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F.R. Note No. 83/1954
Research Programme
Objective I/I(P)

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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THERMOPILES FOR MEASURING HIGH INTENSITY RADIATION

by

D. L. Simms and R. W. Pickard

Summary

The slow change in output of a Moll-type thermopile when exposed to radiation has been shown to depend upon the relative rate of rise in temperature of the thermojunction housing and the hot junction, and not as usually stated, upon the ambient temperature. By surrounding the housing with a water jacket, stable readings have been obtained. The sensitivity of the thermopile has been derived in terms of the dimensions and thermal properties of the thermojunction metals. Two instruments built for work at intensities of radiation up to 12.5 watts cm^{-2} (3 cal cm^{-2} sec^{-1}) have stable readings almost independent of the quality of the radiation. Two later instruments are suitable for measurements up to 40 watts cm^{-2} (10 cal cm^{-2} sec^{-1}) and 200 watts cm^{-2} (50 cal cm^{-2} sec^{-1}) respectively, but the stability of their calibrations is not yet known.

May, 1954.

Fire Research Station,
Boreham Wood,
Herts.

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1. Introduction

The study of the ignition of materials by high intensity radiation requires instruments capable of measuring radiation intensities ranging from 0.4 watts cm^{-2} (0.1 cal cm^{-2} sec^{-1}) to 200 watts cm^{-2} (50 cal cm^{-2} sec^{-1}). The sources in use at the Fire Research Station covering this range of intensities are a gas fired furnace panel working at 1100°K as measured by a Thwing pyrometer, a tungsten filament lamp working up to 3000°K as measured by an optical pyrometer, and a high intensity carbon arc working at an effective black body temperature of about 5800°K (1). The instruments therefore had to have a reading independent of the quality of the incident radiation. They had also to be robust, simple to calibrate, and to have a quick response and an output signal which could be recorded automatically.

The Moll-type thermopile (2) has these characteristics and its suitability as a radiometer for this work was therefore investigated.

2. Theoretical analysis and discussion

The Moll microthermopile consists of a number of thin thermojunctions in series, supported on, but electrically insulated from, a brass block. When the thermopile was exposed to a constant intensity of radiation the output after an initial rapid rise, continued to increase slowly instead of reaching equilibrium. Further, if the radiation was cut off, even for a short time, the output did not immediately regain the value it had before the interruption.

Each junction of the thermopile can be considered to be a thin metallic strip receiving heat from the source of radiation and from the junction housing, and losing heat by radiation and convection from its surface and by conduction through its ends. Since it is thin, the strip may be considered to be uniform in temperature in cross-section and to vary in temperature along its length. In the following analysis a mean temperature has been assumed for the length of the strip in order to calculate the heat losses from it by radiation and convection: it is further assumed that the end of the strip which is the cold junction, is at the same temperature as the housing.

Let I be the intensity of the incident radiation
T " " temperature of the hot junction
T_0 " " temperature of the cold junction
T' " " mean effective temperature of the strip
and let T_1 " " ambient temperature

At equilibrium.

$$I A = 2 A\epsilon\sigma (T'^4 - T_1^4) + 2AH (T' - T_1)^{1.25} + \frac{2a(K_1 + K_2)}{L} (T - T_0)$$

$$- B\phi\epsilon\sigma (T_0^4 - T_1^4) - RBH(T_0 - T_1)^{1.25} \qquad \text{......} \ (1)$$

where
A is the surface area of one face of the strip
a is the cross-sectional area of the strip
K_1 K_2 are the thermal conductivities of the junction metals
L is the length of the strip
ϵ is the emissivity of the surface
σ is the Stefan-Boltzman constant
B is the surface area of the mounting visible to the strip and ϕ is its configuration factor
R is the convection transfer coefficient

The expression $A\epsilon\sigma\,(T^{1\,4} - T_1^{\,4})$ and $AH(T^1 - T_1)^{1.25}$ represent the radiation and convection losses from one face of the strip, and the expression $\frac{2a\,(K_1 + K_2)}{L}\,(T - T_0)$ represents the conduction loss. The hot junction is assumed to be located at the centre point between the two mounting posts and hence conduction takes place along each of the two metals over a length L/2. The expression

$$B\,\phi\,\epsilon\,\sigma\,\,(T_0^{\,4} - T_1^{\,4}) \text{ and } RBH\,(T_0 - T_1)^{1.25}$$

represent the heat gained by the strip due to radiation and convection from the mounting block.

The output from the thermopile is proportional to $(T - T_0)$ and any change in output is given by the value of $\frac{\delta T}{\delta T_0}$. This may be obtained from equation (1). As a first approximation put $T = T^1$, assuming that the temperature of the strip is uniform and equal to that of the hot junction with a discontinuity at the cold junction posts.

Differentiating the modified form of equation (1) with respect to T_0 gives:

$$\frac{\partial T}{\partial T_0} = \frac{\partial T_1}{\partial T_0}\left(\frac{8A\epsilon\sigma T_1^3 + 2.5AH(T-T_1)^{0.25} - 4B\phi\epsilon\sigma T_1^3 - 1.25RBH(T_0-T_1)^{0.25}}{8A\epsilon\sigma T^3 + 2.5AH(T-T_1)^{0.25} + 2a(K_1+K_2)/L}\right)$$

$$+ \frac{4B\phi\epsilon\sigma T_0^3 + 1.25BHR(T_0-T_1)^{0.25} + 2a(K_1+K_2)/L}{8A\epsilon\sigma T^3 + 2.5AH(T-T_1)^{0.25} + 2a(K_1+K_2)/L} \quad \ldots\ldots (2)$$

$\frac{\partial T_1}{\partial T_0}$ is probably very small and the value of $\frac{\partial T}{\partial T_0}$ is therefore determined by the value of the second expression in equation (2).

