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A NEW RADIOMETER FOR MONITORING FIRE EXTINCTION EXPERIMENTS

by

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SUMMARY

A design is described for a new type of radiometer for use in monitoring flame radiation in fire extinction experiments. The radiometer eliminates many of the practical difficulties encountered with the conventional thermocouple type of radiometer currently in use. Preliminary tests on a prototype radiometer gave results consistent with those produced by conventional radiometers.

DEPARTMENT OF THE ENVIRONMENT AND FIRE OFFICES COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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INTRODUCTION

The ultimate assessment of extinguishing agents must be based on their performance in fire tests. The progress of such tests may be measured in various ways but the criteria used should be as free as possible from random fluctuations. Extinction time of liquid fuel spill fires is not an easily reproducible measurement due to difficulties experienced in extinguishing the last flickers, and so, in a number of standard tests, the time to "control" the fire is measured. For instance, the nine-tenths control time may be used, this being defined as the time taken to reduce the heat radiation to one-tenth of the mean value measured during the last 5 seconds of the free-burning period before extinction is attempted.

The current Defence Standards[1,2] for foam liquids specify the use of four radiometers connected in series and positioned symmetrically around the fire. These radiometers[1] (see Plate 1) contain two thermocouple junctions, one exposed to the radiation and the other shielded from it and used as a reference. Since a single chromel/alumel junction produces 1 millivolt for a 25°C temperature rise, this type of radiometer must be placed fairly close to the fire to give a reasonable output. If a single radiometer were used, errors would occur if there were persistent flames on the side of the fire nearest the radiometer. Several radiometers, usually four, are therefore connected together in series and placed symmetrically around the fire, and leads are taken from the fire area to amplifying and recording equipment. On a large fire, this involves considerable quantities of wire, with all the attendant problems of damage from vehicles, people and the fire itself. Because the output is small, even small stray voltages can produce substantial errors. These errors can arise from electrolytic effects, from wire with damaged insulation earthing to damp ground, or even from wires swaying in any wind, especially near pieces of iron. The sun may also cause small errors where four radiometers are used since two will always be exposed to it.

A second source of trouble with thermocouple radiometers has become noticeable recently. The 0.28 m^2 (3 ft^2) standard fire of Defence Standard 42-3 is monitored by four radiometers. Using modern foam liquids, very rapid control of this fire is possible. Due to the radiometers viewing only the bottom part of the flames, the recorded radiation often stays constant until the foam has covered all the fuel surface, when it drops suddenly. On some occasions the radiometers have not shown control until after the fire has been extinguished. This is because some radiometers have been found to take five seconds for the output to drop to one-tenth when the radiation was cut off suddenly. This delay was found to depend on the thickness of the mica window which varied from .02 mm (.0008 in) to .06 mm (.0025 in). When this window was removed, there was still a delay of about one second due to the thermal inertia of the junction. The thermal junctions are made by butt welding two 46 swg (0.06 mm) wires, a difficult task.

The new radiometer, illustrated in Plates 1 & 2 and Fig. 1, overcomes these shortcomings without introducing any others - as far as can be ascertained. It monitors the radiation by means of a photocell driving an operational amplifier to give an output proportional to the incident radiant intensity (see Fig. 2).

The design criteria for the radiometer may be stated as follows:

1. Output to be a linear function of incident radiation.
2. The output to be large, i.e. volts rather than millivolts.
3. Sufficient sensitivity for the radiometer to be situated at a distance from the fire, both to protect it from heat and so that errors due to the position of flames in the fire area may be reduced.
4. No long lengths of connecting wire.
5. Battery operated.
6. Sensitive only to radiation typical of a hydrocarbon diffusion flame.
7. Fast response.
8. Simple to produce and to use.

For further points on the design of a radiometer system see Appendix 1.

A lead sulphide photoconductive cell (Mullard RPY 76A) was chosen in order to satisfy points 1, 3, 7 and 8. The sensitive element is 1 mm x 1 mm housed in a metal envelope with a plane glass viewing window and an integral germanium filter. The thickness of the window does not affect the response time.

