FACTORS OF MERIT FOR RADIATION DETECTORS

by

ALEXANDER MATTHEW UNWIN

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
in the Department of
PHYSICS

We accept this thesis as conforming to
the standard required from candidates
for the degree of MASTER OF SCIENCE

Members of the Department
of Physics

THE UNIVERSITY OF BRITISH COLUMBIA

April, 1953

ABSTRACT

A discussion is given of the many uses of photoconductive cells, especially of those of the lead sulphide type.

A Factor of Merit for radiation detectors as proposed by Clark Jones is presented, which is intended to cover all types of detectors, and which is applied to the lead sulphide cells studied. Other Factors of Merit are also mentioned. From information obtained the Factors of Merit are evaluated for the cells. These Factors of Merit are found to vary with the temperature of the cell layer. It is found that limiting noise is not due to Johnson noise, but rather to radiation fluctuations; and that the ultimate sensitivity has been reached in some cells. The cells are assumed to be type II detectors according to Clark Jones's classification. It is found that the engineering limit proposed by R. J. Havens does not apply here. Particularly good agreement between various expressions for the Factor of Merit is shown, assuming a type II detector.

A description of the apparatus is given in some detail. A black body radiator and associated temperature control, a 900 cycles per second tuned amplifier, a wide band preamplifier and a multivibrator used in measuring time constants of such cells are described.

The methods of measurement of responsivity to noise ratio, of noise, of time constants, frequency response curves and spectral response of a detector are outlined. It is found that the black body is optically aligned; tests show that the response of a cell is directly proportional to the intensity of the illumination.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. A. M. Crooker for his help and encouragement in directing this research. Thanks are also due to Mr. P. A. Lee for much assistance and for many invaluable suggestions. The author wishes to acknowledge his indebtedness to the Defence Research Board for use of the 900 cycles per second tuned amplifier, and for permission to use some of the cells studied.

CONTENTS

ILLUSTRATIONS

FIGURE

Chapter I

INTRODUCTION

Much attention has been given to photoconductive cells as infrared detectors in the past few years, especially to those operating in the region between one and six microns. Such cells, which were developed mainly during the war years, now find many interesting applications in pure and applied research.

A brief summary of such research will now be given, for it is the purpose of this research to study the properties of several such detectors with a view to evaluating their relative merits and demerits in a single comprehensive "Factor of Merit".

Many applications, together with a summary of performance of such cells, are given in a review article by Simpson and Sutherland (1). Detectors to be considered are sensitive above one micron; those with a cut-off in this region are already well known and include thallium sulphide cells, whereas such detectors as are studied here extend our present knowledge in many fields.

Three substances, photoconductive beyond one micron, are of greatest interest and form the basis of the most research;

lead sulphide, lead selenide and lead telluride. Such materials are normally deposited in thin layers from 10^{-4} to 10^{-5}cm. thickness on glass or some other non-conductor, by evaporation or a chemical process. Dark resistances so far encountered are from 10^{4} to 10^{8} ohms, and response times are found to be between 10^{-5} and 10^{-3} seconds. It will be seen in Chapter V that all measurable properties of the cells encountered in this research fall within the ranges given. It is also immediately apparent that one great attribute of such detectors, compared to bolometers, thermocouples and other heat detecting devices, is their relatively short time of response.

An excellent article by Sosnowski, Starkiewicz and Simpson (2) describes the preparation of lead sulphide cells and also the main aspects of the theory. Many such cells have been made, which operate at room temperature and are exposed to the atmosphere. However, most layers are kept in vacuo; a further betterment in their responsivity being obtained by cooling the layer, either to solid carbon dioxide or liquid oxygen temperatures. This is also known to extend the long wave limit of such cells from about 3.3 microns to about 3.6 microns. On the other hand, lowering the temperature also raises the resistance and increases the time constant; consequently a cooled cell is not always advantageous. Selenide and telluride cells must be cooled to the neighbourhood of dry ice temperatures before photoconductivity takes effect.

At present, only lead sulphide cells are commercially available. Each of the semiconductors hitherto mentioned has its own response versus wavelength curve, characteristic of the material in the layer and also of the method of preparation. Such a curve is shown in figure (13), for three different temperatures of the same detector. For lead sulphide cells, the peak in the curve generally occurs at two microns, for lead selenide between three and four microns, for lead telluride a little beyond four microns.

It is interesting to observe how such detectors approach their theoretical ultimate sensitivities. This limit, determined by the responsivity and the noise of any detector, is discussed in several of the papers quoted, the most important of which is that by Clark Jones (3); this paper is discussed at some length in Chapter IV, section (1). Fellgett (4) calculates the limiting sensitivity imposed by radiation fluctuations on a lead sulphide cell, from its measured responsivity wavelength characteristics, assuming the cells to have been cooled and exposed to a solid angle 2π of radiation (from surroundings taken to be at 15° C). The ultimate sensitivity was then calculated to be 2.1×10^{-13} watt at the optimum wavelength, compared with an actual measured noise equivalent power per unit bandwidth of 4.9×10^{-13} watt. These results indicate that the theoretical limit for the lead sulphide cell had been reached; the total noise being only twice as great as that due to the radiation fluctuations alone.

Moss (5) has also studied the ultimate sensitivity and its dependence on the spectral response curve. For photoconductive detectors, the background radiation is normally of greater wavelength than the wavelength at maximum response. Upon cooling a cell, Moss found the limiting sensitivity to deteriorate from 5.2×10^{-14} watt at $273^{o}K$ to 17×10^{-14} watt at $90^{o}K$ at 2.3 microns. This is because of the preferential increase of the response at longer wavelengths upon cooling. On the other hand, at 3.5 microns the situation is reversed. The limiting sensitivity for the same detector improved from 2×10^{-11} watt to 15×10^{-14} watt.

It is then of particular importance, in choosing a detector for some specific purpose, to define a suitable Factor of Merit for detectors in general. Without such a simple criterion, it would be necessary to compare the performance of all available types of detector under the proposed experimental conditions. This long standing need for a Factor of Merit has been met by many workers, notably Clark Jones (6) and Daly and Sutherland (7). These references are discussed in the next chapter.

Some of the interesting applications for photoconductive cells in pure physics are in the field of infrared spectroscopy. By using photoconductive cells, notable progress has been made in resolving power and scanning speed; the point having been reached where the infrared spectrometer is becoming limited by optical considerations and not by the detecting element as heretofore. Sutherland, Blackwell and Fellgett (8) reported that they achieved a resolving power of 30,000 in the water vapour spectrum near 2.5 microns, whereas previously only a resolving power of 7,000 had been attained in this region. Advances have also been made, using photoconductive cells, in the observation of spectra of extraterrestrial objects.

Rapid changes in spectra occurring in explosions or in the early stages of a chemical reaction are often items of interesting study. With a fast bolometer, the scanning time for the range of a few microns is of the order of several seconds if resolving power is to be maintained (9). Bullock and Silverman (10), by using photoconductors, are able to scan a range of two microns between one and five microns in some thousandths of a second and with a resolving power of 100 near three microns. In this way they have been able to study the first stages of the explosive reaction between oxygen and carbon monoxide.

Infrared spectroscopy has already made a large contribution to the study of the atmospheres of planets. Kuiper (11), using photoconductive cells, has shown that the polar caps on Mars do not consist of solid carbon dioxide but are almost certainly composed of ice.

In industry, lead sulphide cells open up new possibilities in radiation pyrometry. Lee and Parker (12) have shown that temperatures as low as 100°C can be measured this way with fair accuracy, and those of 500^{o} C, sometimes encountered in the rapid braking of locomotive wheels, can be followed continuously and measured to an accuracy of one per cent.

The purpose of this research will be to study the properties of several photoconductive cells, and evaluate several Factors of Merit for them. Any inconsistencies in these will be noted, the whole with a view to enabling future workers in the field to choose the best of these detectors on merits of size of sensitive layer and time constant.

Chapter II

FACTORS OF MERIT

1. The Clark Jones Factor of Merit (6)

In his paper on Factors of Merit, Clark Jones (6) points out the need for " ... a single, quantitative Factor of Merit for use in comparing the sensitivity of various radiation detectors." A criterion is needed for comparison of similar detectors, such as an evaporated thermocouple and a wire thermocouple, as also for the comparison of dissimilar detectors, such as a Golay pneumatic heat detector and a lead sulphide photoconductive cell.

This Factor of Merit must be capable of comparing detectors with greatly different sensitive areas, response times and spectral response curves, when measured with an amplifier having any given frequency-response curve.

In part I. of the second of three papers dealing with radiation detectors, (3, 13, 6) Clark Jones defines a type n detector as one whose noise equivalent power (defined in 13) P_m in the reference condition A depends upon the reference time constant τ and the sensitive Area A according to

$$P_m = \left(A^{\frac{1}{2}} / k_n \tau^{\frac{1}{2} n} \right) \tag{1}$$

where k_n is a parameter independent of A and τ, but which has different values for different detectors. Clark Jones (6) proposes a suitable multiple of k_n as a numerical Factor of Merit.

For type 1 detectors Clark Jones uses equation (3.8) of paper I (3). For a detector whose quantum efficiency is unity at every radiation wavelength, equation (3.8) states that the minimum value of the noise equivalent power is given by

$$P_m = (4\sigma T^4 kT)^{\frac{1}{2}} (A^{\frac{1}{2}}/\tau^{\frac{1}{2}}) \tag{2}$$

where k is Boltzmann's constant, σ is the Stefan Boltzmann radiation constant, and where T is the absolute temperature of the detector and of the surrounding radiation field. At the temperature T = 300 °K. the last equation may be written

$$P_m = 2.76 \times 10^{-12} (A^{\frac{1}{2}}/\tau^{\frac{1}{2}}) \tag{3}$$

where P_m is in watts, A is in square millimeters, and τ is in seconds. If a detector satisfying the above is considered to have a Factor of Merit equal to unity then the Factor of Merit for any other type I detector may be written

$$\begin{aligned} M_1 &= 2.76 \times 10^{-12} k_1 \\ &= 2.76 \times 10^{-12} (A^{\frac{1}{2}}/P_m \tau^{\frac{1}{2}}) \\ &= 5.52 \times 10^{-12} R_o A^{\frac{1}{2}} \end{aligned} \tag{4}$$

where P_m is in watts, A is in square millimeters, τ is in seconds, k is in the units resulting from using the units just mentioned in equation (6) and R_o is in watt $^{-1}$.

Equation (4) is Clark Jones's proposed Factor of Merit for a type I detector.

For type II detectors, Clark Jones (6) bases his multiple, chosen for k_2, on Havens's Limit. This limit -- based on an estimate of the minimum value of the noise equivalent power which could be obtained with thermocouples and bolometers with currently available materials and techniques -- was made in 1946, by R. J. Havens (4) for a detector at room temperature. This limit, which is of an optimistic engineering and not of a fundamental nature, has been very well confirmed.

Havens's Limit is

$$P_m = 3 \times 10^{-12} (A^{1/2}/\tau) \tag{5}$$

where P_m is in watts, A is in square millimeters, and τ is in seconds. If a detector which satisfies equation (5) be considered to have a Factor of Merit equal to unity, then the Factor of Merit for any other type II detector may be written

$$\begin{aligned} M_2 &= 3 \times 10^{-12} k_2 \\ &= 3 \times 10^{-12} (A^{1/2}/P_m \tau) \\ &= 6 \times 10^{-12} (R_o A^{1/2}/\tau^{1/2}) \end{aligned} \tag{6}$$

where P_m is in watts, A is in square millimeters, τ is in seconds, k_2 is in the units resulting from using the units just mentioned in equation (1) and R_o is in watt $^{-1}$.

Equation (6) is the proposed Factor of Merit for a type II detector.

In discussing the significance of the Factors of Merit, Clark Jones (6) then goes on to show that two detectors with the same Factors of Merit and of the same type (e.g. both bolometers) but with different sensitive areas and different time constants will not in general yield the same results in any particular application. However, if the two detectors are so reconstructed that they each have the optimum sensitive area and the optimum time constant for the particular application, then the performance of the two will be the same.

This point cannot be stressed too greatly, since this is the great significance -- and explains in the best fashion the importance and usefulness -- of Clark Jones's proposed Factor of Merit. Thus with a knowledge of the Factors of Merit of different types of radiation detectors, one may, by knowing the optimum value of sensitive area and of time constant, choose a detector type of the appropriate size and response time which has a Factor of Merit close to unity, regardless of whether the detector be a bolometer, thermocouple, or photoconductive cell. Thus a knowledge of the Factor of Merit of many different detectors of known area and time constant seems highly desirable. This has been attempted for several photoconductive cells in this research.

Clark Jones (6) carries the argument further, in that if the two detectors have different Factors of Merit and are constructed so that each has the optimum sensitive area and time constant for a particular application, the signal to noise ratios so obtained will be directly in proportion to their Factors of Merit.

For detectors such as bolometers and thermocouples, where it is assumed that the only source of noise is the Johnson Noise associated with the resistance of the detector, M_2 may be written (6)

$$M_2 = 0.0468\, S_o \left(A/R\tau \right)^{\frac{1}{2}} \qquad (7)$$

where S_o is the effective zero frequency responsivity, measured in volts per watt, A the sensitive area in square millimeters, R the resistance in ohms, and τ is the reference time constant in seconds.

In the case of photoconductive cells, the noise is not limited by Johnson noise only, and where the noise is actually measurable, the following Factor of Merit is obtained. Let P_o be the steady incident power which produces a steady output voltage equal to the noise voltage under the actual conditions of measurement. Where the measurement is made with a squarely modulated signal, P_o is obtained by reducing the measured result to zero frequency by making use of the measured square wave frequency response curve of the detector.

The quantity Δf is the noise equivalent band width in the actual measurement, and A and τ denote the sensitive area and the reference time constant. Clark Jones then shows (6), that M_2 may be written

$$M_2 = 6 \times 10^{-12} (A \Delta f / \tau)^{1/2} / P_0 \qquad (8)$$

where P_0 is in watts, A is in square millimeters, Δf is in cycles per second, and τ is in seconds.

All the Factors of Merit have been stated for detectors operating at room temperature. The values for detectors operating at the dry ice and liquid oxygen temperatures, 201°K. and 90°K., are given in Chapter V. [illegible]

In his discussion, Clark Jones (6) notes that no thermopile or bolometer operating at room temperature has a Factor of Merit as large as unity. Only the super-conducting bolometers and the Golay pneumatic heat detector have Factors of Merit greater than unity (viz., from 1.29 to 13.9, and 4.69 respectively). The Golay detector operates at room temperature, but since it is a type I detector (3) it is not permissible to state the Factor of Merit M_2 for this detector. The Factor of Merit M_1 for the Golay heat detector is 0.30.

Clark Jones also notes that the maximum attainable Factors of Merit at room temperature are substantially the same for thermocouples and bolometers.

The suitability of his proposed Factor of Merit is also borne out, according to Clark Jones (6) by the results obtained for three thermistor bolometers, which use the same type of sensitive element, but employ greatly different coefficients of thermal conductivity between the sensitive element and its surroundings. The time constant for a bolometer is defined as the ratio of the heat capacity per unit area to the thermal conductivity. In spite of the hundred to one range of time constant, the largest Factor of Merit for these thermistor bolometers is only 15 per cent greater than the smallest.