$\frac{\partial T}{\partial T_0}$ may be greater or less than unity depending on the relative areas of the strip and mounting block and the geometry of the system.

$\frac{\partial T}{\partial T_0}$ greater than unity would account for the increase in output measured when the thermopile already mentioned was exposed to a constant intensity of radiation. The failure to regain its previous value after interruption would then be due to the fall in temperature of the mounting block during the period of interruption.

If $\frac{\partial T}{\partial T_0}$ were less than unity, the output from the thermopile would decrease as the mounting block temperature increased. This was observed by Fastie (3). On this argument, the variation in output is not primarily a function of the ambient temperature as is normally thought (2, 3).

A single junction thermopile was constructed with a water jacket surrounding the mounting block. The output from this instrument remained constant when there was a high rate of water flow. With a low rate of water flow the output increased as the water temperature and therefore the mounting block temperature increased. The results are given in Fig. 1.

A Moll thermopile thus modified may therefore be used as a radiometer.

3. Design of the instrument

The theory of the instrument may be used to give some guide to the design of the thermojunctions.

Neglecting radiation and convection losses from the strip (Appendix I) the equilibrium conditions are given by

$$IA = 2a\frac{(K_1 + K_2)}{L}(T - T_o) \qquad \ldots\ldots (3)$$

$$\text{or } (T - T_o) = \frac{L^2 . I}{2d(K_1 + K_2)}$$

where I is the intensity of radiation
d is the thickness of the strip

Assuming a linear relation between $(T - T_o)$ and the output v of a junction then

$$v = C(T - T_o)$$

or for a thermopile of n junctions the output is nv or $nC(T - T_o)$. Assuming that the measuring device has an internal resistance very much greater than the instruments, the sensitivity of the instruments is given by

$$S = \frac{v}{I} = \frac{nCL^2}{2(K_1 + K_2)d}$$

Hence a large output from the instrument may be obtained by having a large number of long and thin junctions.

4. Construction of the instruments

The method of constructing the junctions was copied from Moll's original paper, but the metals used were copper and constantan.

The junctions were mounted in the following way. An annular brass ring B was constructed in two halves (Fig. 2). Holes were drilled through the two halves so that insulated copper posts could be fitted into the ring. A small cavity was drilled out of each half of the ring and filled with warm wax. After the ring had been fitted together the copper posts consisting of 22 S.W.G. insulated wire were drawn through the holes. When the wax hardened the posts were held rigidly in position with their ends projecting from the faces of the ring. The instruments in which more than one junction was used had the junctions soldered in series so that the hot junctions lay along a straight line (Fig. 2). The junction mounting was fitted into a water jacket turned out of brass with a wall thickness of about $^1/32$ in. The ends of the thermopile were connected to two terminals mounted on a panel fitted into one end of the jacket.

Four instruments were constructed, the first two had thirteen and ten junctions and are referred to as Radiometers A and B respectively. Radiometer B is shown in Plate I. The leads and tubing to the instruments were protected from the radiation by an asbestos wood shield fitted to the back of the water jacket (Plate II). The front face was covered with a thin metal plate C with a bevelled edge slit at the centre (Fig. 2). This served the dual purpose of preventing damage to the junctions and protecting them from draughts.

In the two later models, Radiometers C and D (Plates III and IV), which were designed for use at higher intensities, only one junction was used. The whole of the junction strip was exposed to radiation.

Table I gives the dimensions and number of junctions used in each of the instruments.

TABLE I

Radiometer	Number of junctions	Length of junction (in)	Width of junction (in)	Thickness of junction (in)
A	13	0.75	0.02	0.002
B	10	0.75	0.01	0.002
C	1	0.19	0.05	0.003
D	1	0.09	0.05	0.006

5. Calibration of the instruments

Radiometer A was calibrated against a copper block absolute calorimeter (4). The output of the instrument was linear with the intensity of incident radiation over the range covered (Fig. 3). Repeated calibrations showed that the sensitivity of the instrument remained constant over a period of several months.

This instrument was also calibrated in the range 0-2 watts cm^{-2} (0-0·5 cal cm^{-2} sec^{-1}) by the National Physical Laboratory (Appendix II). Comparison of these results with those given in Table II show that the calibrations agree to within one per cent.

The variation of sensitivity with quality of radiation was also examined by the National Physical Laboratory (Appendix II) and the results show that the sensitivity remains almost independent of the quality of radiation for sources between 2850°K and 1250°K and it is approximately 96 per cent of this value for a source at 470°K. The variation in sensitivity is due to the change in absorptivity with wavelength of the paint with which the junctions were sprayed.

Radiometer B was calibrated against Radiometer A and the results are given in Fig. 3 and it, too, has given stable readings over a period of months.

Radiometers C and D have a much lower sensitivity and were therefore calibrated using a tungsten filament lamp with an ellipsoidal mirror as a source of high intensity radiation. These calibrations are given in Figs. 4 and 5.

The theoretical and measured sensitivities of all four instruments are given in Table II below.

TABLE II

Radiometer	Theoretical sensitivity mv watt^{-1} cm^{+2}	Measured sensitivity mv watt^{-1} cm^{+2}	N.P.L. measured sensitivity mv watt^{-1} cm^{+2}
A	46.3	10.0	9.9
B	35.6	7.5	-
C	0.148	0.157	-
D	0.019	0.019	-

The theoretical and actual sensitivities of Radiometers C and D are in good agreement. The junction strips were partly shielded in Radiometers A and B whereas the theory assumes that the whole strip was irradiated.