These cells are photon detectors; that is, a release of charge carriers occurs when a quantum of energy is absorbed. Unlike thermal detectors, this is not a process dependent on a temperature rise of the sensing element and hence they are capable of a more rapid response. The energy of a quantum (E) must exceed the energy band gap (E_g) of the material before it is absorbed. Since $E = hc/\lambda$, there is a critical wavelength (λ_c) above which radiation will not be absorbed: $\lambda_c = hc/E_g$. With these cells $E_g = 0.4$ electron volts, resulting in a nominal cut-off wavelength λ_c of 3 μm. The germanium filter also limits the spectral response by excluding all irradiation below 1.5 μm. There is evidence that the spectral distribution of hydrocarbon flames from fires greater than 300 mm diameter is "gray" and therefore similar to blackbody radiation[3]. It is only when flames became small that the emission bands of the combustion products appear, superimposed on the continuum from the carbon particles. Since these emission bands are mainly outside the wavelengths measured by the photocell, and since the proportion of the total radiation registered by the radiometer is assumed to remain constant, the total radiation will, in fact, be underestimated slightly. However when the radiometer is used for measuring fire control times the radiation is expressed as a percentage of the maximum radiation intensity and so errors occurring when the fire becomes small are less significant. (Tables 1 and 2 show that the radiometer has proved satisfactory in use). For a given radiation energy the number of photons is inversely proportional to the wavelength and so in theory is the response of the photocell. In practice this is not so, as a photon of sufficient energy may release more than one charge carrier. The response of this cell is shown in Fig. 3.

The change in conductance G is proportional to the change in radiant intensity I_r when the spectral characteristics of the incident radiation remain constant. If a constant voltage bias V_b is applied to the cell, the current flowing i is proportional to the irradiation, $i = V_b G = V_b kI_r$. By the use of an operational amplifier, this current may be converted to an inverted voltage output, (Fig. 2). The gain of this amplifier (in this case 1 volt per 8 μa) is set by the value of the feedback resistance, $R_1 + R_2$. The response time is set by the feedback capacitor C_1. If the circuit is undamped, and the incident radiation level is suddenly increased, the time taken for the output to reach 90 per cent of the maximum is about 500 μs. This is much shorter than necessary for fire test purposes and it is convenient to increase the response time to about 0.25 s to give a smoother, more easily read, record.

In the present radiometer, the cell is positioned in a heat sink (purely for convenient mounting) and all circuits and the power supply are contained in a metal case. Provision is made for adjustment of gain and zero offset by means of potentiometers R_1 and R_3. An external power supply may also be used. The output may be fed into a recorder thus providing a continuous record of the fire. If a battery powered recorder is used, the whole system is independent of a mains supply.

The basic design allows for much flexibility - the sensitivity and response time may be changed by several orders of magnitude by a simple component change. The radiometer was designed for relative measurements but can be used for absolute measurements if calibrated. However frequent recalibration may be necessary as the photocell can age, particularly at high ambient temperatures.

EXPERIMENTAL RESULTS AND DISCUSSION

Comparisons with conventional thermocouple radiometers have been made on both 0.28 m^2 (3 ft^2) and 81 m^2 (875 ft^2) fires. Initial tests with 0.1 m^2 fires showed that the output of each type of radiometer was inversely proportional to the square of the distance from the heat source.

In the 0.28 m^2 fire tests, the new radiometer was placed 2 m away from and 0.7 m above the fire. The four conventional radiometers were arrayed 0.6 m from the centre of the fire[1]. These two systems gave somewhat different control times (see Table 1), the new radiometer giving a shorter 90% control time (i.e. radiation 10% of maximum value) in every case. When a conventional radiometer was fixed beside the photocell radiometer, it gave results similar to those from the photocell. Presumably this is due to the fact that the radiometers close to the fire are only able to view the lower portion of the flames.