Clark Jones also states the need for the proper specification of the relevant properties of radiation detectors. He states what he considers to be the necessary information about detectors: a) whose only source of noise is the Johnson noise associated with their resistance as

1. The electrical resistance
2. The sensitive area
3. The curve of relative responsivity versus frequency. If the frequency response may be characterized by a single time constant, a statement of its value is sufficient.
4. The relative response to different radiation wave lengths
5. The responsivity (in volts per watt) at a single frequency with a specified spectral energy distribution.

and b) for detectors other than the above as

1. The sensitive area

2. A curve of relative responsivity versus frequency
3. A curve of the relative noise power per unit band width versus frequency, under the same conditions used to determine item 2
4. The relative response to different radiation wavelengths
5. A single measurement of the signal to noise ratio under fully defined conditions.

In the case of photoconductive cells, the necessity of 4 in both a) and b) is due to the large variation of sensitivity as a function of wavelength.

It is worthwhile to consider further the classification system proposed by Clark Jones (3).

A detector is defined to be a type n detector for a given range of reference time constants if over that range of reference time constants the zero frequency responsivity to noise ration R_o depends upon the A and the reference time constant τ in accordance with

$$R_o = k_n \tau^{\frac{1}{2}(n-1)} / 2A^{1/2} \qquad (9)$$

where k_n is a constant which is independent of A and τ.

Clark Jones then lists eight different kinds of radiation detectors (3) which he can classify as either type I or type II detectors on the basis of theoretical considerations. The list is as follows:-

Detector - Type I	Range of τ in seconds
Golay pneumatic heat detector	?
Vacuum phototubes limited by shot noise	$10^{-2} - \infty$
Gas phototubes limited by shot noise	$10^{-3} - \infty$
Photomultiplier tubes limited by shot noise	$2.5 \times 10^{-10} - \infty$
Dipole antenna limited by temperature noise = shot noise	$10^{-9} - \infty$
- Type II	
Bolometers	$10^{-3} - 1$
Thermocouples and Thermopiles	$10^{-2} - 1$
Photographic plates limited by grain structure	Reciprocity law

This paper will try to assess the type number of the various types of photoconductive cells under consideration purely on the basis of experimental evidence.

The actual reference condition of measurement proposed by Clark Jones (3) is the following. It satisfies these conditions:-

1. The noise equivalent power of the detector is measured in the presence of the noise in a manner such that the band width of the noise is approximately equal to the band width of the detector.
2. The band width of the detector is measured after the amplifier gain has been equalized so that the noise spectrum is flat.

Then follows a prescription for the adjustment of the amplifier and for the measurement of the noise equivalent power. However, this has not been carried out in the present work, but it is felt that time and material do not justify such a step as the measurements carried out allow enough leeway for effective values to be obtained at the expense of only slight loss in precision and generality. The above is mentioned as a further step necessary only to the absolute fulfillment of all the conditions laid down by Clark Jones (3) for the assignment of Factors of Merit. However, since Clark Jones (6) has assigned Factors of Merit to various detectors on the basis of previous published reports on their characteristics which do not follow his unique specifications, and since he has assumed certain evidence to be able to convert published figures to his own specifications, it is thought to be sufficient merely to do the same. Further, Clark Jones uses such above mentioned evaluations of Factors of Merit in straightforward comparisons between detectors, which is essentially the purpose of this paper.

In summary, Clark Jones (6) has devised a thoroughly practical and widely applicable method for assigning to certain types of radiation detectors a number, called their Factor of Merit, which when properly interpreted allows complete comparison of all detectors covered, and which also indicates the best detector available for a thoroughly specified purpose. To a large extent, this paper seeks to extend his definition to the large number of photoconductive cells now being developed or already in use, in order to aid workers in fields associated with their use in choosing satisfactory detectors.

2. The Daly and Sutherland Factor of Merit (7)

One may express (7) the mean square fluctuation voltage at the detector output as

$$\overline{V_n^2} = \mu \Delta f \tag{10}$$

where μ is characteristic of the detector alone and Δf is characteristic of the amplifier (and display) alone. Further, defining σ as the responsivity in microvolts per microwatt and τ as the time constant of the detector, Daly and Sutherland (7) propose taking

$$\sqrt{\mu \tau / \sigma} \tag{11}$$

as the Figure of Merit of a detector, when sensitivity, speed, and noise level have all been taken into account.

To compare the Daly and Sutherland Figure of Merit with that proposed by Clark Jones, the inverse of the former must be considered, since it is itself proportional to the minimum detectable power, whereas the number proposed by Clark Jones is inversely proportional to the minimum detectable power. Also, Daly and Sutherland omit reference to the sensitive area, which, being combined with the above remarks, gives as a suitable Factor of Merit as proposed by Daly and Sutherland

$$A^{\frac{1}{2}}\sigma/\sqrt{\mu\tau}\ . \tag{12}$$

3. Other Factors of Merit.

The Hornig and O'Keefe Factor of Merit (15)

Hornig and O'Keefe propose a factor of Merit (15) for thermal detectors which employ thermoelectric properties in thermocouples of various materials. They propose a figure

$$M = Q/(k\rho)^{1/2}\ . \tag{13}$$

where Q is the thermoelectric power of a thermoelectric junction attached to the receiver, k is the thermal conductivity of the wire material, and ρ the resistivity of the wire material. Denoting the two wire materials by the subscripts 1 and 2, a precise Factor of Merit is established, of the form

$$M = (Q_1 - Q_2)/[(k_1\rho_1)^{\frac{1}{2}} + (k_2\rho_2)^{\frac{1}{2}}]\ . \tag{14}$$

Q is measured in microvolts per degree Centigrade, k in watts per centimeter degree Centigrade, and ρ in ohm centimeters.

It is felt that the Factor of Merit given by Clark Jones carries the greatest weight since it is universal, applying to all types of detector, whereas both the above are specialised cases. It also considers the sensitive area, which is a matter merely of adjustment to the above figures. However, Clark Jones's Bactor of Merit is chosen on the basis of theoretical prediction, and is not merely a good guess, and embodies considerations such as minimum detectable power, proper time constant and class of detector.

Chapter III

THE APPARATUS

The apparatus must be able to measure responsivity to noise ratio, time constant, and also the sensitive area. The latter may be measured by the usual means of travelling microscope, since for most detectors it is impossible for a detailed examination of the sensitive area to be made, as the detectors are in vacuum.

The responsivity to noise ratio is measured by using a 900 cycles per second tuned amplifier with properties described in section (3) of this chapter. The measurement of time constants is performed by using a neon flash bulb as a source of variable modulation frequency (square wave modulated) radiant energy, a wide band preamplifier after the detector whose time constant is being measured, and an oscilloscope, all of known frequency response, a plot then being made of response versus frequency from which the time constant is determined.

A detailed description of the above-mentioned instruments follows.

1. The Black Body Radiator.

The radiator is shown in figure (1). A is a steel cylinder 10 centimeters long and 6 centimeters in diameter. A conical hole subtending an angle of fifteen degrees is bored in one face (the cylinder then being thoroughly baked for oxidisation purposes) and is surrounded by a disc of air of 6 centimeters diameter and 1 centimeter thickness. It is covered with a circular aperture of 1 centimeter drilled in a brass disc B. Another brass disc is placed in a symmetrical position, 1 centimeter from the latter face of the steel cylinder. The whole is enclosed in an alundum cylinder C which is wound non-inductively with a nichrome heater E. A resistance thermometer F is then wound over the heater, shorts being avoided by having all wires E and F embedded in alundum cement. This cylindrical roll is then covered by a roll of several thicknesses of asbestos sheeting D, surrounded by rock wool, which constitutes a rectangular filling of a wooden box, whose inner dimensions are 12 cm. by 12 cm. by 20 cm. The front end of this box is covered by a thickness of aluminum J with a 1 cm. aperture. A hole was bored through the back brass disc B and the steel cylinder A to the apex of the conical hole as shown in figure (1). This hole contains the thermocouple, which is of iron constantan. The thermocouple calibration curve was plotted, indicating close agreement with the calibration curve for such a couple found in the Wheelco tables.

The resistance thermometer has a temperature coefficient of .0045 per degree Centigrade. The wire used has a length of 20 feet, resistance at 0° C. being 24.6 ohms, and at 200° C. 25 ohms.

In figure (2), the optical system of the black body radiator is shown. All plates of aluminum are highly polished on the side facing the source, and painted with a mixture of lamp-black and methyl hydrate on the side away from the source. Originally, the baffle system consisted of two baffles of type A (figure (2)), and two baffles made of single aluminum plates, of the dimensions illustrated and of square area. The present system, which necessitated removal of all baffles except that shown at A, was due to standardization of the length of separation between the sensitive area of the detector and the virtual source to 20 centimeters. The asbestos used in shield A is of the sheet type. F is a sliding shutter of aluminum, also originally of several air separated aluminum plates with polished and blackened sides, now consisting of a single plate of aluminum.

The chopper disc B (figure (2)) may be used either for sinusoidal modulation or square wave modulation of the incoming radiation, depending on the desired application. This is effected by having holes and spaces of equal widths for square wave modulation, or in a specified ratio for sinusoidal modulation. There are 30 holes in the chopper wheel at a radius of 10.2 centimeters. The chopper motor D is an 1800 r.p.m. synchronous motor, and is mounted below a brass tube J, blackened on the inside.

C is an aperture disc, with eight holes drilled in it. The diameters of these holes, as measured by a travelling microscope, are .798, .631, .577, .482, .369, .3, .189 and .109

centimeters respectively. The aperture standard normally used is 3 millimeters in diameter.

The detector is held by means of clamps with its sensitive area at K. Great care was exercised in designing this optical system, so that all cells would be uniformly radiated from the black body, for all sensitive areas encountered. The maximum radius for the sensitive area of a detector centrally mounted on the axis of the optical system is of 1 centimeter radius for an aperture of 3 millimeters required to act as a virtual source.

A brief digression is in order here to explain how the circular 3 millimeter aperture acts as a virtual source. A complete treatment is given by Roberts (16) on page 390 and is as follows with reference to figure (3).

The small hole cd is the 3 millimeter aperture in question, the receiver is ab, and the radiator is a'b'. The essential feature is that the lines ad and bc produced intersect the radiator, taken as the 1 centimeter conical hole. This condition ensures that the radiation received by any and every point on the receiver is the same as if the radiator were of the same area as the aperture cd in the screen and were situated in the plane of the aperture. For proof of this, consider the radiation received by an infinitesimal area at the point P on the receiver. As far as the point P is concerned, the only part of the radiator which is effective is represented by c'd'. If A_1 is the area of cd, and A_1' that of c'd',

$$A_1/A_1' = (Pc)^2/(Pc')^2 \tag{15}$$

that is, the areas are proportional to the squares of their distances from the point P. But the intensity of radiation falls off inversely as the square of the distance from the source. Since this intensity is also proportional to the area of the source, the increase in area compensates for the increased distance, and the radiation at P from the surface c'd' is the same as the radiation from a surface of the size of cd situated in the plane of the screen would be.

Under experimental procedure in Chapter IV, section (6) it will be seen that an experiment was performed to test whether the source was actually a virtual one.

The whole framework containing the black body may be mounted either vertically or horizontally, depending on whether cells which have to be cooled have side or end windows, since the cells must always be mounted vertically to allow their being cooled.

2. Temperature Control for the Black Body Radiator.

The standard setting of the black body is 500° K., and to ensure that this temperature is produced with no change over long durations of measurements, it was found necessary to use a temperature control of the type described.

A bridge network is made up, of which two arms are the resistance thermometer already described in the preceding section, and a control, R_{th} and R_x respectively. The control is made up of two wire-wound potentiometers in series; one has a value of 200 ohms and acts as the coarse control, the other being a 5 ohm resistance in series with it which may be used as the fine control.

Essentially, the function of the circuit is the mixing of two a.c. voltages, one of which has a constant amplitude and a constant phase, the second having varying amplitude and approximately constant phase. When the amplitude of the second voltage is varied, the output signal varies in phase and its amplitude increases. This signal is applied to the grid of an F.G. 57 thyratron.

The first signal is provided by an a.c. network across the 6.3 volt heater supply, and can be adjusted to have a phase varying within plus or minus of 120^{o} with respect to the a.c. voltage supplied to the thyratron anode. This phase is adjusted by means of a 50 kiloohm potentiometer so that, when the bridge is in balance, the signal which is applied to the grid of the thyratron gives exactly the current through the heater winding of the black body needed to maintain the black body radiator at its balance temperature.

If the R_x setting is above the present black body temperature, the bridge goes off balance and this additional signal produced across the temperature bridge is added to the network signal, increasing the grid voltage in amplitude and changing its phase. This phase change is such that the on period of the thyratron is increased, which in turn gives an increase in the heater current. The heater is in the anode load of the thyratron.

If the black body is too hot, however, the phase angle varies such that the on period decreases.

A 6K6 tube is linked in the circuit as a cathode follower to provide a low impedance signal to the grid with little or no distortion.

The overall circuit gain is about 30,000, and regulation has been found better than 0.1°K. for 500°K. operation, by measurements made with a thermocouple.

The thermocouple which measures the effective black body temperature may be read on a small millivoltmeter marked "Centigrade" on the apparatus. For higher accuracy than this, an external potentiometer must be used for the temperature measurements.

The advantage of this type of control unit over other types is that the black body can be brought from room temperature to anywhere in the $(400-600)^{\circ}$ K. region in a matter of one and one-half hours without having to bring the radiator to within a few degrees first, as is necessary with most other conventional types.

3. The 900 cycles per second tuned amplifier.

The amplifier was built after a design by Brown (17) and is illustrated in figure (4). The merits of the amplifier are that it has a flat peak of several cycles to compensate mains voltage changes affecting the chopping frequency, a high gain and a linear response.

There are three main stages of amplification in the original circuit, each consisting of three tubes. The cathodes of the first and third tubes are connected to give negative feedback. An attenuator is placed between the first and second group of three tube stages, to step up the amplification by convenient factors of three. A tuned anode load is placed on the third tube in each of the first two stages, one tuned at 880 cycles per second and the other at 920 cycles per second, to give a flat-topped frequency response curve at 900 cycles per second. The coils are toroidal, and are mounted in mumetal cases to give magnetic and electrostatic screening.

The output is fed through a transformer with a 1 : 1 ratio from the primary to each half of the secondary.

The present amplifier is essentially the same as the above with the following modifications. Firstly, a low noise twin triode 12AY7 replaces the first two pentodes in each of the three groupings. Secondly, some positive feedback is employed between the cathodes of the second and third tubes of each ring of three. Thirdly, the output twin diode has been replaced by two 1N34 rectifiers. The heater voltage is adjusted to give least hum by means of a 150 ohm potentiometer across the heater winding connected to some point on the power supply.

The output is shown on a 0-200 microammeter whose full-scale deflection corresponds to 10 millivolts output.

The data for the amplifier is as follows.

The gain = (50) + (50) + (24) = (124) db = 1.5×10^7

With input terminals shorted the noise level is equivalent to (.22) μV. No noticeable change on the output meter is noted for a mains voltage range 90 - 135 volts on amplifier scale 11. On open circuit-noise level is equivalent to (1.53) μ volts. Figure (5) shows the frequency-response curves for inputs of 2.5 millivolts and of 5.01 microvolts respectively. Figure (6) shows the linearity of response for a gain setting of (11). The peak of the frequency-response curve occurs at a frequency of 895 cycles per second. The bandwidth is 44 cycles per second at minus 3 db.