The time constants of the instruments were determined by photographing the output trace on an oscilliscope and found to be less than 0.5 seconds for all the instruments. An approximate derivation of the time constant is given in Appendix III.

6. Conclusions

The slow variation in output of a Moll thermopile on exposure to high intensity radiation has been shown to be due to the increase in temperature of the junction mounting and the geometry of the housing of the thermopile block. Stable readings have been obtained by surrounding the mounting block with a water jacket and thus controlling its temperature. An approximate analysis has predicted the sensitivity of a Moll thermopile. Where the whole of the junction is exposed to radiation there is excellent agreement between the predicted and experimental sensitivities.

Radiometers A and B have been in use for a year and have been found to have stable characteristics and outputs almost independent of the quality of radiation except in the far infra red.

The stability of Radiometers C and D is not known since they have only recently been built.

This type of instrument can therefore be used as a substandard radiometer for sources whose temperatures are above 1100°K.

Acknowledgements

The authors would like to thank Mr. C. Shore for his help and advice with the design and construction of the instruments. Miss M. Law has assisted with the experimental work.

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APPENDIX I

Heat losses from a thermojunction

The heat loss by conduction was calculated assuming temperature differences between the hot and cold junctions of 250°C and 100°C. The total radiation and convection losses were determined for Radiometer B assuming mean effective temperatures of the strip of 125°C and 50°C. The results are given in the table below.

Temperature difference °C	Conduction loss: watts	Radiation and convection loss: watts	Total heat loss: watts
250	0.14 (.038)	0.021 (.005)	0.16 (.038)
100	0.054 (.013)	0.0063 (.0015)	0.060 (.014)

The figures in parentheses are the values of heat loss in cal/sec.

The results show that the radiation and convection losses represent 13 per cent of the total heat loss with a junction temperature difference of 250°C and 10 per cent with a junction temperature difference of 100°C.

APPENDIX II

National Physical Laboratory calibration of Radiometer A

The sensitivity of the instrument was determined using a source with a colour temperature of 2850°K. The sensitivity S_o, with an incident radiant intensity of about 0.05 watts cm^{-2} (.012 cal cm^{-2} sec^{-1}) was found to be

$$S_o = 9.9 \text{ mv watt}^{-1} \text{ cm}^{+2} \ (41.4 \text{ mv cal}^{-1} \text{ cm}^{+2} \text{ sec}^{+1})$$

For higher intensities up to about 2 watts cm^{-2} (0.5 cal cm^{-2} sec^{-1}) the sensitivity S was found to be

$$S = S_o \ (1 + .006I)$$

where I is the incident radiation intensity in watts cm^{-2}. The thermopile was examined for selectivity by measuring its sensitivity to sources at 1270°K and 470°K relative to its sensitivity with a source at 2850°K. The results are given in the table below.

Source temperature	Relative sensitivity
2850°K	1.000
1270°K	0.992
470°K	0.962

APPENDIX III

Derivation of time constant of the instrument

By neglecting radiation and convection losses (Appendix I), and by assuming that the temperature of the thermojunction is the average of the hot and cold junction temperatures, then the transient heating equation may be written, writing for the temperature difference between the hot and the cold junctions at any instant, θ

$$I\,A = \left(\frac{m_1 s_1 + m_2 s_2}{2}\right)\dot{\theta} + \frac{2(K_1 + K_2)}{L} a\,\theta \qquad \ldots\ldots \ (1)$$

where m_1, m_2 are the masses of the two metals comprising the junction and s_1, s_2 are their specific heats

The solution to equation (1) is

$$\theta = \frac{IL^2}{2(K_1 + K_2)d}\left(1 - \exp\frac{-8(K_1 + K_2)}{(\rho_1 s_1 + \rho_2 s_2)L^2}t\right)$$

where d is the thickness of the strip and ρ_1, ρ_2 are the densities of the two metals. The time constant τ of an instrument is therefore

$$\tau = \frac{(\rho_1 s_1 + \rho_2 s_2)L^2}{8^1(K_1 + K_2)}$$

The calculated and actual sensitivities are given in Table I.

TABLE I

Time constant $\frac{1}{\text{sec}}$

Radiometer	Calculated	Actual
A	0.80	0.45
B	0.05	0.15
C	0.013	0.25

No great accuracy can be claimed for the theory, because of the number of approximations made, but it does give a rough guide to the time-constant to be expected.

PC.