In the 81 m^2 fires, a 9 m x 9 m square bunded area was used. The primary purpose of these tests was to compare various foam liquids, and a full description of the test method is given elsewhere[2]. 1590 litres (350 gallons) of kerosine was burnt on a water base and extinguished with foam. Four conventional radiometers were placed 8 m from each corner on extensions of the diagonals and about 1 m above the ground. The photocell radiometer was positioned upwind of the fire approximately 50 m distant and 1.5 to 3 m above the level of the fire, which was on uneven ground. Good agreement was obtained between the two types of radiometer - see Table 2. It was found necessary for the photocell radiometer to be positioned where it could not view the sun since, due to the sensitivity of the radiometer, the sun's radiation produced an appreciable error signal subject to variation when the smoke obscured the sun.

Table 2 also includes estimates of the control time by visual observation. It may be seen that these do not always agree with the radiometer control times. This is believed to be due to the observers estimating control by the proportion of the fire area extinguished rather than by the decrease in radiation. This is the reason for the observed times often being shorter than the radiometer measurements. Both observed and radiometer times are valid results but it must be remembered that they are different measurements. Occasionally fuel was splashed over the edge of the bund causing small fires outside the bunded area. The observers ignored such fires but, of course, the radiometers did not. In this series of tests, the errors from this source were small, as care was taken to minimise such splashing.

No faults arose in the photocell radiometer system during these tests. The conventional system failed completely in one test due to the polarity of two of the radiometers being reversed. The conventional radiometers are normally checked by holding a match in front of one radiometer and checking for an output on the recorder. This test will indicate circuit continuity but may not indicate that the radiometers are incorrectly connected. Various sections of the circuit had to be removed on numerous occasions to replace burnt lengths of wire or to prevent damage by the fuel bowser.

Although the photocell radiometer system has no compensation for ambient temperature changes, this has not caused any problems. A temperature rise of 10°C will cause a zero displacement of about eight per cent of the maximum output at the gain used in the large fire tests. Since the ambient changes over a period of a few minutes are quite small, it is sufficient to zero the system just before the test. The gain will be affected by ambient temperature changes but this is of little consequence when the radiometer is used to measure relative changes in radiation.

CONCLUSIONS

1. The photocell radiometer described above may be used advantageously in place of the conventional systems to measure control times on both small and large fires.

2. It is simpler to manufacture than the conventional radiometer system and more reliable in use.

3. The basic design allows great flexibility. Considerable performance changes may be attained by minor circuit modification. The field of view may be altered by the use of suitable shielding.

ACKNOWLEDGEMENTS

Thanks are due to Mr B K Ghosh and Mr R H Kennedy for their assistance with the design of the radiometer.

REFERENCES

1. Foam liquid, fire extinguishing.
   Defence Specification 42-3 June 1, 1969.

2. Foam liquid, Fluoroprotein, Fire Extinguishing. February, 1972.
   Draft Defence Standard.

3. RASBASH, D. J., ROGOWSKI, Z. W., STARK, G. W. V. Properties of fires of liquids. Fuel, 1956, 35, 94 - 106.

APPENDIX

The specification for an ideal radiometer system, comprising sensor and recorder, for monitoring liquid fuel fire tests, might be as follows:

1. The output should be linear with respect to radiation.
2. Response times less than 0.5 s.
3. The sensitivity should be sufficient to detect a one per cent change in the maximum output of the fire. (For the radiometer described in this note the sensitivity is of the order of 200 watts/m^2).
4. A gain control must be supplied to adjust the recorder trace.
5. The radiometer must have a sufficient field of view to receive radiation from all parts of the fire. Other sources should be ignored.
6. The radiometer should either measure the radiation from the fire over the entire spectrum, or where only part of the spectrum is measured this should remain a constant proportion of the whole. (Further measurements of the spectral characteristics of large fires of various fuels are needed to clarify this point).
7. The total system should be both simple to use and reliable under fire site conditions. Battery power is usually more convenient outdoors. The provision of an event-marker is useful for recording "start of foam application" etc.

