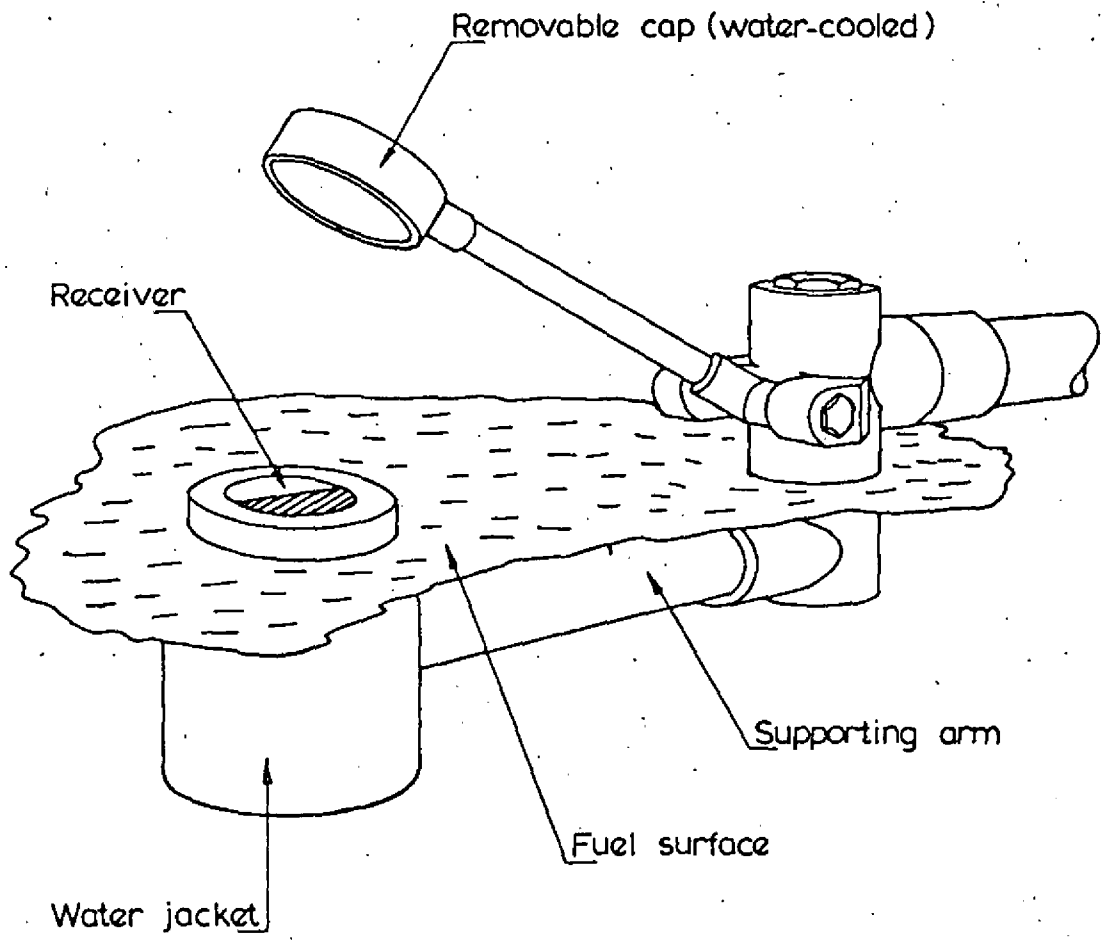
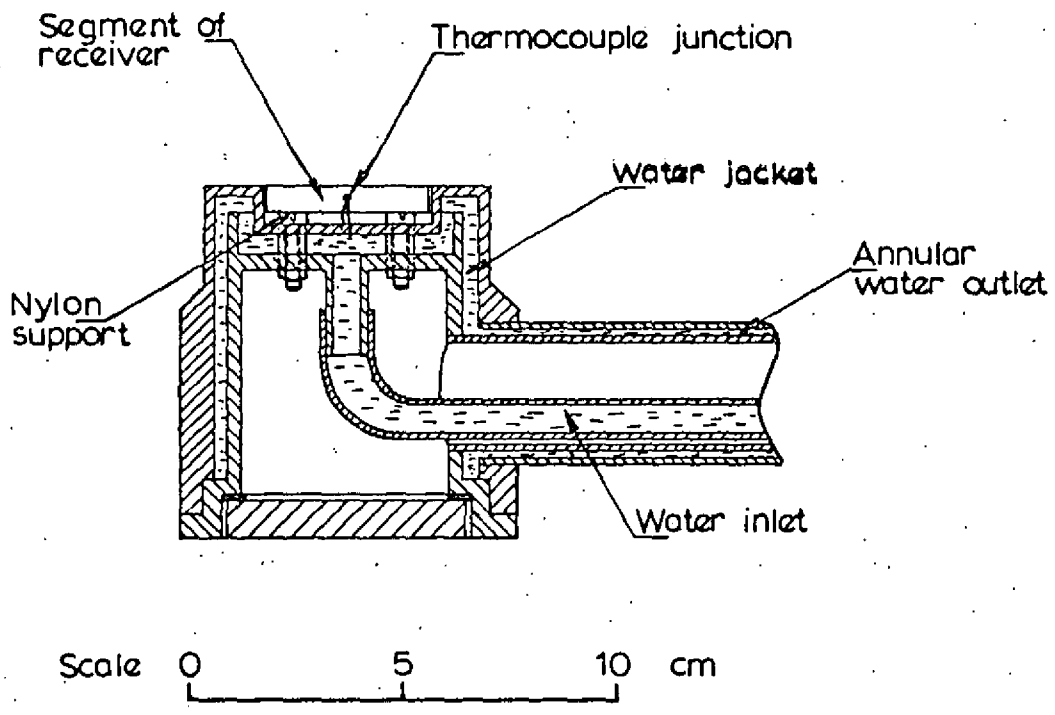