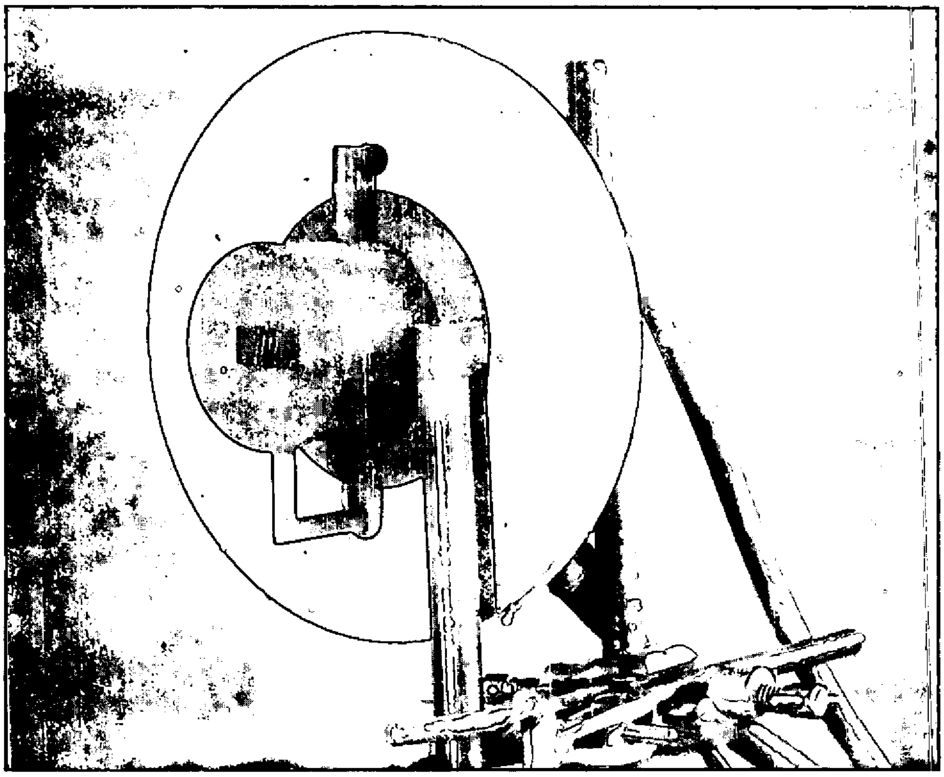

PLATE. 1. FRONT VIEW OF RADIOMETER B

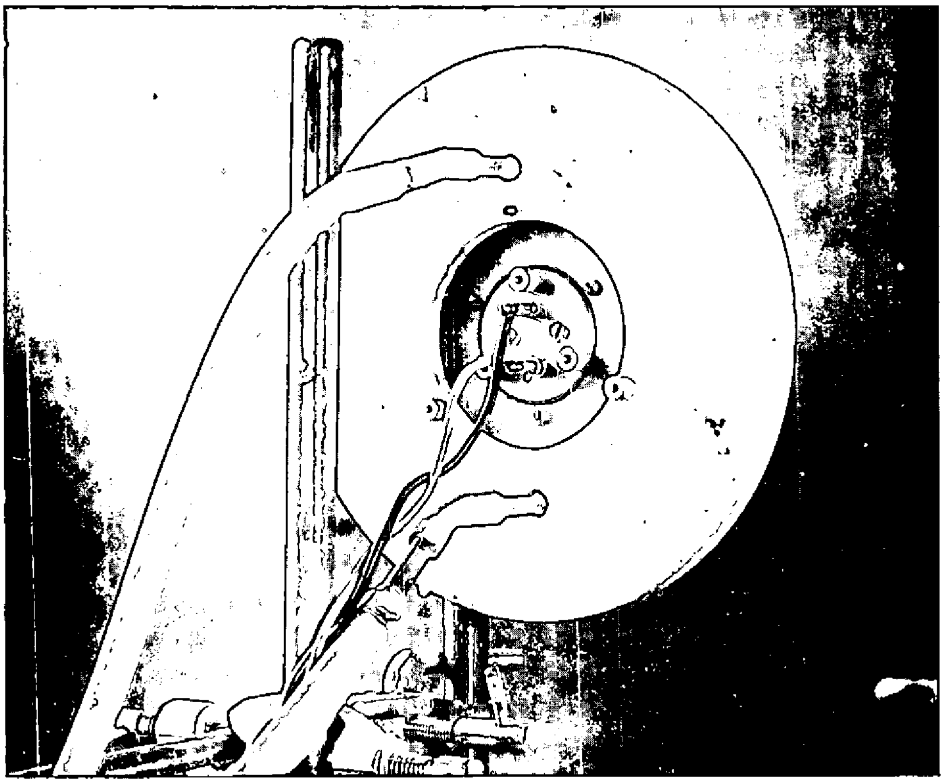

PLATE. 2. REAR VIEW OF RADIOMETER B

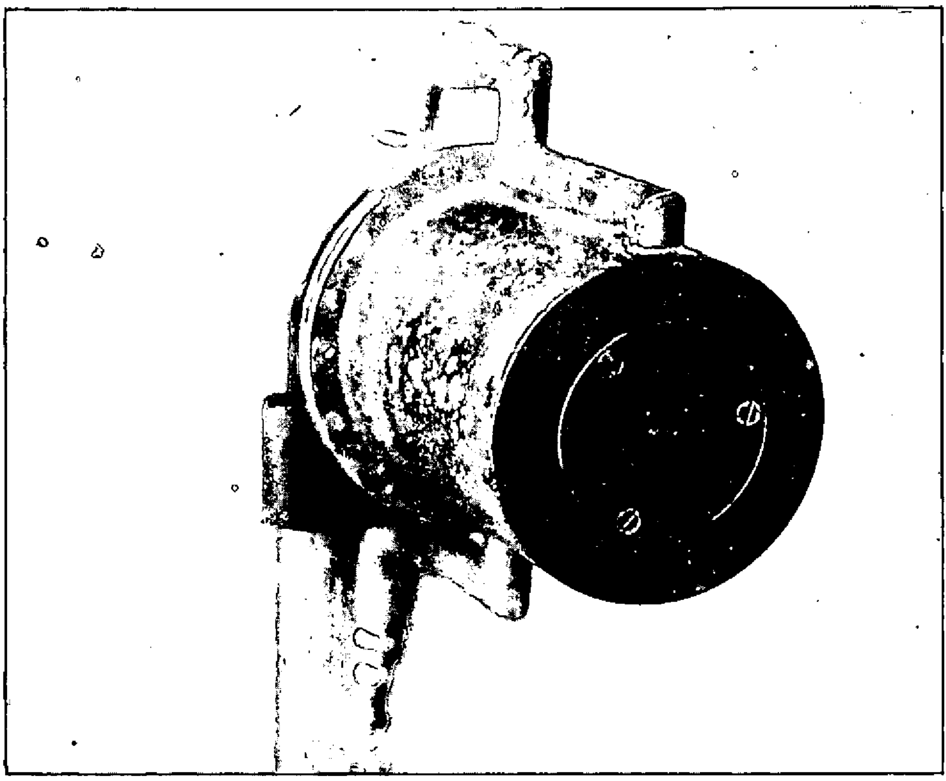