TABLE 1

Comparison of thermocouple and photocell radiometers on five 0.28 m^2 fires

Percentage of maximum output	Four thermocouple radiometers in series (s)	Photocell radiometer (s)	Thermocouple radiometer in same position (s)	Extinction (s)
25	30	29	25	Not achieved
10	43	39	41	
0	110	77	130	
25	37	29	30	Not achieved
10	50	37	37	
0	190	n.a	n.a	
25	69	61	60	Not achieved
10	115	76	75	
0	n.a	n.a	n.a	
25	93	93	94	Not achieved
10	Almost achieved	123	112	
0	n.a	n.a	n.a	
25	33	32	30	63
10	48	44	39	
0	65	57	75	

TABLE 2

81 m^2 fire control times

Test number	Photocell radiometer (s)	Thermocouple radiometer (s)	Observed control times (s)	Average observed time (s)
1 †	No control	No control	No control	-
2	30	35	33, 30	32
3	26	29	23, 24	24
4	27	28	29, 28	29
5	31	33	17, 16	17
6	30	33	17, 16, 17	17
7	17	Rad. failed	15, 18, 14	16
8 †	160	164	59, 59, 69	62
9	43	46	39, 42, 40, 39	40
10	37	37	33, 35, 39, 31	35
11	42	45	35, 32, 25, 39	33
12	28	28	27, 28, 24	26
13	26	35	34, 40, 55, 30	41
14 *	50	48	46, 37, 40	41
15 †	68	70	60, 50, 60	57
16 *	68	57	65, 44, 56	55
17	67	68	67, 67, 65	66
18	103	103	103, 107, 104	105
19	34	28	20, 24, 24	23

† Splash fires outside bund area.

* Isolated areas of flame causing slow progress at about 90 per cent control. Attack on one area allows flames to grow in another.

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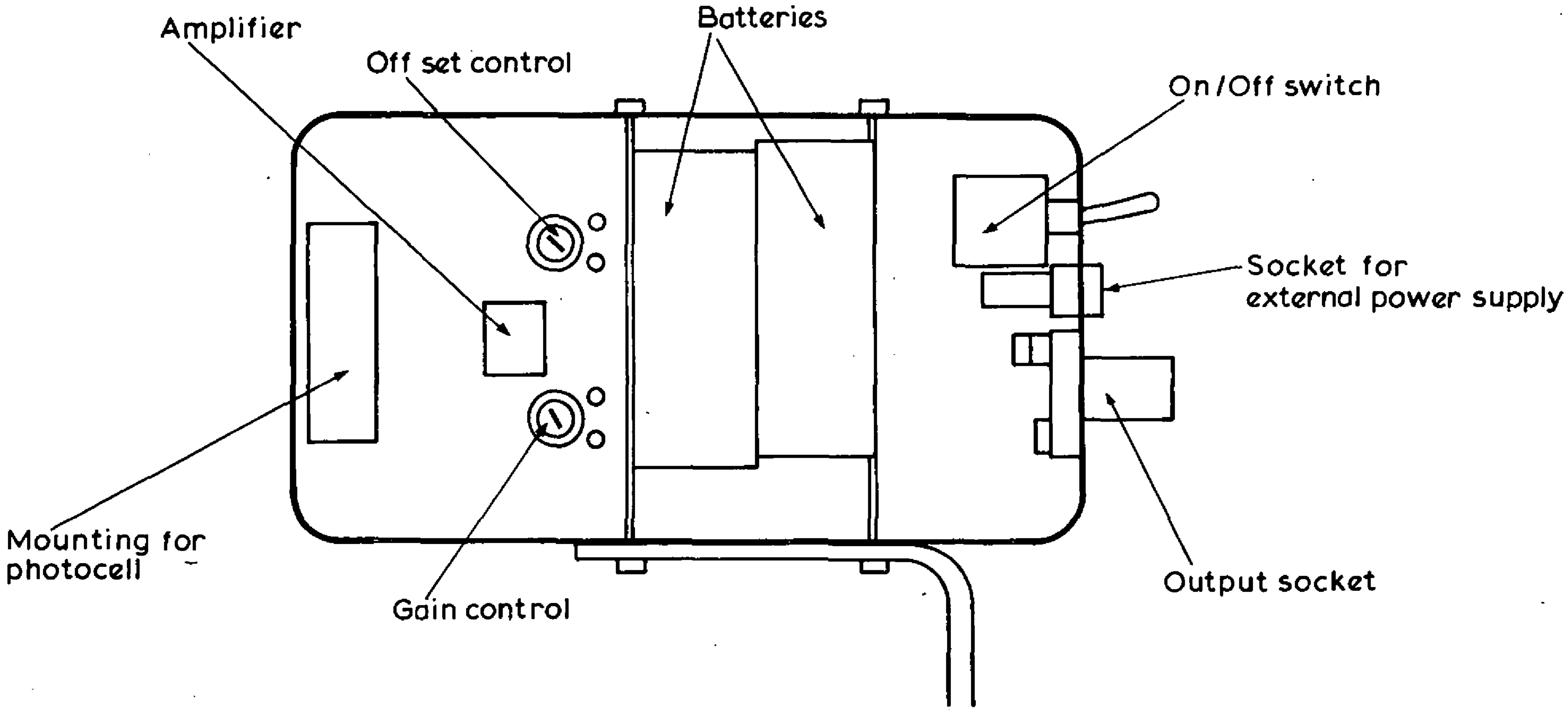