Considering R_2 as the dynamic impedance of the tuned load at the operating frequency, the gain per ring of three stage is R_2/R_1, where R_1 is the cathode load of the third tube. With desired values of the tuning coil and the "Q" of the tuned load, Brown (18) has shown that R_2 is approximately equal to 40 kiloohms at the required operating frequency. To obtain maximum gain, one must make R_1 small, which calls for a tube of short grid base and high g_m in both the third and first tubes.

Brown (18) shows that a fractional change of loop gain dA/A and the fractional change of gain dG/G are related by

$$\frac{dG}{G} = \frac{1}{1+A} \frac{dA}{A} \tag{16}$$

Thus, for A = 999, a 10% change in A gives a 0.1% change in G.

The amplifier gives long-term stability of gain, low noise level, and linearity of response, and is therefore ideally suitable in the work attempted here.

4. Time Constants Apparatus.

The time constants are measured by a method explained under Experimental Procedure, chapter IV, section (2).

A neon 30 tube is used whose time of response is characterised by a time constant of $\sim 10^{-6}$ sec. Its response curve was obtained using the method outlined in chapter IV, section (5). Neon, as the gas for discharge, was chosen because although the time constants of such tubes may be somewhat longer than for other gases, notably hydrogen, hydrogen sources lead to other complications due to the scarcity of infra-red lines obtainable from them.

The limiting factor to be scrutinised in choosing a suitable source of infra-red radiation, is the ionisation time of the gas, which for the tube used was found to be $< 10^{-6}$ sec..

The Multivibrator used consists of six tubes, and employs a plate-to-grid coupling. The signal is taken from a cathode follower to give a low impedance source for switching the neon. The range of the multivibrator extends for square waves with half-widths from 5 microseconds to 10 milliseconds, and the edges of the square waves are less than 0.5 microseconds long; a figure good in comparison to that quoted by Elmore and Sands (19) on page 81, who give a steepness of 0.1 microseconds as a theoretically attainable limit, for a multivibrator using two pentodes and having a large consumption of power; a similar scheme to that used in this multivibrator as mentioned in this paragraph.

The frequency of oscillation can be varied fairly conveniently in steps, each step having a continuous range overlapping those of other steps, and covering the total range of 5 to 10,000 microseconds mentioned above.

Voltages are supplied by an electronically regulated power pack. Special attention has been given to the building and design of this power pack, to enable use of various neon tubes with a large variation of striking voltages.

A wide band preamplifier was designed for use with the apparatus for measurement of time constants. Originally, a single stage preamplifier was built with a gain of 50; this was not of high enough gain for measuring time constants of some of the lead selenide and lead telluride cells, whose output is smaller than that of most lead sulphide cells, for which latter this amplifier was originally intended. Therefore a new wide band preamplifier was built with a gain of 2000, which could be used to measure time constants of most of the detectors studied in this research. The circuit is shown in figure (7), and consists of two high g_m sharp cut-off 6AG5 miniature pentodes and a cathode follower. The output is put either directly on the Y_2 plates of a double-beam oscilloscope, or through the low gain amplifier on the oscilloscope, which has a flat response out to seven megacycles per second.

The frequency range of the preamplifier is governed at the low end by the condition that 1/RC be very much less than 50 where R and C are as in figure 7. The values of R (3.3 Megohms) and C (0.5 microfarads) satisfy this condition. At high frequencies, the value of R must be much larger than 1/Cw, where C is the input capacitance of the 6AG5 tube, and w is the highest angular frequency used. This condition is also fulfilled. Decoupling between stages has been used to eliminate positive feedback, and the screens of the two pentodes are decoupled by 8 microfarad electrolytic condensers as shown. Use of negative feedback has not been found necessary (by the removal of the 250 microfarad cathode self-bias condensers). The grid of the cathode follower has been put at 150 volts to allow output pulses of this height to be seen on the oscilloscope. The actual maximum signal into the oscilloscope is 22 volts.

Figure (8) shows the frequency-response curve for the wide band preamplifier, which covers the range of square wave signals from the multivibrator fairly adequately and with no distortion, as has been found by using a frequency adjusted attenuator for using the 120 volt multivibrator output as an input signal to the preamplifier, and comparing the input and the ouput by means of the double-beam oscilloscope.

5. Cell Mountings

Most of the cells studied were either lead sulphide or lead telluride. The lead sulphide Admiralty cells were used at room temperature, and mounted in brass shielding (figure (9)) with coaxial cable connectors. The other lead sulphide, lead telluride and lead selenide cells were either commercial ones and already mounted with a tube base (e.g. the B.T.H. lead sulphide and lead telluride cells) and thus required a metal screen with the tube socket in one side and a coaxial connector in the other with a screened lead carrying the signal inside the can, or the cells were sometimes of glass with two tungsten electrode leads at one end and a window at the other, in which case a screened lead with brass connectors was used, and the whole screened in a roll of grounded tinfoil.

6. Spectral Response Measuring Equipment

The equipment consisted of a Brown recording potentiometer, whose full scale reading corresponds to 10 millivolts, a Perkin and Elmer model 12C infra-red monochromator with a rocksalt prism, a globar for a source of black body radiation, a standard Perkin Elmer thermocouple detector and associated d.c. amplifier, and a 900 cycles per second tuned amplifier, a chopping wheel and motor.

The globar operates with a current of 2.25 amps. at a temperature of 1400° K. and with an emissivity of about .9.

More details are given in section (4) of chapter IV dealing with the experimental procedure.

Chapter IV

THE EXPERIMENTAL PROCEDURE

The Factor of Merit M_2, as defined in Clark Jones's paper (6) uses the following measureable properties of a detector, namely: responsivity, minimum detectable energy, time constant, the electrical resistance and the sensitive area.

Dealing with each of the above in order, it may be said that the measurement of the electrical resistance and the sensitive area poses no great difficulty, only in certain cases of high resistance or of unusual envelopes and surfaces of detectors may difficulties be encountered.

1. Responsivity and Responsivity to Noise Ratio

For the measurement of the responsivity, defined as the ratio of the output voltage of a detector with an electrical output to the power incident upon the detector (13), and written as S, a standard radiation signal is the first requirement. To obtain this, use is made of Stefan's Law of radiation from a perfectly black body, that the total emissive power of such a body is proportional to the fourth power of its absolute temperature, the constant of proportionality, σ, being Stefan's constant, and numerically equal to 5.672×10^{-5} ergs cm^{-2}

degrees $^{-4}$ sec^{-1}. The amount of radiation in the form of energy received per second by a perfectly black receiver of area A_2 (the chopper wheel being at a temperature of T_1 °K.) from a radiation of perfectly black body type at temperature T_2° K., where A_1 is the area of the virtual aperture mentioned in chapter III, section (1) is an amount

$$Q = \frac{\sigma(T_2^4 - T_1^4)A_1 A_2}{\pi D^2} \tag{17}$$

where D is the distance of the receiver from the aperture. From (17), using $\sigma = 5.67 \times 10^{-12}$ joules cm.$^{-2}$degree^{-4}sec.$^{-1}$, $T_2 = 500$ ° K., $T_1 = 300$° K., $A_1 = (\pi/4)\ (.3)^2$ cm.^{2} and D = 20 cm., Q/A_2 may be obtained, and will be in units of watts per square centimeter.

A number of standard values are seen to have been used. The black body is heated to a temperature of 500° K., the circular aperture is made to be 3 millimeters in diameter, and the distance used from the aperture to the sensitive layer of the cell is made equal to 20 centimeters. (The cells are worked at the temperatures of liquid oxygen (90° K.), a mixture of dry ice and methyl hydrate (201° K.) and at room temperature (300° K.)). The exact amount of radiation received by any detector placed at the standard distance and centered on the optical axis of the black body system is thus known, making the following assumptions. The source must be a virtual one, and that this is so may be seen by reference to the experiment mentioned in section (6) of this chapter. Secondly, the optical-system must be perfectly aligned; thirdly, the black body must be black and at a temperature of 500° K. Tests have not been performed as to the blackness of the black body, an assumption of 0.9 total black body emission as a minimum conservative estimate seems to be quite justifiable, and certainly not an unreasonable figure. The temperature control is accurate to 0.1° K. in 500° K. (see chapter III, section (2)), and the temperature scale is calibrated by means of an accurate Leeds and Northrup potentiometer, using the calibrated iron constantan thermocouple of the black body. The values of the detector's sensitive area (A_2 in equation (17)) and of A_1 are the least well known, A_1 is known to approximately one per cent, A_2 to within as little as ten per cent.

The incident power must be corrected for modulation; since this is square wave then the root mean square value of the incident power falling on the radiator is equal to one half of the value given in equation (17). The photoconductive cell is also a poor black body receiver for wavelengths greater than the neighbourhood of 3 to 5 microns, which corresponds to a very small percentage of the total power from the black body, of the order of one per cent. Therefore equation (17) must also be corrected by multiplying it by a factor of the order of 1/100. These corrections are applied in the next chapter.

The detector is connected to the 900 cycles per second tuned low noise amplifier by means of a short coaxial cable going directly to the input condenser of the amplifier, bypassing any input connectors, and is shielded, as shown in figure (9) by a brass cylinder. The sensitive layer lies inside the tube J of figure (2), which is blackened inside by a mixture of lamp-black, alcohol and a small trace of shellac.

The amplifier passes a current through the detector (a photoconductive cell) producing a voltage across it of some number of microvolts. The detectors have resistances of the order of kiloohms, and the current used is of the order of microamps. The detector "sees" the black body through a succession of baffles and the aperture, which latter are all at room temperature. A chopper wheel, painted black, cuts the radiation into approximately square bursts at a frequency of 900 cycles per second; each burst of radiation changes the conductivity of the cell by some fraction of the zero frequency change of conductivity from 300° K. to 500° K. (or from the operating cell temperature to 500°K.). This fraction may be taken as unity, and is actually given in chapter V. Thus a signal is generated, at a frequency of 900 cycles per second, and is amplified and rectified by the amplifier to give a reading equivalent to the root mean square value of volts input (or volts output from the detector).

The reading taken is on a microammeter calibrated for each scale to give root mean square volts input from the detector.

The amplifier has the following characteristics:-

1. A bandwidth of 44 cycles per second at minus 3 db.
2. A peak centered at 895 cycles per second on all ranges (see figure (10))
3. A flat response from 890 to 900 cycles per second on all ranges (see figure (10))
4. Linear response on all ranges (see figure (11))
5. A gain of (124) db = 1.5×10^{7} on scale 11
6. An open circuit signal of (1.53) microvolts
7. A shorted input signal of (.22) microvolts
8. No detectable change in output on the top of scale 11 for a variation in mains voltage from 90 to 135 volts
9. Good reproducibility at all times

These considerations make the amplifier ideal for measuring signals from the detectors under study, and mean that the amplifier can be used for detectors with short time constants and of resistance ranges from 50,000 to 1,000,000 ohms, and which have noise appreciable in comparison with the noise value of the amplifier (i.e. with (.22) microvolts).

A change in mains frequency will change the chopper frequency but will not change the output signal because of the flat amplifier response. A change in mains voltage is also seen to have negligible effect on the output. Stray radiation is eliminated by having a tuned amplifier. Linearity of response ensures single-valuedness of output as a function of the input, and speaks for itself. Stability, which is achieved by the use of a great amount of negative feedback, cannot be overemphasised in importance. The fact that a tuned amplifier (or a.c. amplifier) is used eliminates the possibility of drift encountered in d.c. amplifiers, and enables the achievement of a very high gain.

The flat top of the frequency-response curve for the amplifier has been achieved by the use of two tuned stages, each of three tubes, and having equal gain but centered at different frequencies.

The disadvantages are seen to be that the amplifier is a very serious proposition in building, and in achieving low noise. This means great care in soldering joints, difficulty in replacing low noise tubes, careful grounding, and only at one point in the circuit, careful screening between stages and use of screened interstage leads, and the use of expensive and bulky paper and oil condensers rather than electrolytic ones (except for screen decoupling purposes). It is also necessary to use wire-wound resistors in the first stage, which have very low noise of the order of the Johnson noise of the resistor. Avoidance of 60 cycle per second pickup is also of the utmost importance, not only in the amplifier itself, but on the detector too. In the case of the detector, this is accomplished by very careful screening, and care is taken to ensure well-soldered joints on the detector. On the amplifier, the coils used as plate loads are also screened, as are input lead and output for oscilloscope testing and the d.c. output. The bottom of the chassis is tightly covered, and the power supply is kept as remote as possible from the amplifier itself. Any audio-frequency amplifier, such as this one, is also very prone to hum and motorboating, besides which any 900 cycles per second harmonics of the main voltage, unless very carefully kept removed and isolated, will cause oscillations to develop. Oscillations between stages must also be avoided at all costs, by keeping inputs and outputs of stages well removed from each other. The heater voltage windings of the transformer are therefore carefully biased by means of a 150 ohms potentiometer (figure (4)) to give least noise for the amplifier output under shorted input condition of operation. Another problem is microphonics, which at audio-frequencies frequently cause havoc in the readings. These too must be avoided, or measurements made under conditions of least local interruption (preferably at night).

The attenuator itself must be carefully designed so that the grid input of the second stage of amplification is never left floating. For this it is useful to obtain an attenuator which has shorting spacers such that when the amplifier is on no range (between ranges) the grid of the first tube of the second stage (ring of three) is shorted to ground.

For calculating responsivity to noise ratio (R), an accurate determination of the noise voltage needs to be made.

Clark Jones (13) defines R as

$$R \equiv S/N^{\frac{1}{2}} \tag{18}$$

where N denotes the noise power per unit band width. The noise power may be defined as the mean square value of the noise voltage.

In discussing the noise, reference must be made to the following sources of noise. Clark Jones (3) describes these appropriately as:

a) <u>The Radiation Background</u>

This is due to the black body radiation field from the detector itself and from the surroundings. The noise due to this background is called temperature noise (3, 13), and is due to the fluctuations in temperature of the heat detecting element. Since photoconductive cells are not temperature detectors, i.e. do not operate by changes in their temperature caused by the incident radiation, this aspect need not be considered. The photoconductive cell does not operate by changes of its temperature, exchanging energy with its surroundings only by radiation. Thus fluctuations in the output of such a photoconductive cell are due entirely to fluctuations in the radiation, and thus the results quoted by Clark Jones (3) will hold, since he derives these on just such an assumption of fluctuations in the radiation. The results obtained by him hold for detectors whose size is large compared to the wavelengths of the radiation being detected, and which obey Lambert's Law. This radiation background is seen to give rise to a minimum detectable power of the detector, H_m, equal to its noise equivalent power, where for a detector with an emissivity of unity at all frequencies

$$H_m^2 = 4A.\sigma T^4.KT/\tau(\epsilon_u/\epsilon_s^2) \tag{19}$$

where ϵ_s is the absorption coefficient, taken as unity, A is the area of the detector, T is its temperature, τ is its time constant, and σ and k are Stefan's constant and Boltzmann's constant, respectively. The factor $(\epsilon_u/\epsilon_s^2)$ has been taken equal to unity.

b) The Internal Background

This type of background is introduced within the detector itself, and consists of Johnson noise, Current noise and perhaps Semiconductor noise.

c) Signal Noise

Whereas the radiation background is due to the black body noise of the detector itself and of its surroundings, in detecting small changes in steady signals, the statistical variation in the signal may, if large, determine the smallest detectable change. This is of little concern in this paper.