PLATE. 3. FRONT VIEW OF RADIOMETER D

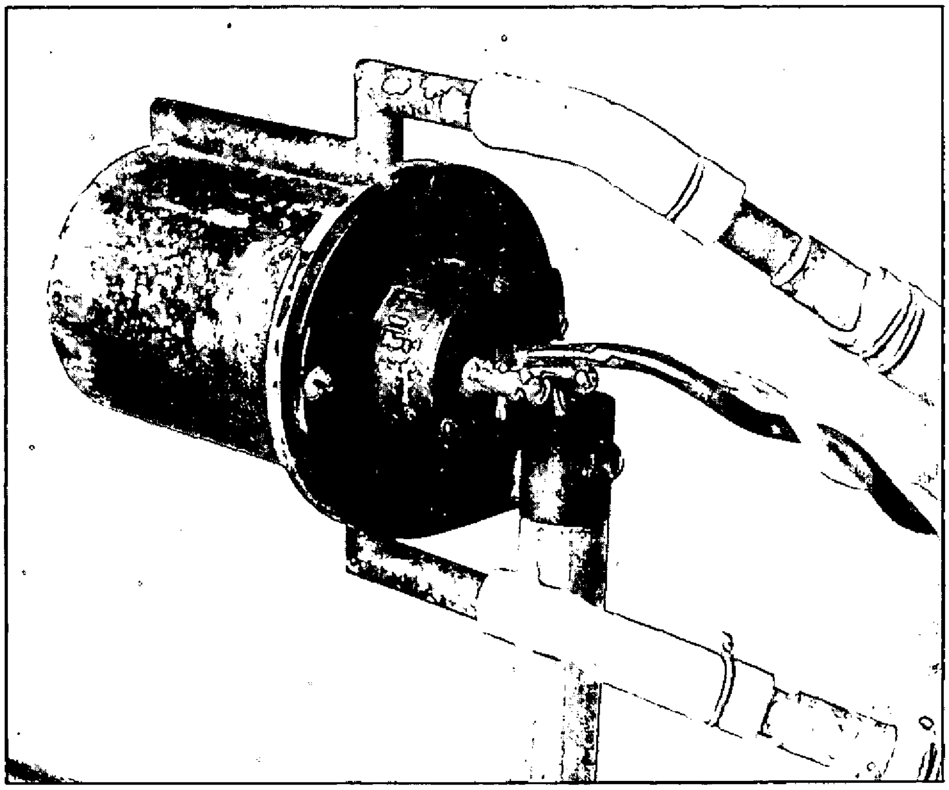

PLATE. 4. REAR VIEW OF RADIOMETER D

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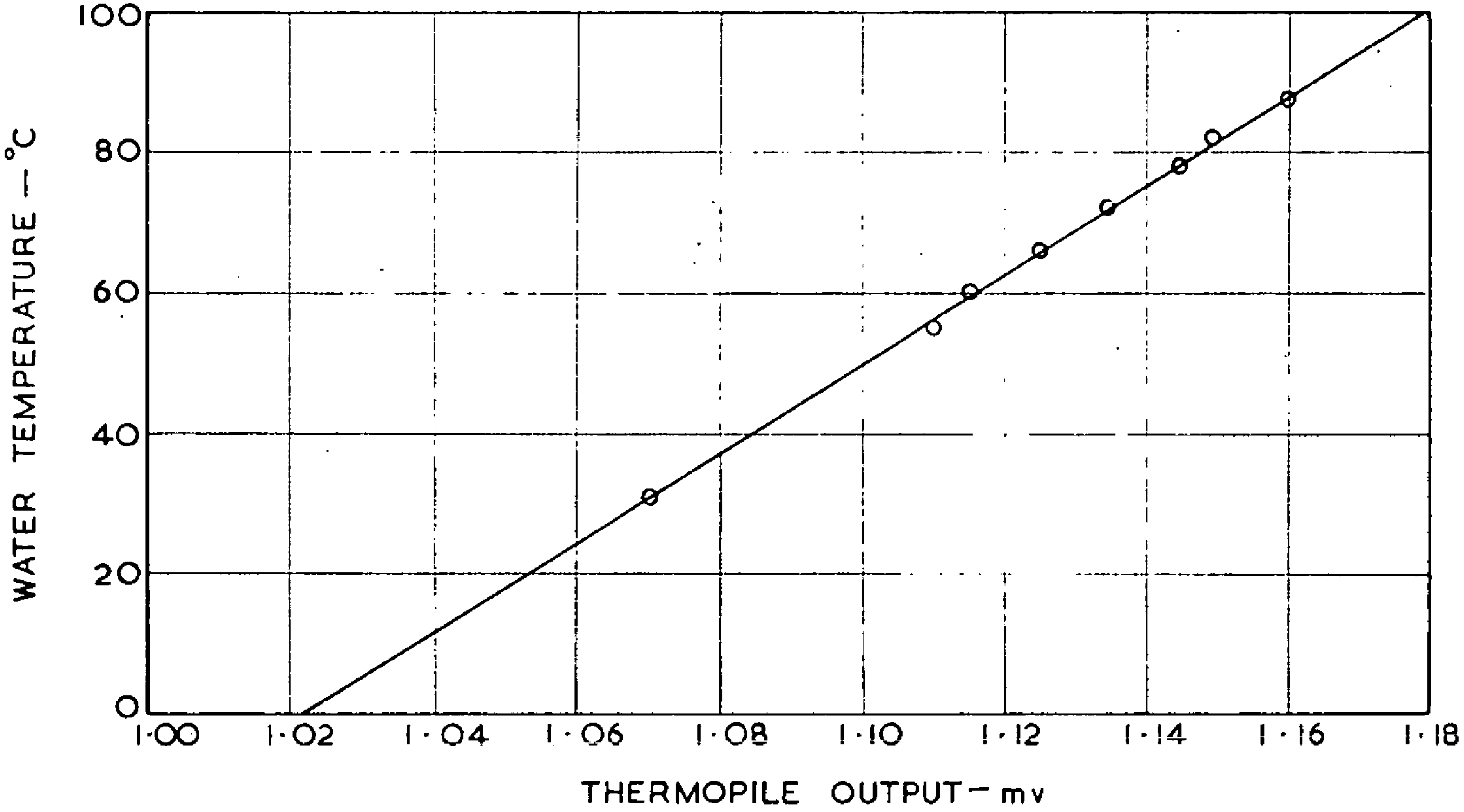