Figure 1 Internal details of radiometer

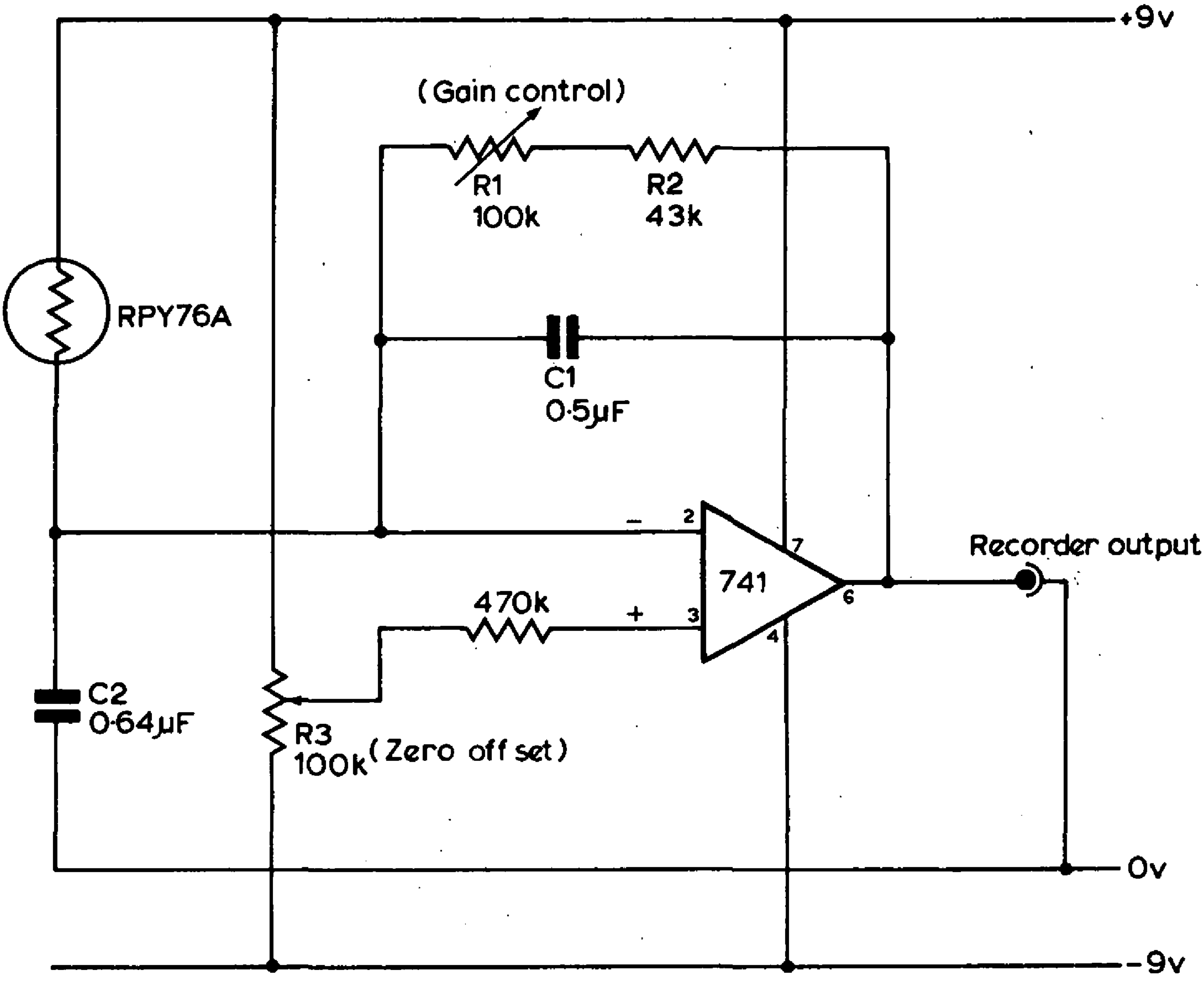

Figure 2 Circuit diagram

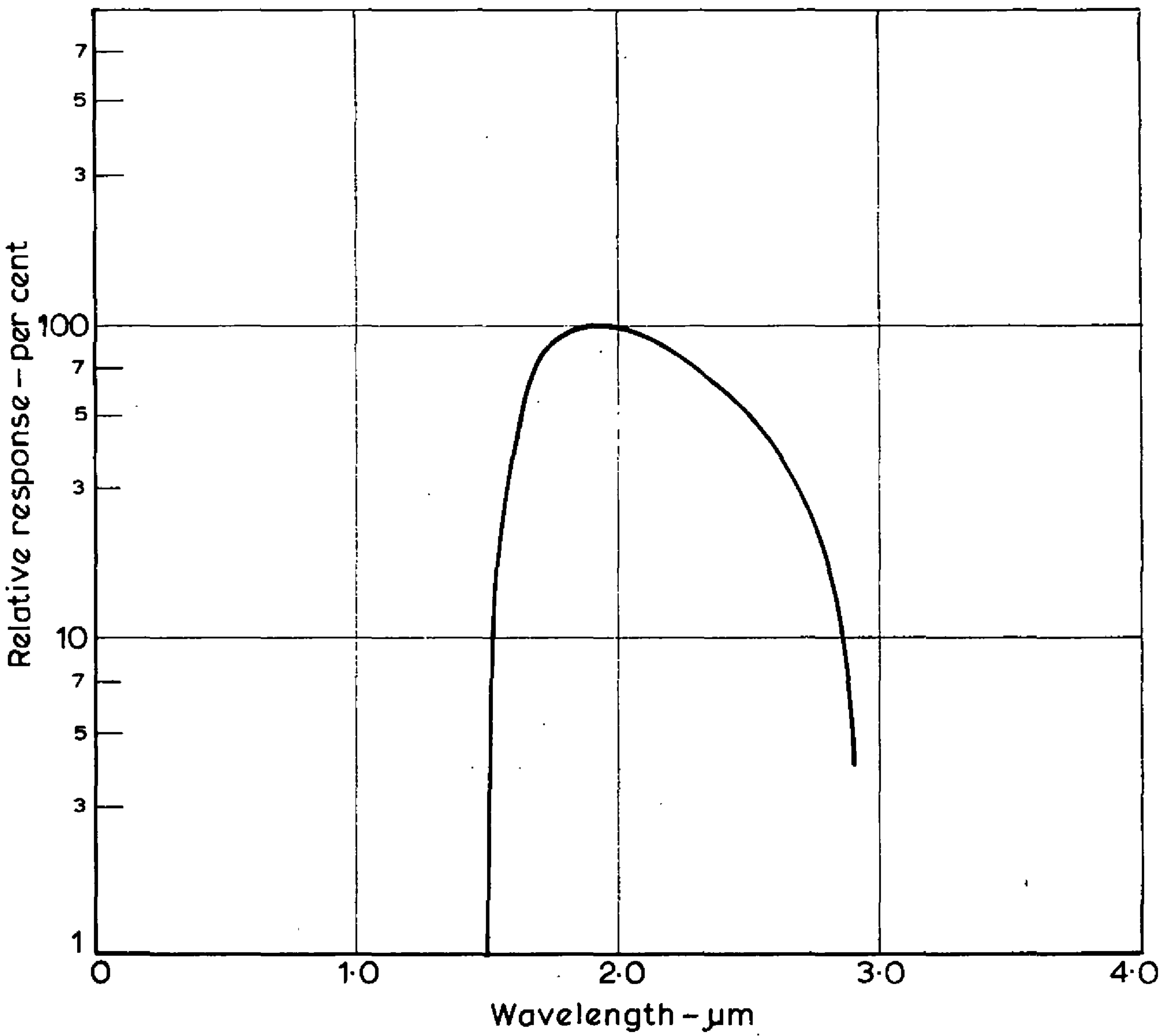