The amplifier is used to measure the noise when a black shutter (figure (2)) is placed across the black body source. The amplifier noise is subtracted from this noise, but is usually too small with the amplifier used to be considered at all compared to the detector noise. The shutter must be cooled or kept cool, and the chopper need not be operated since only the noise in the amplifier bandwidth will appear at the output, and the chopper frequently causes severe microphonics due to vibrations in the system containing the chopper motor and the detector.

A scheme exists therefore, for the experimental determination of the responsivity, the noise, and thus of the responsivity to noise ratio.

2. The Measurement of Time Constants

Figure (12) shows in block schematic form the arrangement of apparatus used to measure time constants of the range which these photoconductive cells under consideration possess.

The multivibrator mentioned in chapter III, section (4) has two outputs. One is applied to the neon 30 tube (III, (3)), the other directly to the Y_1 plates of a double beam oscilloscope. The square wave 120 volts on-off voltage applied to the neon causes infra-red radiation to fall on the photoconductive cell, which is electrostatically screened from the neon by a fine wire mesh. The speed of response of the neon is demonstrated by a procedure outlined in section (5) of this chapter.

The photoconductive cell is attached to the input of the wide band preamplifier, whose output is then displayed on the Y_2 plates of the oscilloscope. The preamplifier is provided with a variable gain control, and has a frequency-response curve covering the range of multivibrator frequencies adequately, as shown in figure (10).

The theory of the measurement of time constants by this method may be outlined as follows. With reference to figure (12), consider a detector receiving a square wave radiation signal of modulation frequency f cycles per second. The half-width t is then seen to be equal to 1/2f. Considering firstly a rise in response of the detector to the signal, figure (10b),

$$B = A\left(1 - e^{-t/\tau}\right) \tag{20}$$

But from figure (10a)

$$\begin{aligned} B &= a - b - c \\ A &= a - c \end{aligned} \tag{21}$$

Therefore

$$a - b - c = (a - c)\left(1 - e^{-t/\tau}\right)$$

which gives

$$b = (a-c)e^{-t/\tau} \tag{22}$$

Similarly, for a fall in response, with reference to figure (10c)

$$c = (a-b)\,e^{-t/\tau} \tag{23}$$

Combining equations (22) and (23)

$$\frac{c}{b} = \frac{a-b}{a-c} \, , \tag{24}$$

which holds for b = c. Thus the response exponential wave is symmetrically placed between the zero and peak amplitudes of the incident square wave, or of the theoretically attainable output wave for τ approaching zero.

A, the observed amplitude, is given by

$$A = (a-b)\left(1-e^{-t/\tau}\right) . \tag{25}$$

Since

$$A = a-b-c$$
$$b = \frac{a\,e^{-t/\tau}}{1+e^{-t/\tau}}$$

and our final result is

$$A = a\,\frac{1 - e^{-t/\tau}}{1 + e^{-t/\tau}} \tag{26}$$

There are two important limiting cases. For low frequencies, where t is very large compared to τ, A becomes equal to a. At high frequencies, τ is very large compared to t, the exponential approaches 1, and A may be written

$$A = at/2\tau . \tag{27}$$

When a plot of the response A versus the half-width t is made, a frequency-response type curve results, which approaches the value a at the high t end, and has the form of a straight line given by equation (27) at the low t end. These lines meet when

$$t = 2\tau = 1/2f \tag{28}$$

where $t = t_o$, the value at the intersection of these lines, and f is the corresponding value of the frequency f_o.

Thus the time constants of detectors may be calculated from the value

$$\tau = t_o/2 \tag{29}$$

or

$$\tau = 1/4f_o . \tag{30}$$

In practice, the preamplifier gain is set so that at low frequencies the Y_1 and Y_2 traces (signal and response) have the same amplitude. A graph with several points at low t values of A versus t is then plotted, t_0 is found from the intersection of the best low t line with the line A = a, from which τ is calculated.

The method outlined is limited only by the range of the multivibrator, the range of the wide band preamplifier, and the range over which the oscilloscope may be triggered. Also, the neon ionisation time constant, if large, may enter in the limitations of this method. In chapter III, section (4), the range of multivibrator half-widths is given as being from 5 microseconds to 10 milliseconds, which means that the theoretical limits over which time constants may be measured is for τ between 2.5 microseconds and 5 milliseconds. In practice, most of the detectors encountered had time constants well within this range.

The neon has a very short time constant (see section (5) below) and does not enter in for purposes of range considerations for the measurements of time constants.

The preamplifier has a range from 0 cycles per second to 1 megacycle per second. The range of the multivibrator, expressed in cycles per second for square waves, is from 50 cycles per second to 100 kilocycles per second, and the range of the preamplifier is, for sinusoidal frequencies from 0 cycles per second to 1 megacycle per second. This gives a factor 10 at either end of the range for conversion between square waves and sinusoidal waves, that is, the preamplifier responds to signals of 5 cycles per second sin waves, and will therefore respond to square waves of 50 cycles per second frequency with little or no distortion; similarly a square wave signal of 100 kilocycles per second, when going into the preamplifier with a flat response out to 1 megacycle per second, will show little or no distortion.

The preamplifier has been designed for photoconductive cells, and supplies them with current, it may also be used in the measurement of bolometer time constants, and, by removing the 1 megohm input to high tension line resistor, and adding more stages if required, the amplifier may be used with high speed thermocouples and other detectors too. Thus a satisfactory method for the measurement of time constants has been described, and the procedure outlined.

3. The Frequency-Response Curves of a Detector

The above method, section (2), for the measurement of time constants conveniently yields curves of relative response versus frequency. If any sources of noise and other radiation exist, small in comparison with the signal achieved, then the curves will intersect the response axis at some positive value for half-widths t equal to zero. This does not alter the time constant when the extraneous radiation or signal is small and steady, also the relative response versus frequency curve may be corrected for this defect, knowing the appropriate time constant. This is so because the slope of the low t straight line is known (and equal to $a'/2\tau$), and since τ is known and a more accurate determination of a may be made using a shutter between the neon and the detector, and subtracting such a signal from a at low frequencies giving a'.

Thus, with these curves, the responsivity to noise ratio $\mathcal{R}$ may be converted to its zero frequency value $\mathcal{R}_0$, since the neon output in watts in the sensitive region of microns of the detector is not presumed to change with its modulation frequency, and the noise of the cells is constant over all chopping frequencies due to the narrow band width of the amplifier.

4. The Measurement of Spectral Response of a Detector.

The detector is placed at the focus of the model 12C Perkin Elmer monochromator (III, (6)), and its output, which is from a high gain 900 cycles per second tuned amplifier, is displayed on a Brown recording potentiometer. The source of radiation is a 1400° K. 900 cycles per second chopped globar source. The wavedrive is set for a certain speed, the Brown recorder is attached, and a spectral curve for each detector is obtained, for any previously chosen slit width.

The same procedure, using the same monochromator settings of slit width, wave drive speed, and a Perkin Elmer thermocouple and its associated d.c. amplifier (III, (6)) is repeated. The graphs are marked at convenient wave drive numbers, which may be converted to wavelengths from a rocksalt calibration curve of wavelength versus wave drive setting obtained for the rocksalt prism used in the monochromator.

The procedure then is to take the ratios of the detector and thermocouple curves at many points (corresponding to many wavelengths), and to draw a graph of relative response of detector to that of the thermocouple, plotted against wavelength in microns; taking the point at long wavelengths at which this relative response has fallen to half of its maximum value as the cut-off point. Such a curve may then be replaced by one having uniform response, equal to maximum response for wavelengths up to the cut-off wavelength, at which the detector wavelength may be conisdered to fall abruptly to zero.

The assumption has been made that the Perkin Elmer thermocouple is a perfect black body radiation detector. That this is so for long wavelengths of the order of 4 microns and higher is known, but for lesser wavelengths corrections may be necessary. Therefore the procedure followed is not altogether satisfactory. However, large errors are not foreseen in this method, and it may be considered as being within the limits of other experimental errors, such as the measurement of sensitive areas and also of time constants.

5. Measurement of the Neon Response

The procedure followed here was to put the neon and a photomultiplier tube of known short time constant inside a light-tight enclosure (to minimise photomultiplier noise). The neon was covered by a brass disc containing a fine pinhole (to prevent flooding of the photomultiplier tube) and was connected to the multivibrator output. It was placed at a variable distance from the photocathode of the photomultiplier, and the photomultiplier output was connected to the input of the preamplifier. The preamplifier output was then put on the Y_2 plates of the oscilloscope, the other output of the multivibrator output was connected to the Y_1 plates of the oscilloscope, as before, the only difference from figure (12) being that the photoconductive cell was replaced by the photomultiplier tube.

The results obtained were, that upon varying the photomultiplier tube to neon tube distance to give a large enough output signal on the oscilloscope to be seen easily, it was found when the two oscilloscope traces were matched in amplitude at the lowest frequencies, they remained so matched to the highest frequency, and the Y_2 (neon tube) trace was seen to remain square to the very highest frequency.

These results clearly indicate the suitability of the neon tube used. They do not indicate what might be the situation at higher frequencies, since a multivibrator going to much higher frequencies (with 120 volts output) than the one used here was not available.

6. Measurement of Signal versus Area of Virtual Source (Intensity of Illumination versus Signal)

The disc with the variable aperture, used with the black body, and labelled C in figure (2), was used here in various positions, and the resulting signals for various detectors were measured. For each detector, a plot of area of source versus output from a certain detector was made for many detectors. These plots were originally parabolic in shape, the signal falling off rapidly with large source areas. The black body was consequently reassembled to give a true virtual source, even when the aperture diameter was 8 millimetres, for the cell sizes in question (see the requirement in chapter III, section (1) for virtual sources). The results showed a straight line graph (figure (III)) for all cells tested and for virtual sources of up to 8 millimeters in diameter.

The conclusions to be drawn from this, neglecting the possibility of pure coincidence, are the following:-

1. The black body system is optically balanced for virtual sources of up to 8 millimeters in diameter, which covers

the standard setting of 3 millimeters diameter, all at 20 cm.

2. The detectors give a signal proportional to incident watts; i.e. volts per watt ratio is independent of power incident on the detector

3. The radiation is black body, since according to Lambert's law a black body is equally bright in all directions (i.e. for all sizes of virtual source), as was found to be the case here.

7. The Measurement of the Sensitive Area and of the Electrical Resistance.

This has already been discussed above at the beginning of this chapter. The sensitive area is defined as the average length of the two outside electrodes times their average separation, expressed in millimeters squared. Since the sensitive layers of most of the cells used are flat this is the sensitive area. For other definitions of area, where the sensitive area is not flat, other prescriptions must be given for the definition of this quantity (3). The area is assumed independent of the temperature of the cell.

The electrical resistance is measured at the temperature of the cell coolant, for coolants such as dry ice or liquid oxygen and also at room temperature. With some detectors, it is found that on cooling, the static temperature equilibrium is reached only after several seconds or even several minutes, and not immediately. This has been taken into consideration both in the measurement of the resistance, and in the measurement of the signal to noise ratio.

Both the resistance and the area have possible errors as great as 10 per cent, the area because of the vague definition of the electrode boundaries, the resistance because of the difficulty of accurate measurement of high resistances, as with an ordinary ohmmeter.

Chapter V

THE RESULTS

Nine photoconductive lead sulphide cells were the main items under study. Four of these were from the Admiralty Research Laboratory (A.R.L.), numbers 73, 119, 123 and 131. Five were British Thomson-Houston Company (B.T.H.) cells. The chemically deposited one which is not in vacuo but is open to the atmosphere is labelled "chemical"; the other four are in vacuo and may be cooled; these are numbered 292, 293, 367 and 395. The A.R.L. cells cannot be cooled, although they are evacuated.

The measurement of the time constants as described in Chapter IV, section (2), was carried out and yielded the results shown in Table I.

TABLE I

Time Constants of Various Lead Sulphide Cells at Three Temperatures (in microseconds)

Cell No.	(300° K)	Cell No.	(300° K)	(200° K)	(90° K)
73	165	292	93	1000	1050
119	135	293	79	292	1750
123	151	367	72	775	980
131	82	395	125	1800	1800
Ch.	79	---	---	----	----

A typical plot for evaluating τ is shown (for cell 131) in figure (14). Most of the measurements, when repeated, showed very similar results; time was allowed for cooled cells to reach a temperature equilibrium. In chapter IV, section (3), mention was made of graphs which showed positive response when extrapolated to zero half width (i.e. to infinite frequency). It has already been pointed out that this will not alter the value of τ. In cases where such a situation existed, it was found on subsequent measurement that normal curves were obtained yielding the same order of value of time constant.

In his second paper, Clark Jones (13) points out that where the response-frequency curve corresponds to the existence of a single time constant, the following relation between frequency and responsivity to noise ratio will hold, namely

$$R(f) = \frac{R_o}{\left(1 + (2\pi f\tau)^2\right)^{\frac{1}{2}}} \quad (31)$$

Assuming that the value of the noise power per unit band width is constant with the frequency f, this relation will hold for the response plotted against frequency. This proposition was checked for several detectors by replacing f in (31) by 1/2h, where h is the halfwidth as in figure (14). In all cases only a very small error was found. This is a good indication that the detectors studied may be characterised by a single time constant.

A very interesting measurement was made of the time constant of a lead selenide cell produced here. This was found to have a time constant of 225 microseconds, and showed the versatility of the time constants apparatus.

The response-frequency curves as mentioned in chapter IV, section (3) are obtained from those used to measure τ by replacing h the half-width by 1/2f (see figure (14)). The factor $(1 + (2\pi f\tau)^2)^{\frac{1}{2}}$ was investigated, being close to unity for some cells with short time constants, and as high as 10.25 for others. The values obtained are shown in Table II.

TABLE II

Frequency Correction Factor for Various Lead Sulphide Cells at Three Temperatures

Cell No.	τ (300° K)	Cell No.	τ (300° K)	τ (200° K)	τ (90° K)
73	1.367	292	1.130	5.736	6.024
119	1.257	293	1.095	1.930	9.940
123	1.314	367	1.080	4.492	5.619
131	1.102	395	1.224	10.25	10.25
Ch.	1.095	---	-----	------	------

The spectral response curves, obtained using the Perkin-Elmer thermocouple as a standard, and described in chapter IV, section (4), yielded curves such as the ones obtained for cell 293 (figure (13)).

The four admiralty cells gave curves indentical in shape, with a strong peak at approximately 2.5 microns. The cut-off (taken at half the maximum) varied from 2.8 to 2.95 microns; the absolute (10^{-5}) cut-off wavelength varied from 3.1 to 3.4 microns.

The B.T.H. evacuated cells have a rather different characteristic shape of spectral response curve. In chapter I, reference was made to the fact that different methods of preparation yielded different spectral curves. Whereas the admiralty cells had a strong maximum at 2.5 microns, the B.T.H. cells and the chemical button cell, all of which are prepared chemically, have two strong peaks; one is at 2.15 microns and the other at from 1.2 to 1.5 microns. It is noted that decreasing the temperature of the layer increases the cut-off for the B.T.H. cells, as shown in figure (13). This effect is not very great, however.

Purely as a matter of interest, two A.R.L. lead telluride cells were also studied. Changing their temperature from 200° K down to 90° K extended the cut-off in one case from 4.65 to 5.45 microns. The other cell gave apparently negative results. The peak of the good cell shifted from 3.8 to 4.6 microns. The ineffective cell had a very large (100%) absorption at 3 microns, and it may have been receiving stray radiation in one case. These results are quoted as a matter of interest only.