FIG. 1. VARIATION OF OUTPUT OF THERMOPILE WITH WATER TEMPERATURE

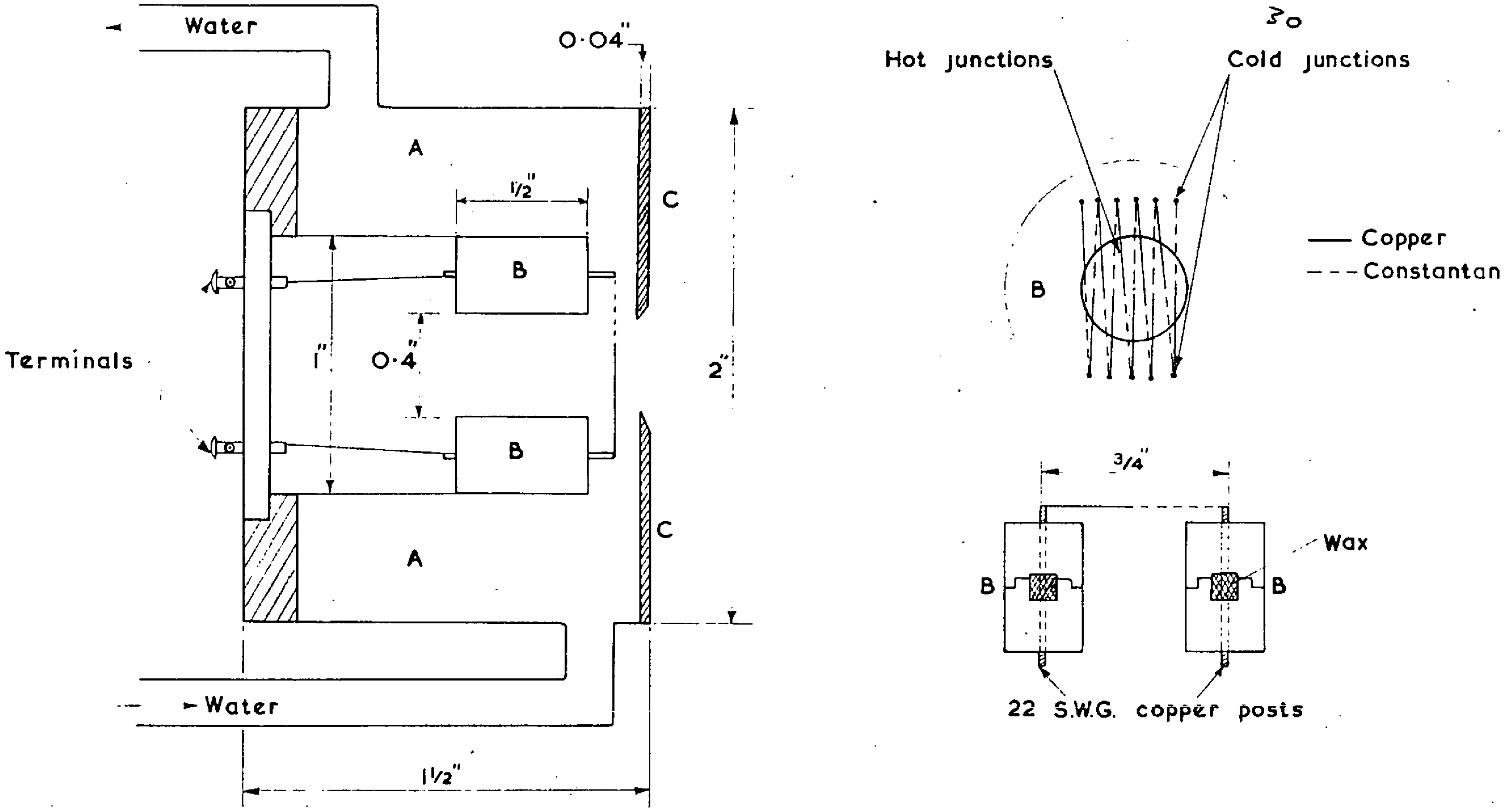

FIG. 2. RADIOMETER B