Figure 3 Relative spectral response curve for RPY76A

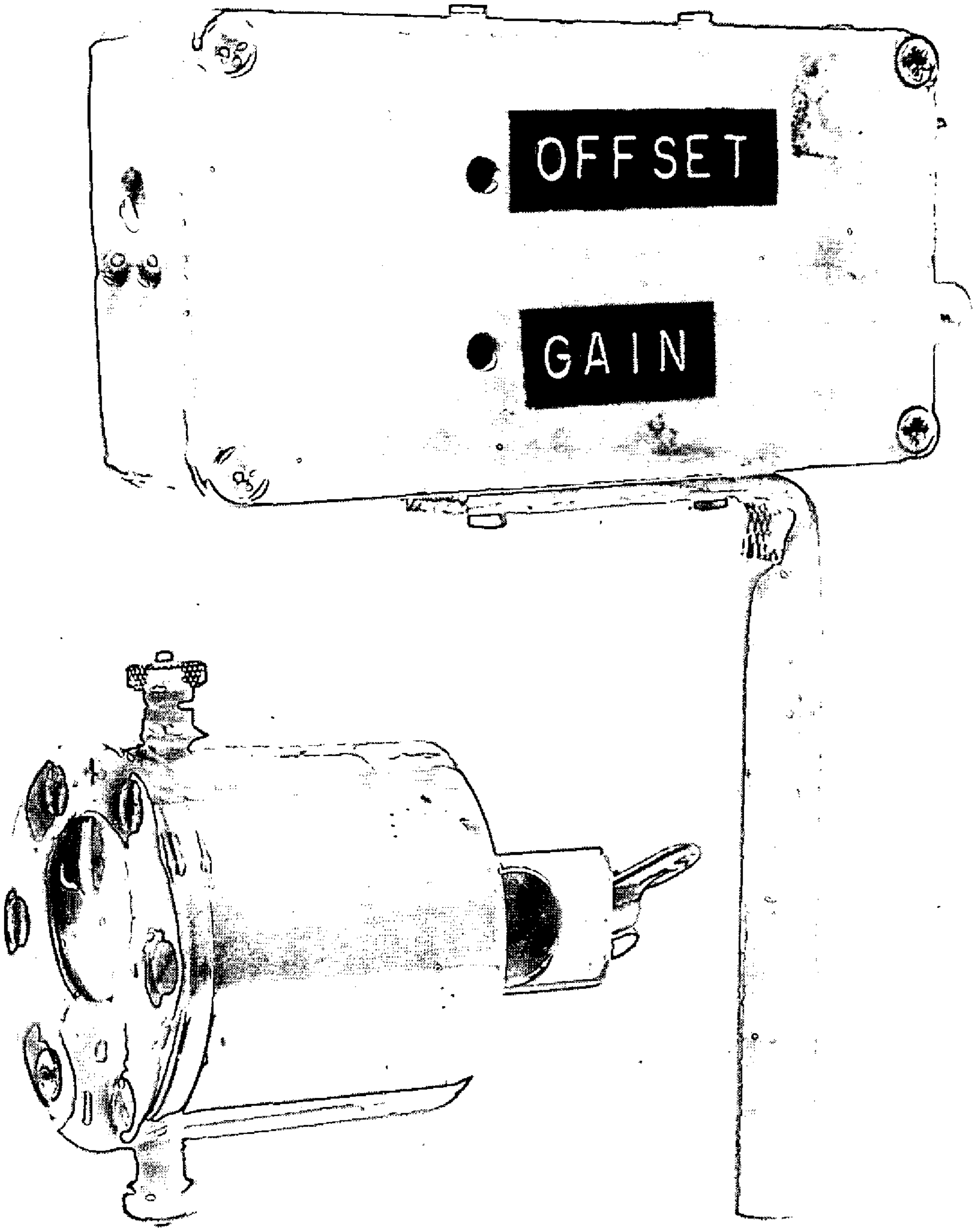

PLATE 1

ABOVE: PHOTOCELL RADIOMETER COMPLETE