Using the 900 cycles per second amplifier (chapter III, section (3)), a series of measurements was performed on all the cells, plotting the variation of the responsivity to noise ratio R (f) as a function of the cell current. R(f) was found to be very constant with the cell current, which was measured by means of a very accurate microammeter. The signal was always found to be linear with the cell current; the noise was also often linear, explaining the constancy of R(f). However, in some cases the noise was parabolic, causing the value of R(f) to be flat only in the middle range of cell currents. A fairly wide range of cell currents may therefore be used. Typical values are from 20 to 100 microamps.

Reproducibility of signal to noise ratios was found to be good, being affected by the cell-to-source distance, and by the centering of the cell layer about the optical axis of the black body system. Care must be taken to avoid heating the shutter, as this increases the noise considerably.

Q, the power incident upon the cell, is obtained from equation (17). The value so obtained is 17.4 microwatts/ cm^2. This value must be halved to give an r.m.s. value for square wave modulation of the power. Another correction must be applied for the spectral response curve of each detector. The cut-off is taken at half the maximum, and the response is assumed to be unity up to this wavelength. The total percentage of Q/A which corresponds to the cut-off wavelength is then calculated. A 500° K black body curve has its peak at 5.8 microns. The radiation up to this value corresponds to 25% of Q/A. Cut-offs encountered are of the order of 3 microns corresponding to approximately 1% of Q/A. These corrections are applied in Table V as shown. Q is also shown. The signal voltage divided by the corrected Q is then shown and gives the estimated value of the responsivity in volts/watt (S), values ranging from 200 to 30,000 volts/watt being encountered. S_o is obtained by using the correction factor shown in equation (31).

The noise equivalent power P_m is obtained by dividing the noise voltage by S_o. To get the noise equivalent power per unit bandwidth, this value must be divided by $\sqrt{\Delta f}$ where Δf = 44 cycles/second, and is the bandwidth of the amplifier used. Table III shows that cells 293 and 367 have a value of this quantity equal to 1.69 and 1.75 ($\times 10^{-13}$ watt) respectively, a value close to the theoretical limit for such cells (4,5).

TABLE III

Noise Equivalent Power per Unit Band Width as a Function of the Cell Temperature (watt x 10^{-13})

Cell No.	(300° K)	(200° K)	(90° K)
292	446	10.8	18.3
293	573	45.5	1.69
367	844	11.4	1.75
395	1270	52.6	22.8

The optimum wavelengths (5) for these B.T.H. cells occur when the cells are at 90° K. with the exception of cell 292, where this occurs at 200° K. . It is suggested that the A.R.L. cells would have better characteristics and properties, if they were built like the B.T.H. cells, which provide for cooling.

Table IV shows the evaluated Factors of Merit. Clark Jones (6) proposes a value of

$$\begin{aligned} M_1 &= 5.52 \times 10^{-12} R_0 A^{\frac{1}{2}} \text{ (at } 300\,°\text{K.)} \\ &= 2.02 \times 10^{-12} R_0 A^{\frac{1}{2}} \text{ (at } 200\,°\text{K.)} \\ &= 0.276 \times 10^{-12} R_0 A^{1/2} \text{ (at } 90\,°\text{K.)} \end{aligned} \qquad (4)$$

for type I detectors, (where the numerical factor depends on the temperature as shown) and proposes

$$M_2 = 6 \times 10^{-12} \left(R_0 A^{\frac{1}{2}} / \tau^{1/2} \right) \qquad (6)$$

for type II detectors; no correction is made to equation (6) for the layer temperature. Equation (6) may also be written

$$M_2 = 3 \times 10^{-12} \left(A^{\frac{1}{2}} / P_m \tau \right) \qquad (6a)$$

as in chapter II, section (1). A derivation is given by Clark Jones (13). There is a difference between these two expressions of a factor 10^{-2}, as seen in Table IV. Since the low frequency cut-off of the detectors has not been considered, this might be thought to be the cause. However, the percentage of the black body radiation below 1 micron is only 0.0001% of the whole. The difference between this value and 1% (corresponding to the long wavelength cut-off at 2.9 microns) is negligible compared to 1%.

The proposed reason is as follows. Clark Jones (13) prescribes adjusting the frequency response curve of the amplifier so that the noise power per unit band width is constant at all frequencies, whereas in this research this has not been done (chapter II, section (1)). From this equalised amplifier, a frequency response curve for the detector is to be drawn from which the time constant is to be determined.

The noise equivalent power for the detector is to be determined with the amplifier now governed by a high frequency RC cut-off which is added, where RC is equal to the time constant.

Since this has not been done, a constant factor of approximately 10^2 has been neglected throughout, and equations (6) and (6a) differ by this amount. The values of τ and P_m as predicted by Clark Jones (13) will also have their product differing from the product obtained by this factor.

Equation (7), assuming that the only noise is Johnson noise, gives a Factor of Merit

$$\begin{aligned} M_2 &= 0.0468\, S_o (A/R\tau)^{\frac{1}{2}} \text{ (at 300°K.)} \\ &= 0.0573\, S_o (A/R\tau)^{\frac{1}{2}} \text{ (at 200°K.)} \\ &= 0.0858\, S_o (A/R\tau)^{\frac{1}{2}} \text{ (at 90°K.)} \end{aligned} \qquad (7)$$

Equation (8) given in chapter II, section (1)

$$M_z = 6\times10^{-12}(A\Delta f/\tau)^{\frac{1}{2}}/P_o \tag{8}$$

may easily be shown to be identical with equation (6).

In chapter II, section (2), Daly and Sutherland's proposed Figure of Merit has been modified by the author to give

$$M_z = A^{\frac{1}{2}}\sigma/\sqrt{\mu\tau} \tag{12}$$

This may also be shown to be equivalent to equations (6) and (8). These results are shown in Table IV. Table V shows the values of Q, P_m, R etc..

TABLE IV

The Factors of Merit of Lead Sulphide Photoconductive Cells

300° K.	M_2	M_2	M_2	M_2	M_2	M_1
Cell No.	(6a) 10^4	(6)	(8)	(12) 10^{13}	(7)	(4)
73	2.26	421	420	7	678	1.03
119	1.73	323	322	5.3	525	0.65
123	1.68	316	318	5.25	545	0.706
131	2.34	382	384	6.38	825	0.533
292	.346	59.3	59.2	.986	83	0.0895
293	.326	52.9	52.6	.877	121	0.071
367	.231	36.4	36.4	.606	67	0.046
395	.0849	15.5	15.4	.256	25.3	0.0293
Ch.	.271	43.6	44	.733	60.3	0.0590
200° K.						
292	1.33	146	146	2.43	257	1.35
293	1.11	195	196	3.26	170	.328
367	1.59	199	198	3.3	230	1.26
395	.141	11.7	11.7	.195	28.6	.259
90° K.						
292	.747	80.8	80.6	1.34	212	.109
293	7.46	624	626	10.4	276	1.8
367	8.2	912	912	15.2	550	1.11
395	.326	26.9	27.1	.451	128	.0815

TABLE V

Showing Corrected Values Needed to Calculate M_2 for the Lead Sulphide Cells

Cell No.	τ μsec	$R\times10^3$ ohms	A mm^2	S/N	Cutoff μ	% Q/A	Correct $Q/A\times10^{-8}$ watt/cm^2	N μv	$Q\times10^{-8}$ watt	S μv	$S\times10^4$ V/watt	$P_m\times10^{11}$ V/watt	$P_m/\sqrt{\Delta f}$ watt$\times10^{11}$	freq. Corrn.
300° K.														
73	165	400	24	550	2.9	0.95	8.26	0.87	1.98	480	3.32	2.63	0.396	1.367
119	135	130	24	440	2.95	1.1	9.58	0.5	2.30	220	1.20	4.17	0.629	1.257
123	151	540	24	312	2.8	0.75	6.53	1.08	1.57	337	2.82	3.82	0.576	1.314
131	82	560	24	335	2.86	0.9	7.83	1.37	1.88	458	2.70	5.09	0.767	1.102
292	93	190	22.8	23.8	2.58	0.4	3.48	0.52	0.794	124	0.176	29.6	4.46	1.130
293	79	155	24	17.5	2.55	0.35	3.04	0.77	0.730	13.5	0.202	38.0	5.73	1.095
367	72	212	22	10.1	2.52	0.32	2.78	0.72	0.612	7.3	0.128	56.0	8.44	1.080
395	125	25	20	7.6	2.62	0.45	3.92	0.22	0.784	1.68	0.0261	84.1	12.7	1.224
Ch	79	380	25	14	2.53	0.33	2.87	0.72	0.717	10.1	0.154	46.6	7.02	1.095
200° K.														
292	1000	3500	22.8	202	2.6	0.42	3.65	2.28	0.832	460	31.8	0.718	0.108	5.736
293	292	3500	24	150	2.6	0.42	3.65	1.13	0.876	170	3.74	3.02	0.455	1.930
367	775	1550	22	198	2.55	0.35	3.04	1.01	0.669	200	13.4	0.755	0.114	4.492
395	1800	80	20	20.4	2.6	0.42	3.65	0.48	0.730	9.8	1.38	3.49	0.526	10.25

TABLE V
continued

90° K.														
292	1050	3500	22.8	123	2.62	0.45	3.92	2.28	0.895	280	18.9	1.21	0.183	6.024
293	1750	10000	24	210	2.8	0.75	6.53	0.65	0.157	137	86.6	0.0749	0.0169	9.94
367	980	5000	22	220	2.8	0.75	6.53	0.65	0.144	143	55.8	0.116	0.0175	5.619
395	1800	270	20	50.3	2.62	0.45	3.92	1.15	0.784	58	7.6	1.51	0.228	10.25

Chapter VI

DISCUSSION

Table IV leads to the conclusion that the best detector is cell 367 at 90° K. Other useful detectors are cell 293 at 90° K., the A.R.L. cells, and cells 292, 293 and 367 at 200° K.. The chemical cell and cell 395 (at all three temperatures), and the rest of the B.T.H. cells at room temperature show the poorest Factors of Merit. Such conclusions are drawn from all columns except those marked (4) and (7), which do not show the close agreement of the other columns.

Both M_2 and M_1 are shown for purposes of comparison. Column (7), by its disagreement, shows that the limiting noise for photoconductive cells is not Johnson noise. Clark Jones, in his first paper (3), points out that for detectors which are cooled by radiation, as these are, the temperature fluctuations would be zero if there were no fluctuations in the transfer of heat by the radiation. He concludes that output fluctuations in this case are due to radiation fluctuations. He gives as the mean square fluctuation in power per unit frequency bandwidth

$$16A\cdot\sigma T^4\cdot kT. \qquad (32)$$

For the size of detector used here this gives 7.36 x 10^{-13} watt, which is of the order obtained in many cases (see Table IV). See also chapter I, where it was quoted (4,5) that the measured noise approaches the limit imposed by radiation fluctuations.

It is proposed that the detectors studied be classified as type II detectors (13). This is because R_0 is not independent of τ, as for type I detectors. However, a definite statement on classification cannot be made, since k_2 of equation (1) corresponding to M_2 is found to vary with temperature. If M_2 remained constant with temperature for the B.T.H. cells, R_0 could be plotted against $\sqrt{\tau}$, a straight line establishing that the type number is II. This follows from equation (33) from the second paper by Clark Jones (13)

$$R_0 = k_n \tau^{\frac{1}{2}(n-1)} / 2A^{\frac{1}{2}} . \tag{33}$$

Since k_2 is not a constant, and is derived from equation (33), this equation can give no clue as to the proper value of n. Another reason for taking n as 2 is the good agreement between the first four columns of Table IV.

M_1 is seen to behave properly, never greatly exceeding unity. M_2 on the other hand is much greater than unity, showing that Havens's limit will have to be revised. It is not a fundamental limit, and is seen to hold for other types of detector (chapter II, section (1)).

The B.T.H. cells are ideal in this work since they can be used at three different temperatures, and since their areas and other physical properties are unchanged by cooling. For this reason, it had been hoped a definite statement on type number could have been made.

The A.R.L. cells could certainly be much improved if they could be cooled. This is indicated because of the improvement cooling makes on the B.T.H. cells (Tables III and IV).

Photoconductive cells have the great advantage over most temperature detectors that they have a selective spectral response, so that used as detectors in the one to five micron region, their ultimate sensitivity is attainable. In the infra red above five microns, they are no better than thermocouples or bolometers for the same reason.

BIBLIOGRAPHY

1. Simpson, O., and Sutherland, G.B.B.M., Science, 115, 1 (1952).

2. Sosnowski, L., Starkiewicz, J., and Simpson, O. Nature, 159, 818 (1947).

3. Jones, R. C., J. Optical Soc. Am., 37, 879 (1947).

4. Fellgett, P. B., J. Optical Soc. Am., 39, 970 (1949).

5. Moss, T. S., J. Optical Soc. Am., 40, 603 (1950).

6. Jones, R. C., J. Optical Soc. Am., 39, 344 (1949).

7. Daly, E. F., and Sutherland, G.B.B.M., Proc. Phys. Soc., London, A, 62, 205 (1949).

8. Sutherland, G.B.B.M., Blackwell, D. E., and Fellgett, P.B., Nature, 158, 873 (1946).

9. Daly, E. F., and Sutherland, G.B.B.M. Proc. Phys. Soc., London, 59, 77 (1946).

10. Bullock, B. W., and Silverman, S., J. Optical Soc. Am., 40, 608 (1950).

11. Kuiper, G. P., Rept. Progress Phys., 13, 247 (1950).

12. Lee, E., and Parker, R. C., Nature, 158, 518 (1946).

13. Jones, R. C., J. Optical Soc. Am., 39, 327 (1949).

14. Havens, R. J., J. Optical Soc. Am., 39, 327 (1949).

15. Hornig, D. F., and O'Keefe, J., Rev. Sci. Inst., 18, 474, (1947).

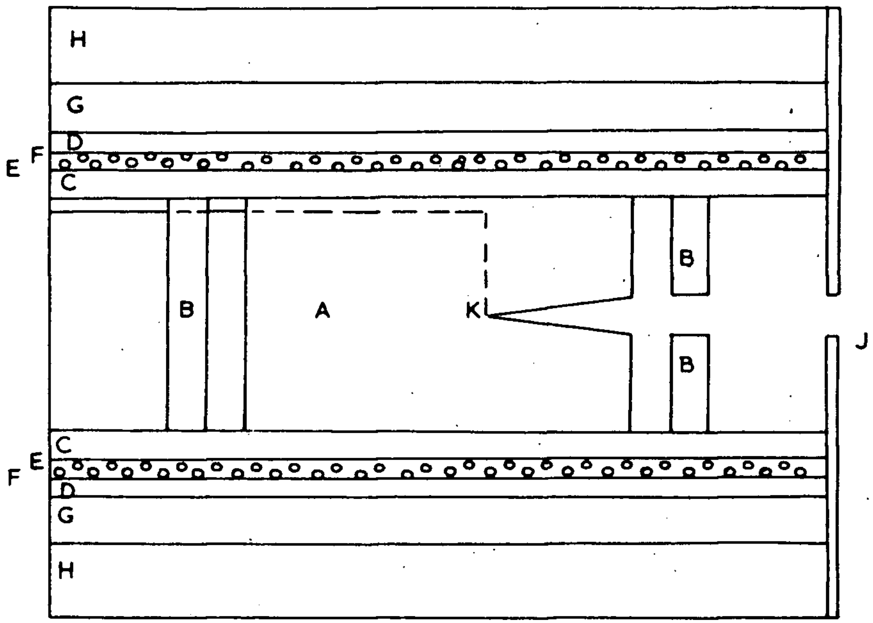
16. Roberts, J. K., Heat and Thermodynamics, London, Blackie, (1945).