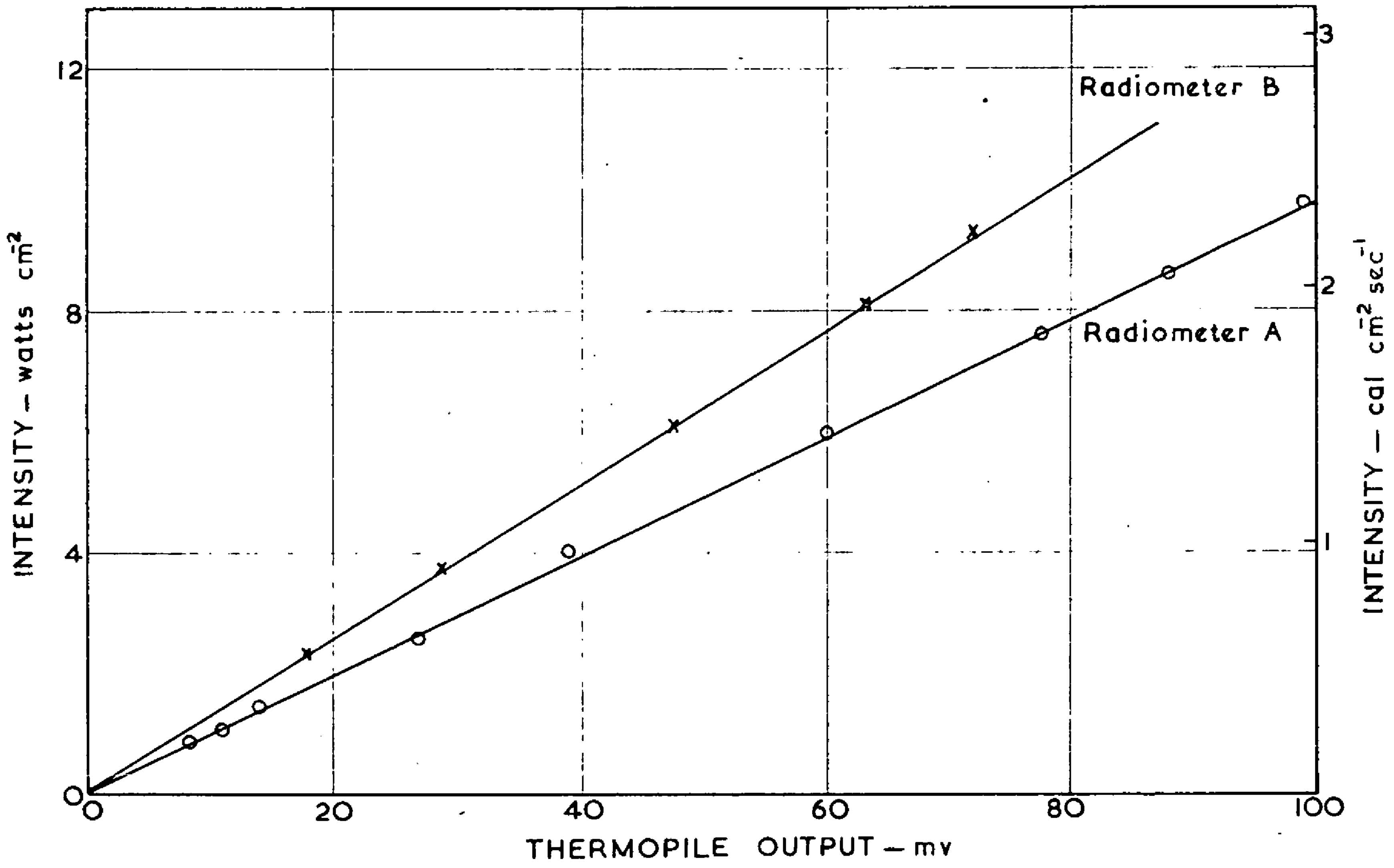

FIG. 3. CALIBRATION CURVES OF RADIOMETERS A & B

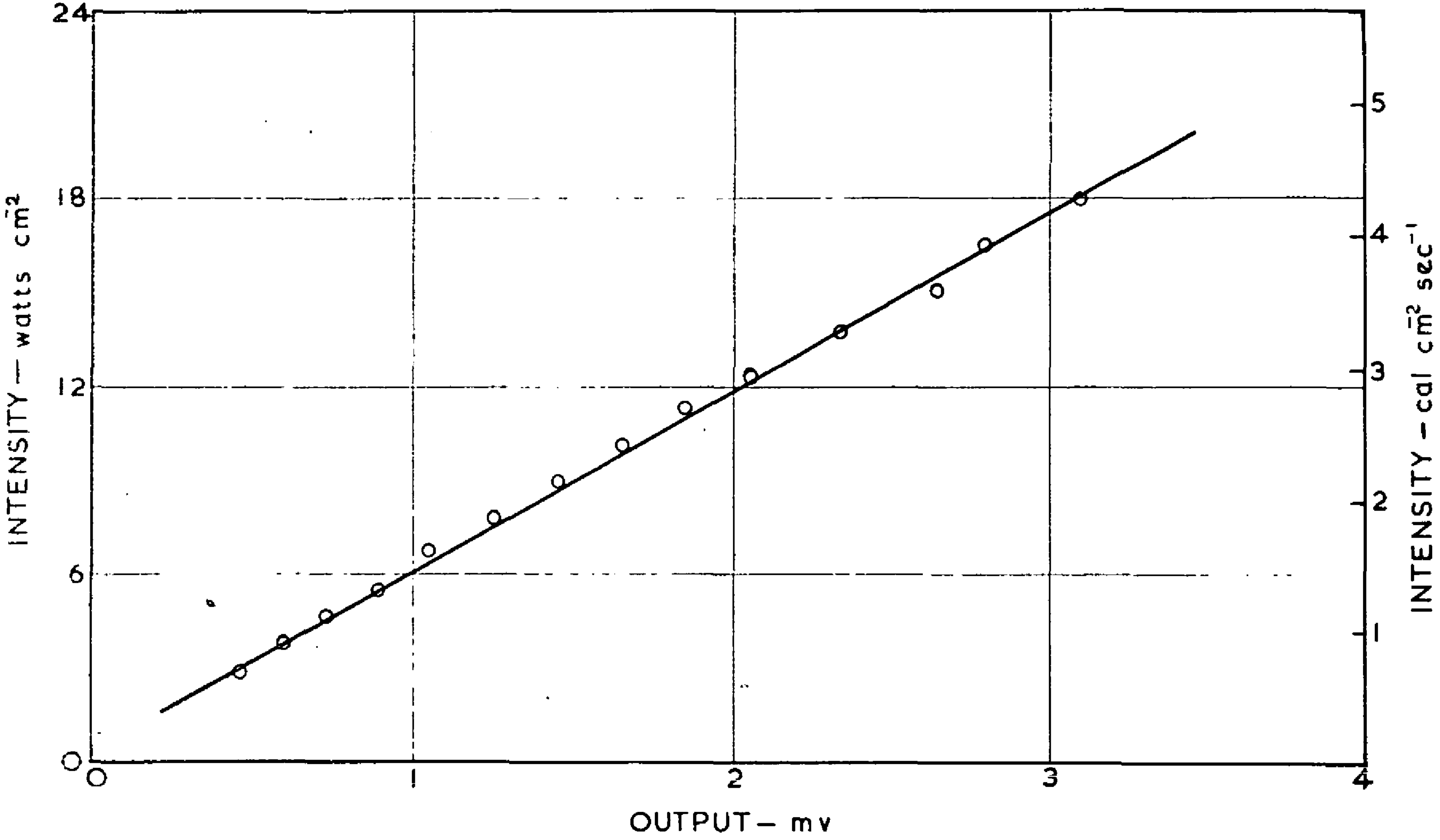

FIG. 4. CALIBRATION CURVE OF RADIOMETER C