(VIEWING WINDOW FOR PHOTOCELL IS SEEN IN THE LEFTHAND SIDE OF THE CASE)

BELOW: CONVENTIONAL THERMOCOUPLE JUNCTION RADIOMETER

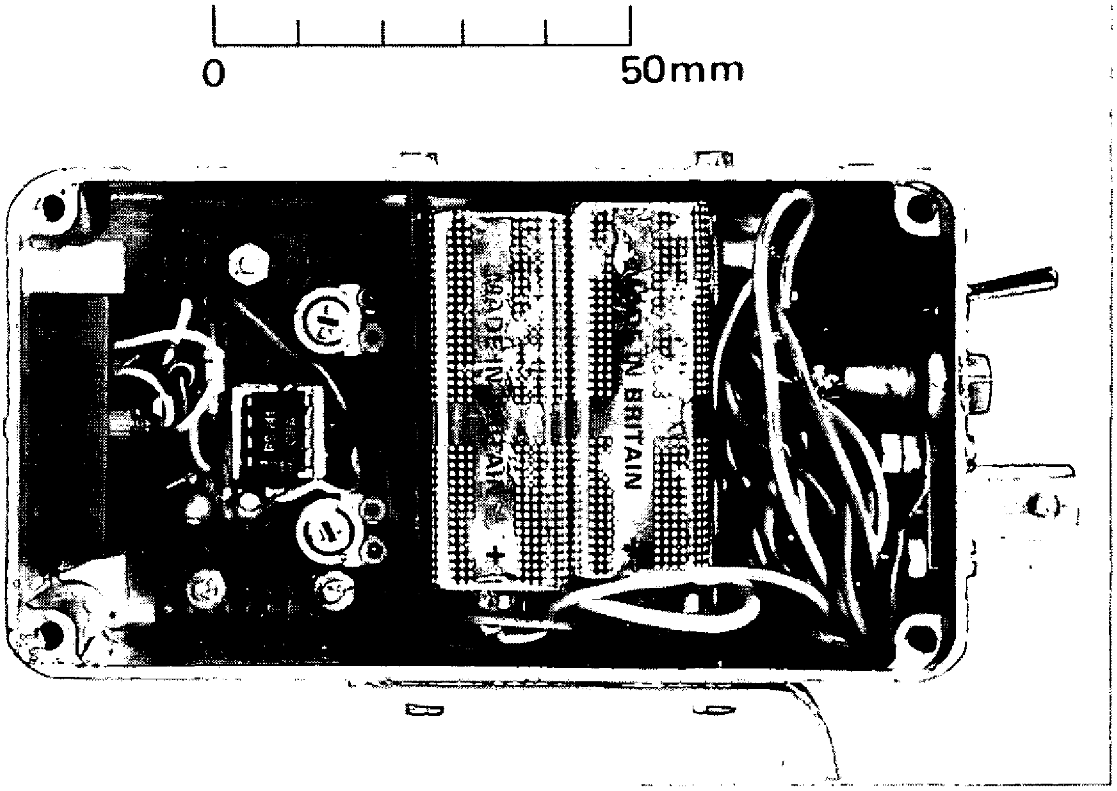

PLATE 2

INTERNAL DETAILS OF PHOTOCELL RADIOMETER
THE LEAD SULPHIDE CELL IS MOUNTED IN THE BLOCK ON THE LEFT