17 Brown, D.A.H., J. Sci. Inst., 29, 292 (1952).

18 Brown, D.A.H., T. R. E. Memo., 330.

19 Elmore, W. C., and Sands, M., Electronics, New York, McGraw Hill (1949).

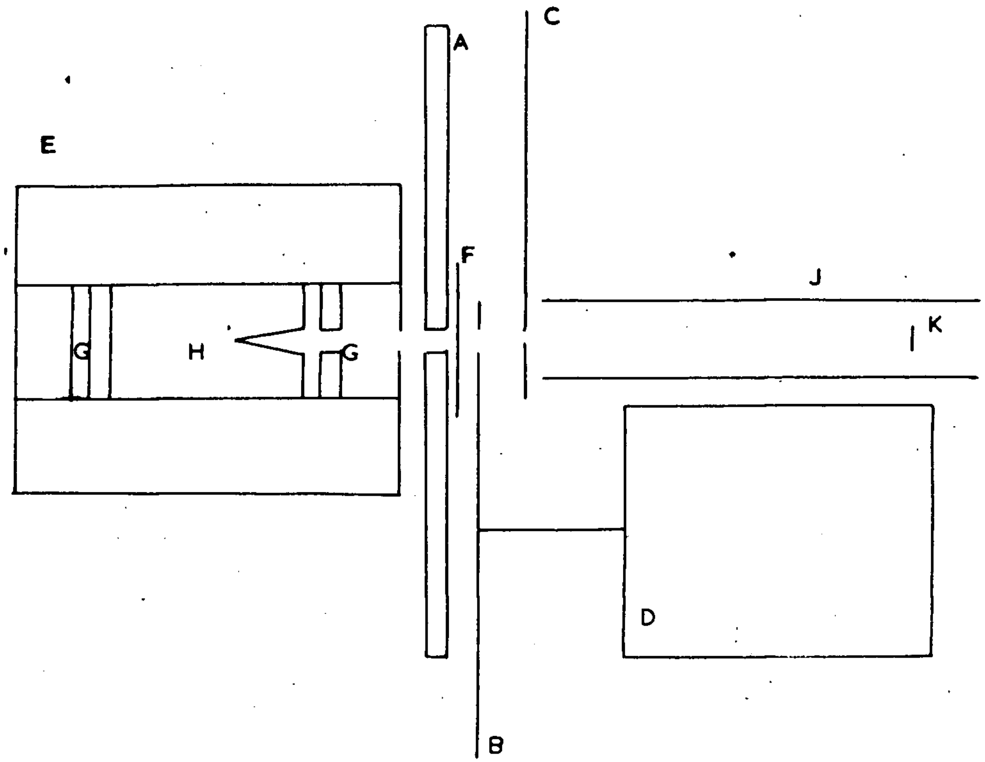
THE BLACK BODY RADIATOR



A STEEL CYLINDER
B BRASS DISCS
C ALUNDUM CYLINDER
D ASBESTOS SHEETING
E NICHROME HEATER
F RESISTANCE THERMOMETER
G ROCK WOOL
H WOOD CONTAINER
J ALUMINUM
K THERMOCOUPLE

FIGURE 1

THE OPTICAL SYSTEM OF
THE BLACK BODY RADIATOR



A ASBESTOS SHIELD BETWEEN ALUMINUM PLATES

B CHOPPER

C APERTURE DISC

D CHOPPER MOTOR

E BLACK BODY

F SLIDING SHUTTER

G BRASS DISC

K SENSITIVE LAYER OF CELL

H STEEL CYLINDER

SCALE I INCH EQUALS 10 CMS.

FIGURE 2

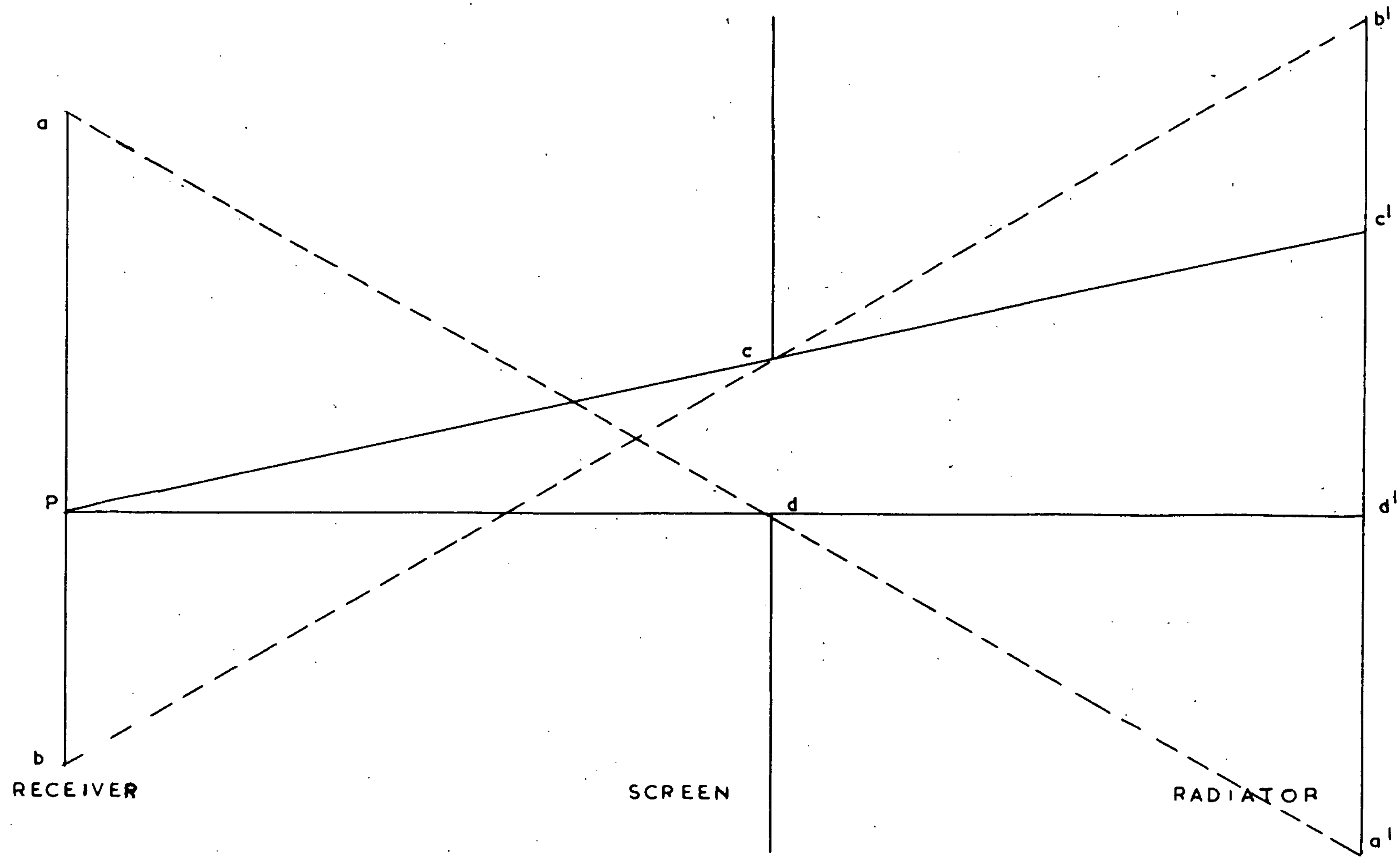


FIGURE 3

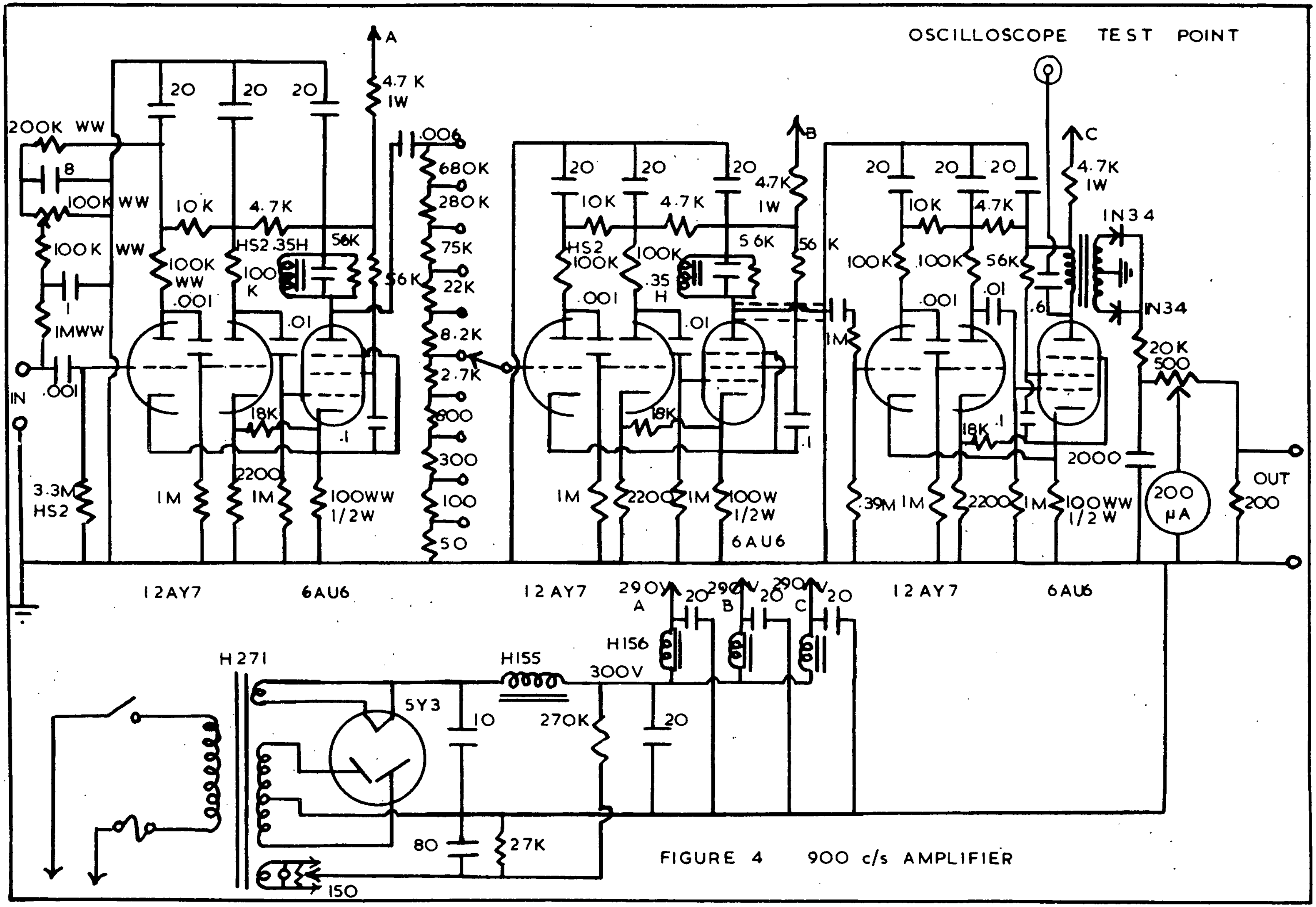


FIGURE 4 900 c/s AMPLIFIER

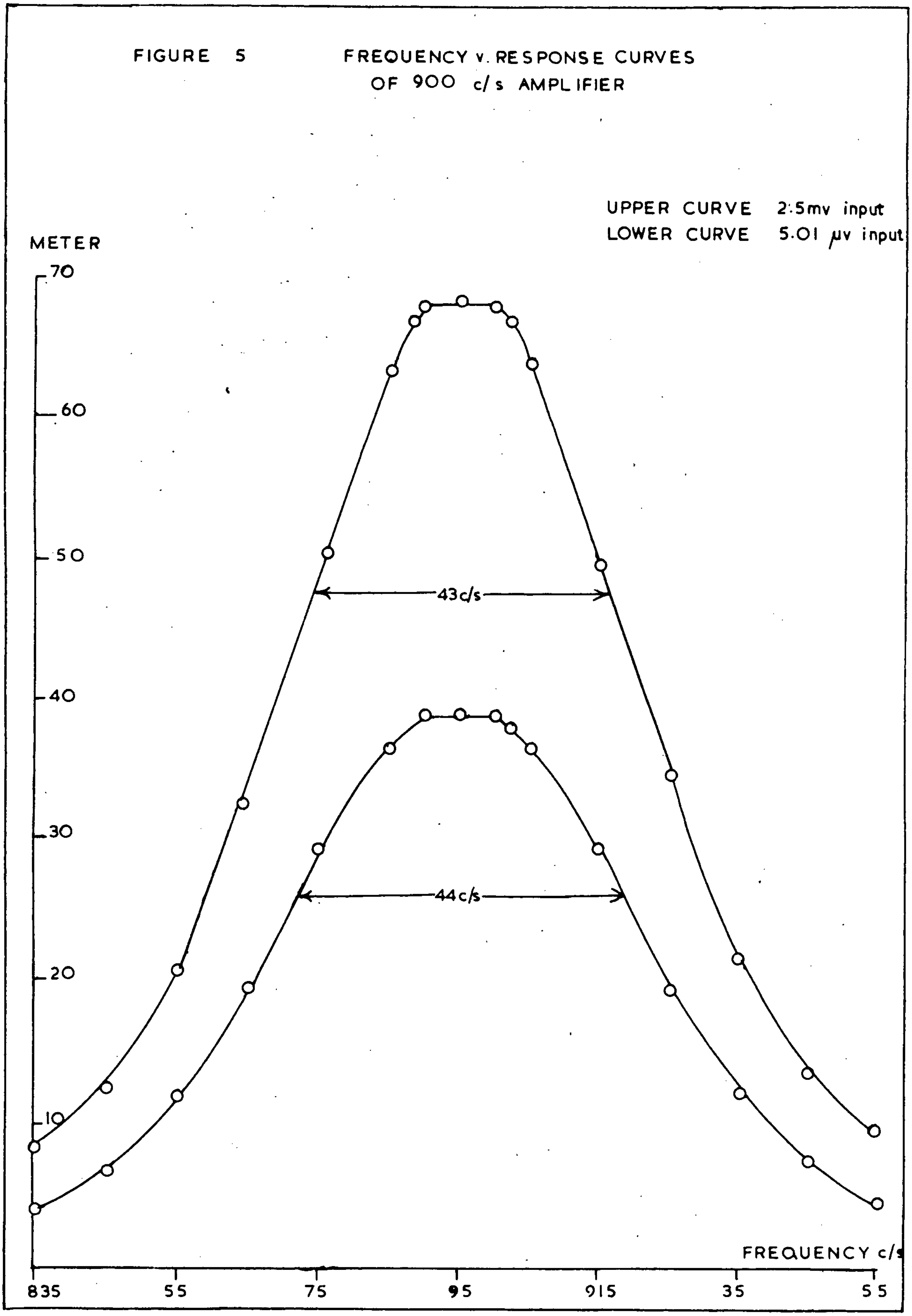


FIGURE 5 FREQUENCY v. RESPONSE CURVES OF 900 c/s AMPLIFIER
UPPER CURVE 2·5mv input
LOWER CURVE 5·01 μv input
METER
70
60
50
40
30
20
10
43c/s
44c/s
FREQUENCY c/s
835
55
75
95
915
35
55