FIG. 2. SCHEMATIC DIAGRAMS OF THE MARK 2 INSTRUMENT

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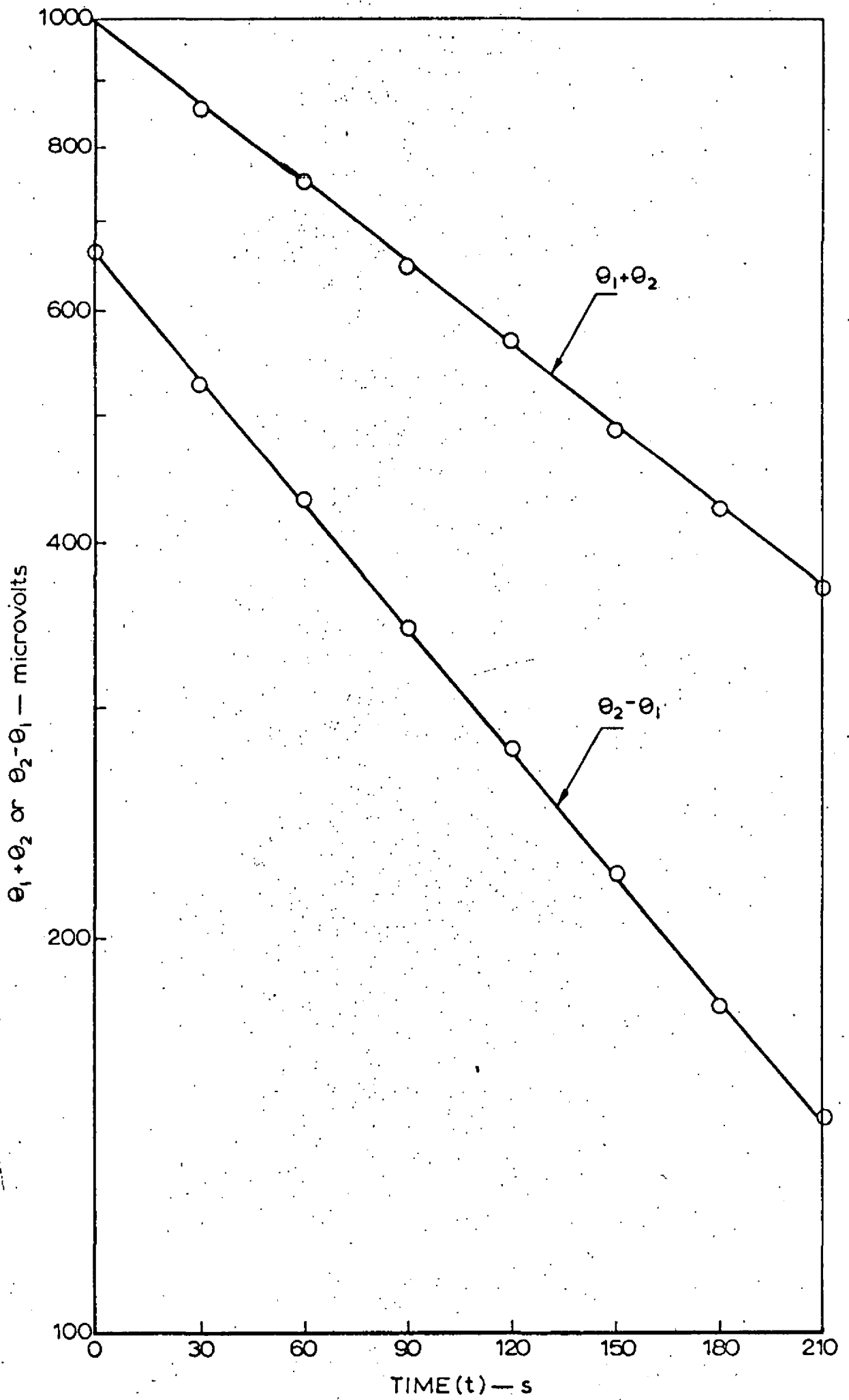