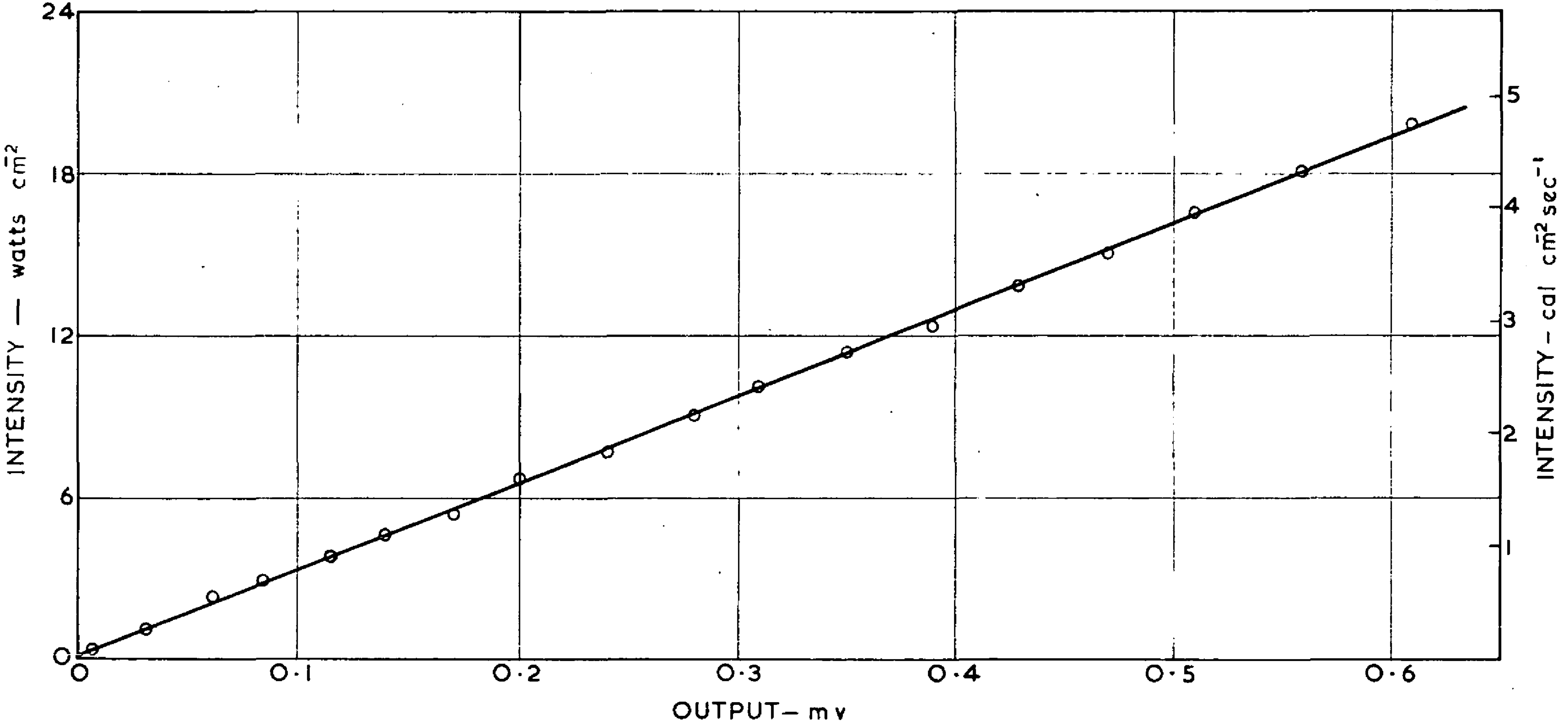

FIG. 5. CALIBRATION CURVE OF RADIOMETER D

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