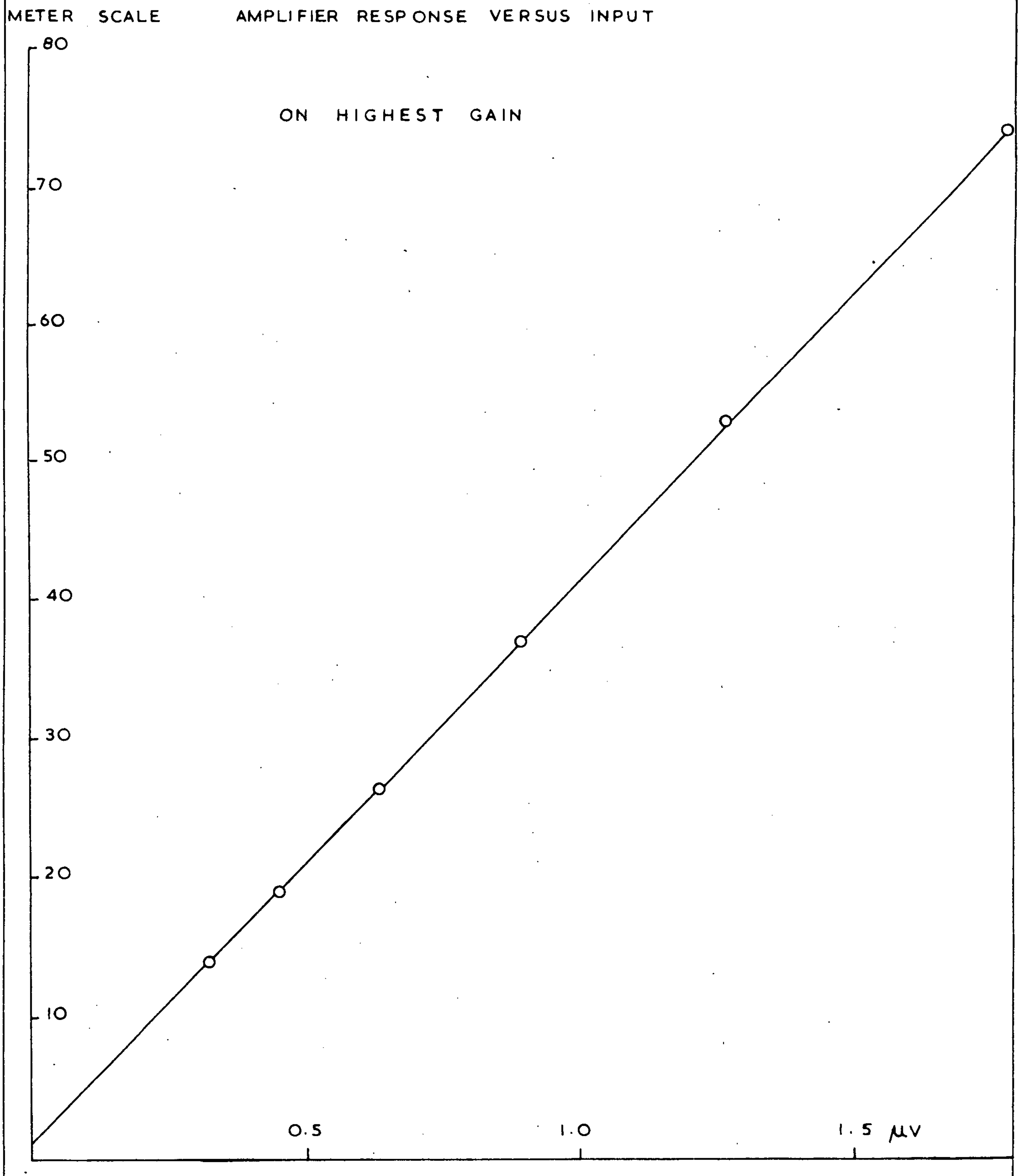

METER SCALE
AMPLIFIER RESPONSE VERSUS INPUT
ON HIGHEST GAIN
80
70
60
50
40
30
20
10
0.5
1.0
1.5 µV

FIGURE 6

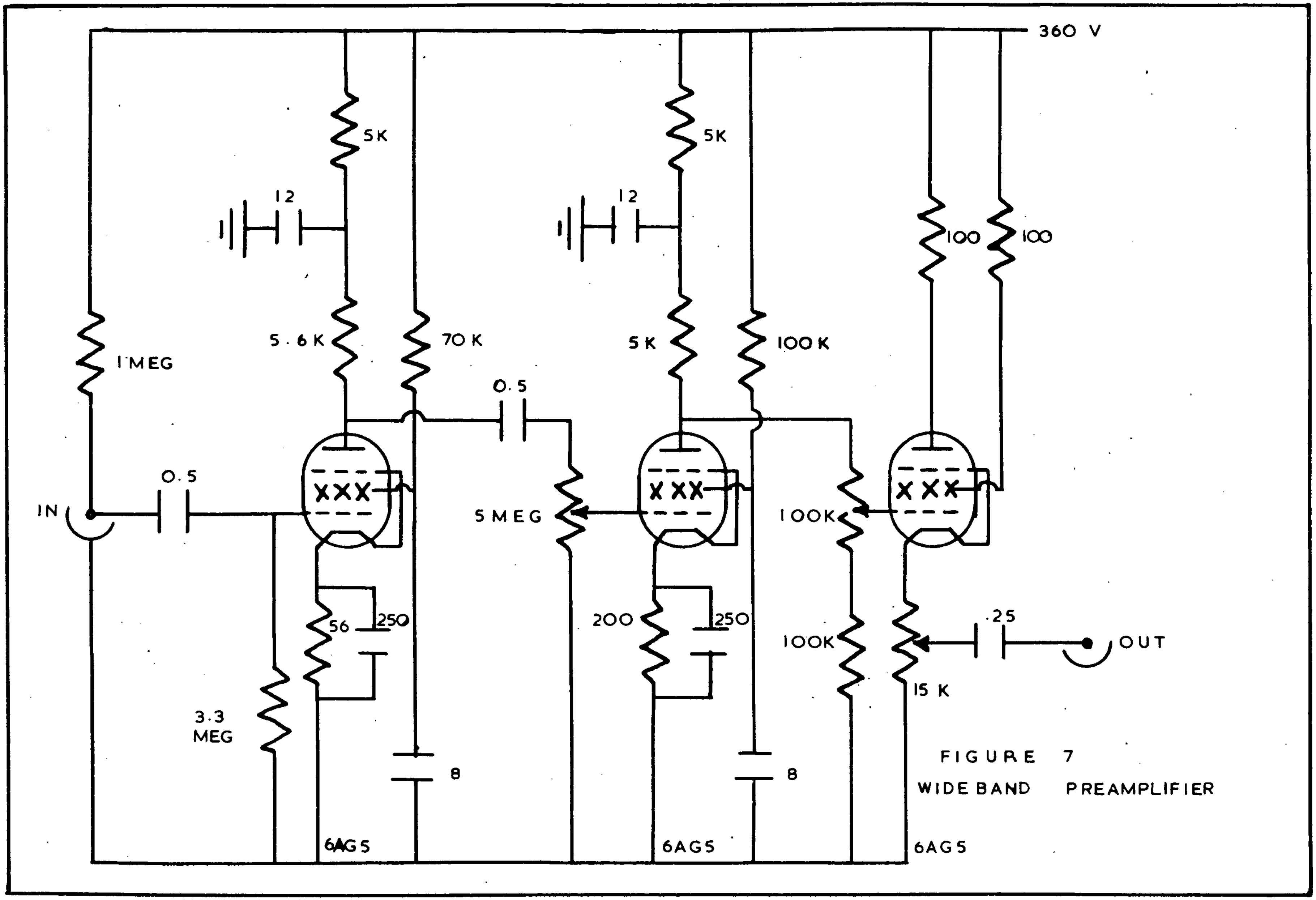


FIGURE 7
WIDE BAND PREAMPLIFIER

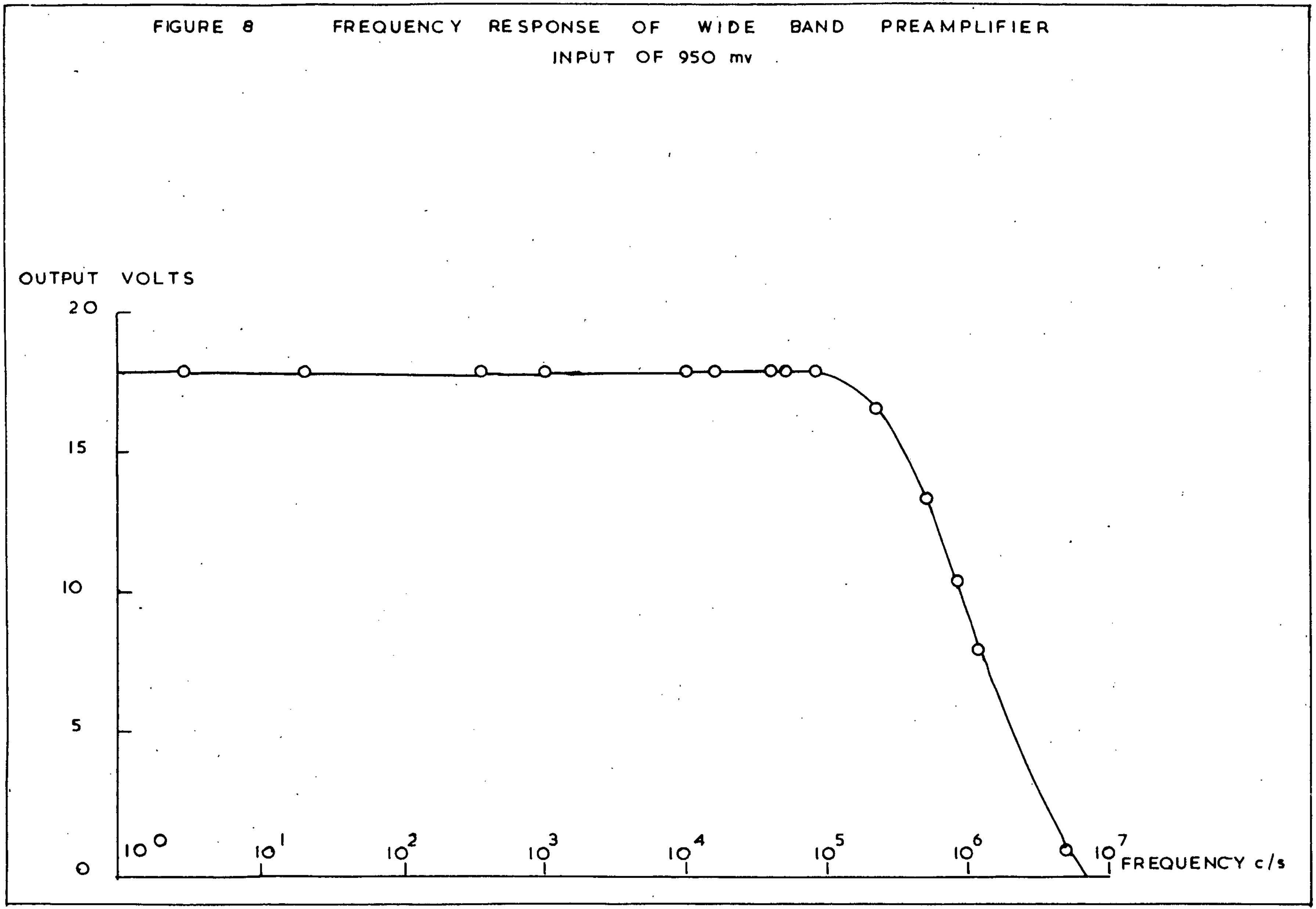


FIGURE 8 FREQUENCY RESPONSE OF WIDE BAND PREAMPLIFIER
INPUT OF 950 mv
OUTPUT VOLTS
20
15
10
5
0
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
FREQUENCY c/s