FIG. 3. EVALUATION OF h AND g FROM COOLING CURVES (RUN 4)

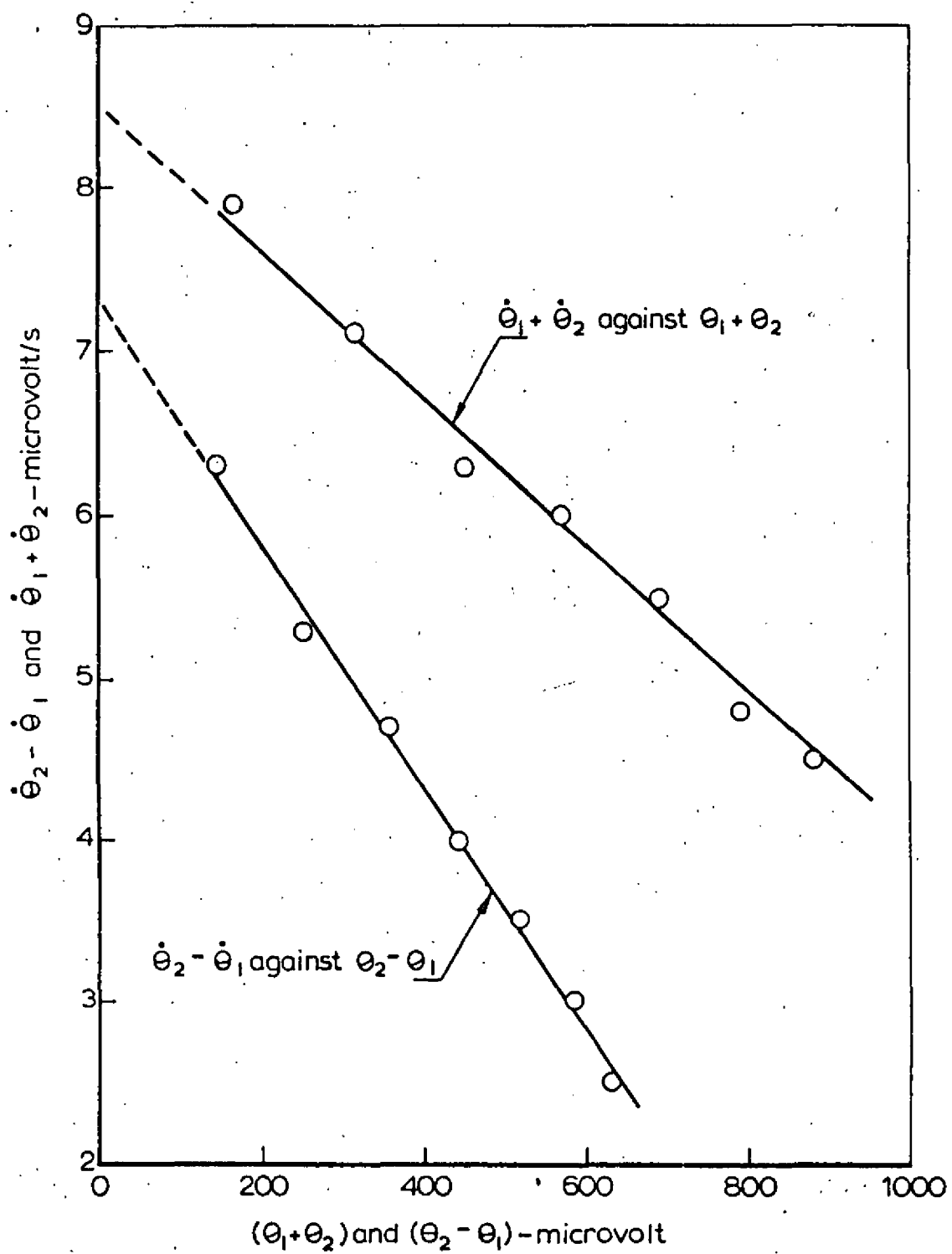
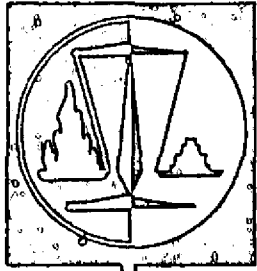


FIG. 4. EVALUATION OF h AND g AND ABSORPTIVITIES



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