Pb-S CELL MOUNTING

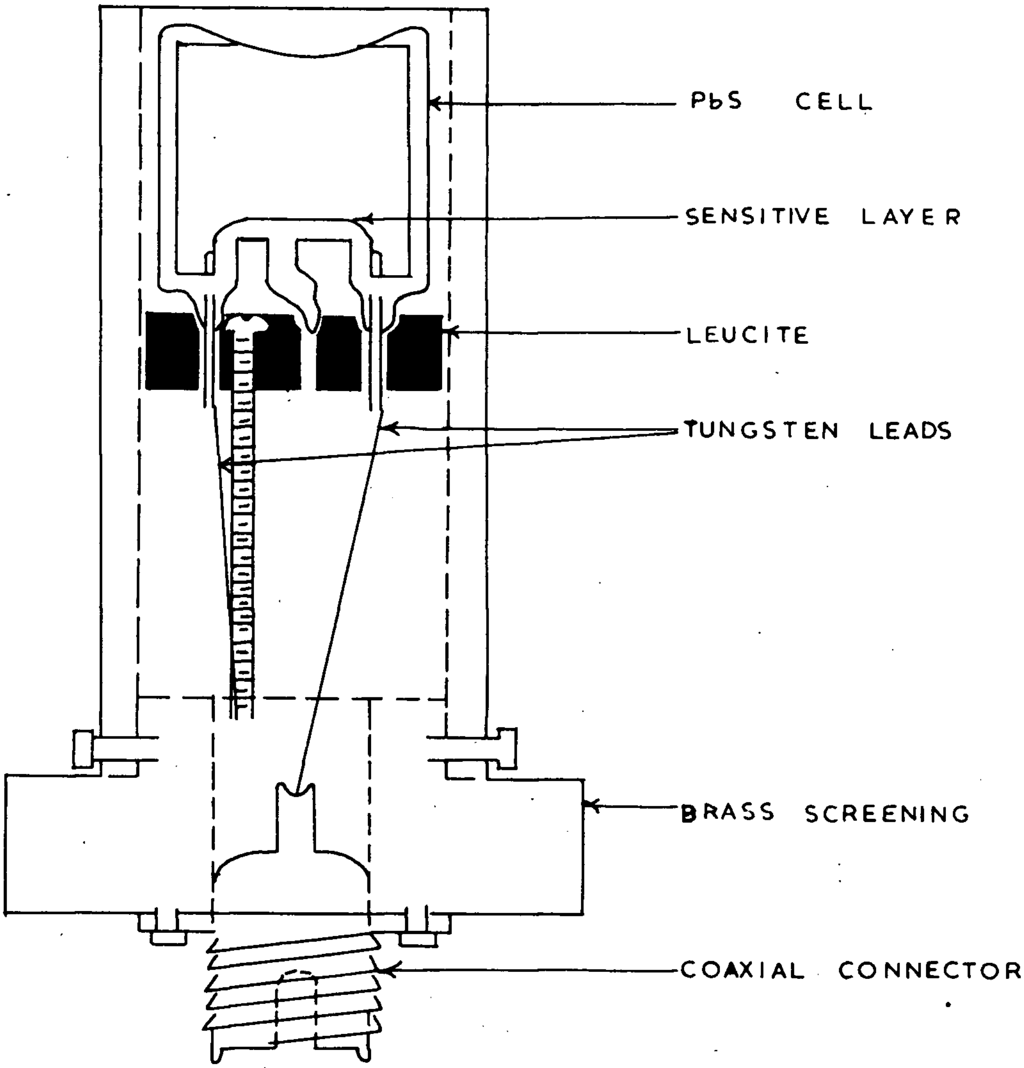


FIGURE 9

THE MEASUREMENT OF TIME CONSTANTS

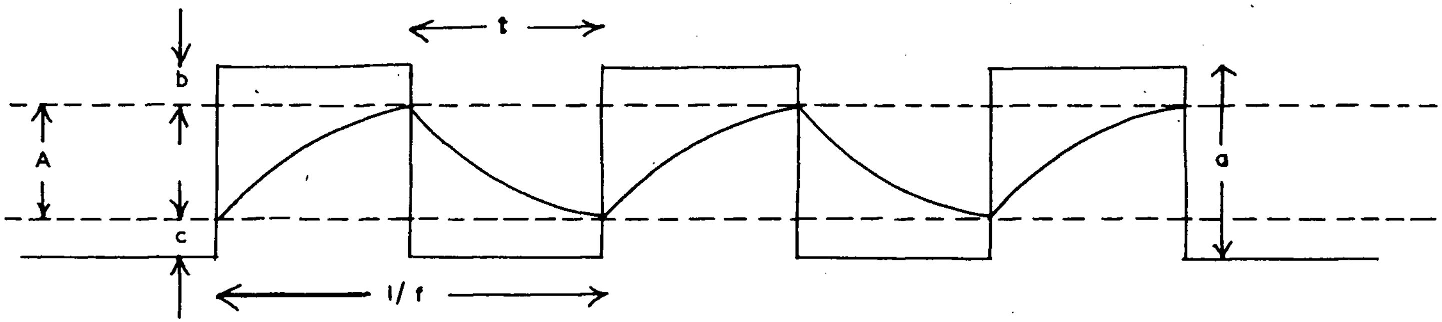


FIGURE A

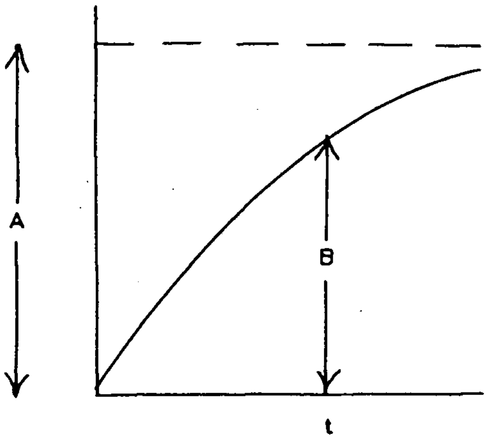


FIGURE B

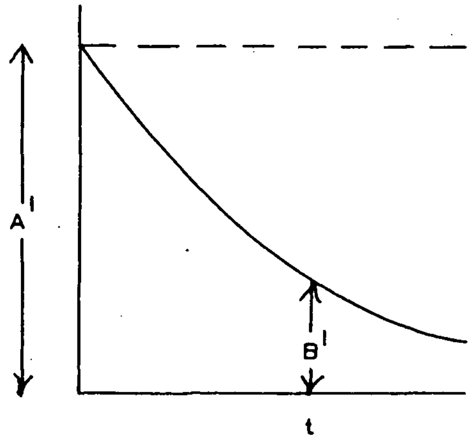


FIGURE C

FIGURE 10

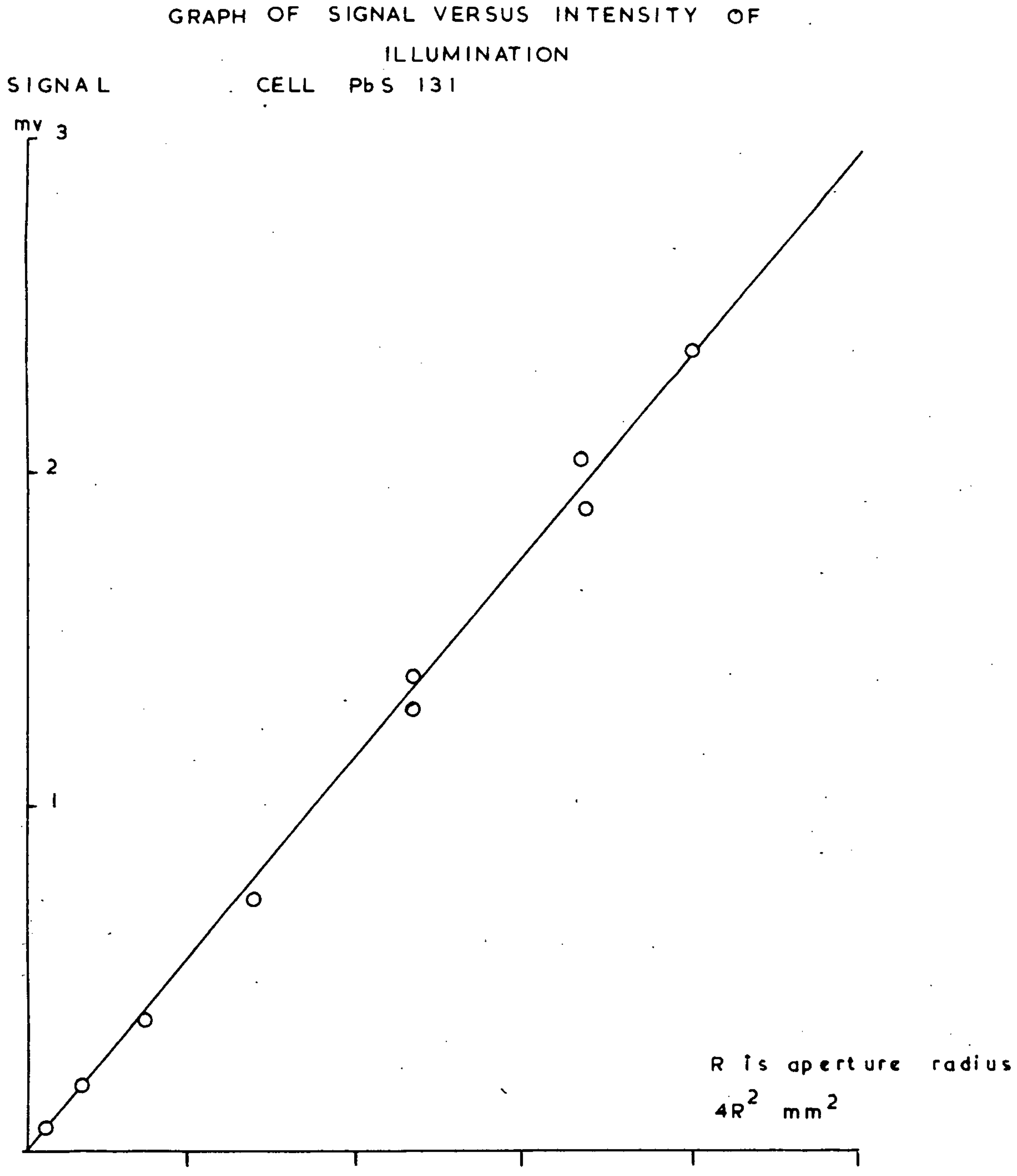

GRAPH OF SIGNAL VERSUS INTENSITY OF ILLUMINATION
SIGNAL
CELL PbS 131
mv
3
2
1
R is aperture radius
4R² mm²
10
20
30
40
50

FIGURE 11

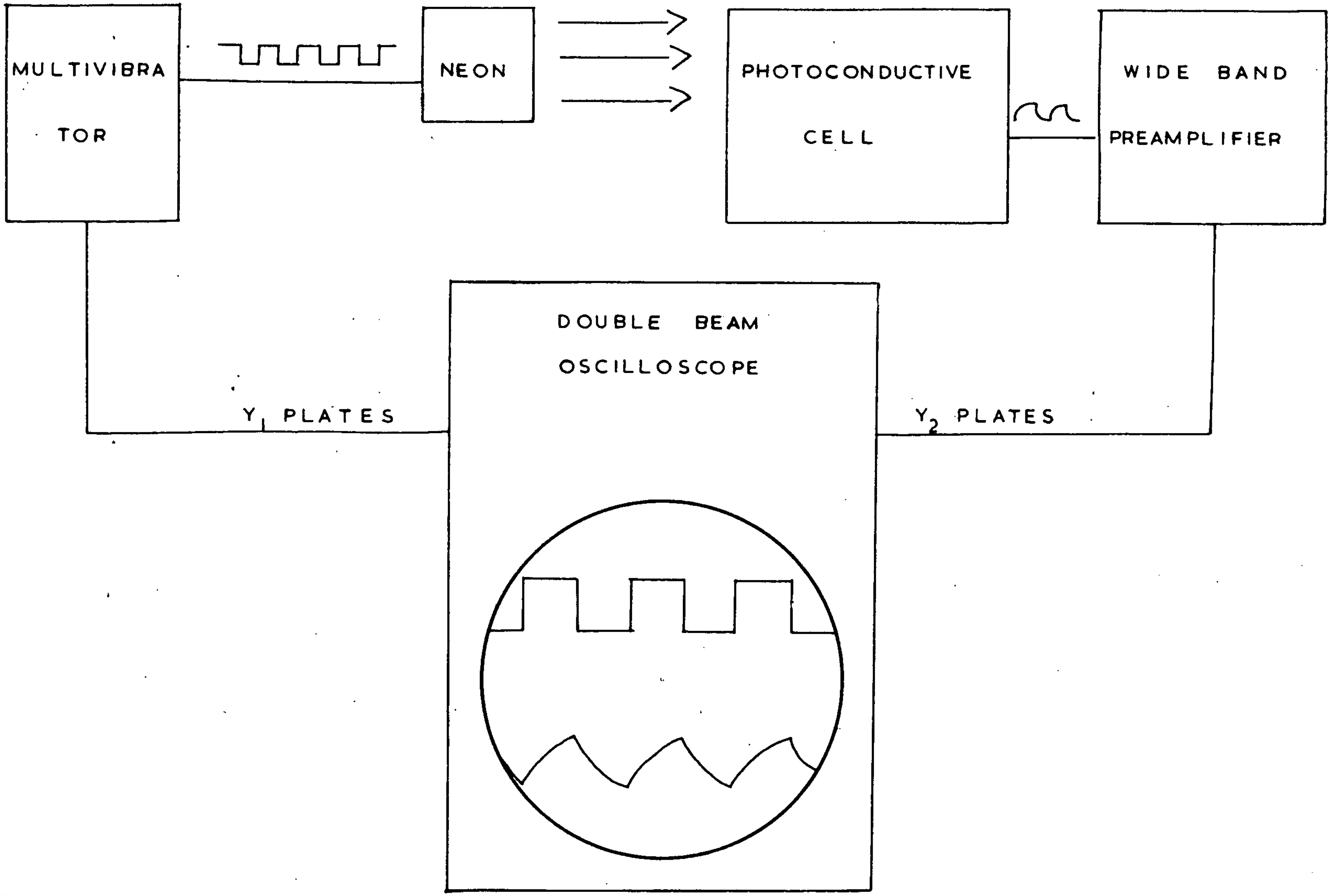
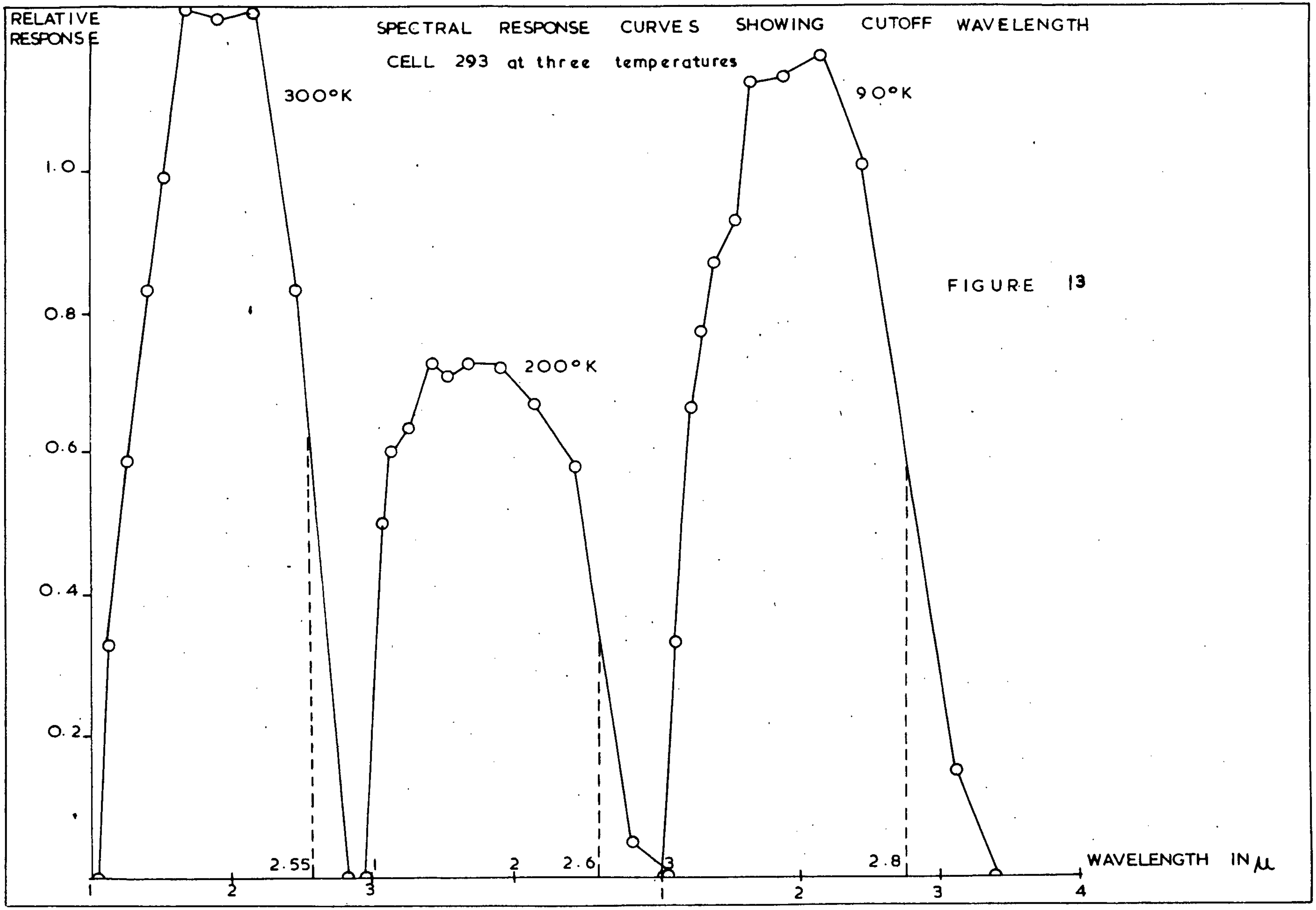

MULTIVIBRATOR
NEON
PHOTOCONDUCTIVE CELL
WIDE BAND PREAMPLIFIER
DOUBLE BEAM OSCILLOSCOPE
Y_1 PLATES
Y_2 PLATES

FIGURE 12



RELATIVE RESPONSE
SPECTRAL RESPONSE CURVES SHOWING CUTOFF WAVELENGTH
CELL 293 at three temperatures
300°K
200°K
90°K
1.0
0.8
0.6
0.4
0.2
2.55
2.6
2.8
1
2
3
4
WAVELENGTH IN μ

FIGURE 13

RESPONSE VERSUS MODULATION FREQUENCY HALFWIDTH
CELL 131

FIGURE 14