COMMONWEALTH OF AUSTRALIA
DEPARTMENT OF NATIONAL DEVELOPMENT
BUREAU OF MINERAL RESOURCES,
GEOLOGY AND GEOPHYSICS

RECORDS 1953 No. 49

NOTES ON RADIATION MEASURING INSTRUMENTS

by

J. DALY

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1. INTRODUCTION

Widespread use of radio-active tracer elements in medicine, and the increased interest in the search for radio-active minerals, have led to the development of a variety of instruments for the detection of ionising radiations, and their general use by scientists who may have had no training in physics or electronics. While these instruments present a great diversity in appearance, the functioning depends on general principles, which apply to all such equipment. The aim of these notes is to present these general principles in a simple form. For details of design, which are often highly complex, and require great skill and experience, reference should be made to the works listed in the bibliography.

It is hoped that these notes will be useful to two classes of people. In the first place, medical men or geologists, while not possessing the training in physics necessary to appreciate all the factors involved in the design of an instrument, can use the instrument more intelligently if they are acquainted with the fundamental principles on which it works. Secondly, it is found that technicians, even after much experience in radio servicing, are often completely at a loss when endeavouring to trace and rectify a fault in an instrument of this type. The main reason for this is that many of the circuits used depend for their functioning on the non-linear property of the characteristics of the valves used. As the non-linear portion of the characteristic is usually carefully avoided when a valve is used in a radio set, the serviceman finds that a valve, with the normal radio use of which he is possibly well acquainted, is working in a manner which is quite unfamiliar to him. If, however, he knows the general function of the various parts of the circuit, the location of faults is usually a fairly simple matter.

2. THE DETECTION OF RADIATION

Electrical methods of radiation detection, which are the only ones to be considered here, all depend on the ionising effects of the radiation. The radiation enters a vessel containing a gas filling at a suitable pressure, and two electrodes between which a potential difference is established. The radiation ionises the gas filling and the positive and negative ions are attracted to opposite electrodes by electrostatic attraction. Each ionising particle thus causes a voltage pulse between the electrodes, which is registered by the methods described later. When a continuous flux of radiation is entering the vessel, the passage of ions causes a steady current between the electrodes and this may be measured.

The behaviour of detectors of this type is extremely complex. For detailed information the standard works cited in the bibliography should be consulted. However, for the present purpose, only the effect of increasing voltage is of interest, and this can be described simply in general terms.

Suppose a single particle enters the gas filling. It produces ions, the number of which depends on the charge and velocity of the incident particle. When the voltage between the electrodes is low, some ion pairs are able to recombine so that all the ions are not collected at the electrodes. As the voltage is increased a value is reached at which no recombination takes place, and all ions are collected.

This is called the saturation voltage. This condition persists over a certain voltage range, which is called the "ionisation chamber region." A detector working at a voltage within this region is called an ionisation chamber, and produces pulses whose amplitude is dependent only on the energy of the original particles. The amplitude of the pulses is of the order of microvolts.

As the voltage is still further increased, the ions in their passage to the electrodes have sufficient energy to ionise atoms with which they collide. These secondary ions are also attracted to the electrodes with the net result that the pulse collected is greater than that which would be obtained by collecting only the total ionisation due to the original particle. This process is known as "gas amplification." The amount of amplification depends on the voltage applied.

A gas amplification of 10^2 to 10^3 is commonly employed. Higher amplification is possible, but is not generally used, for the following reasons :-

(i) As the gas amplification increases, the amplitude of the output pulses tends to level out so that proportionality with the energy of the original ionising radiation is gradually lost.

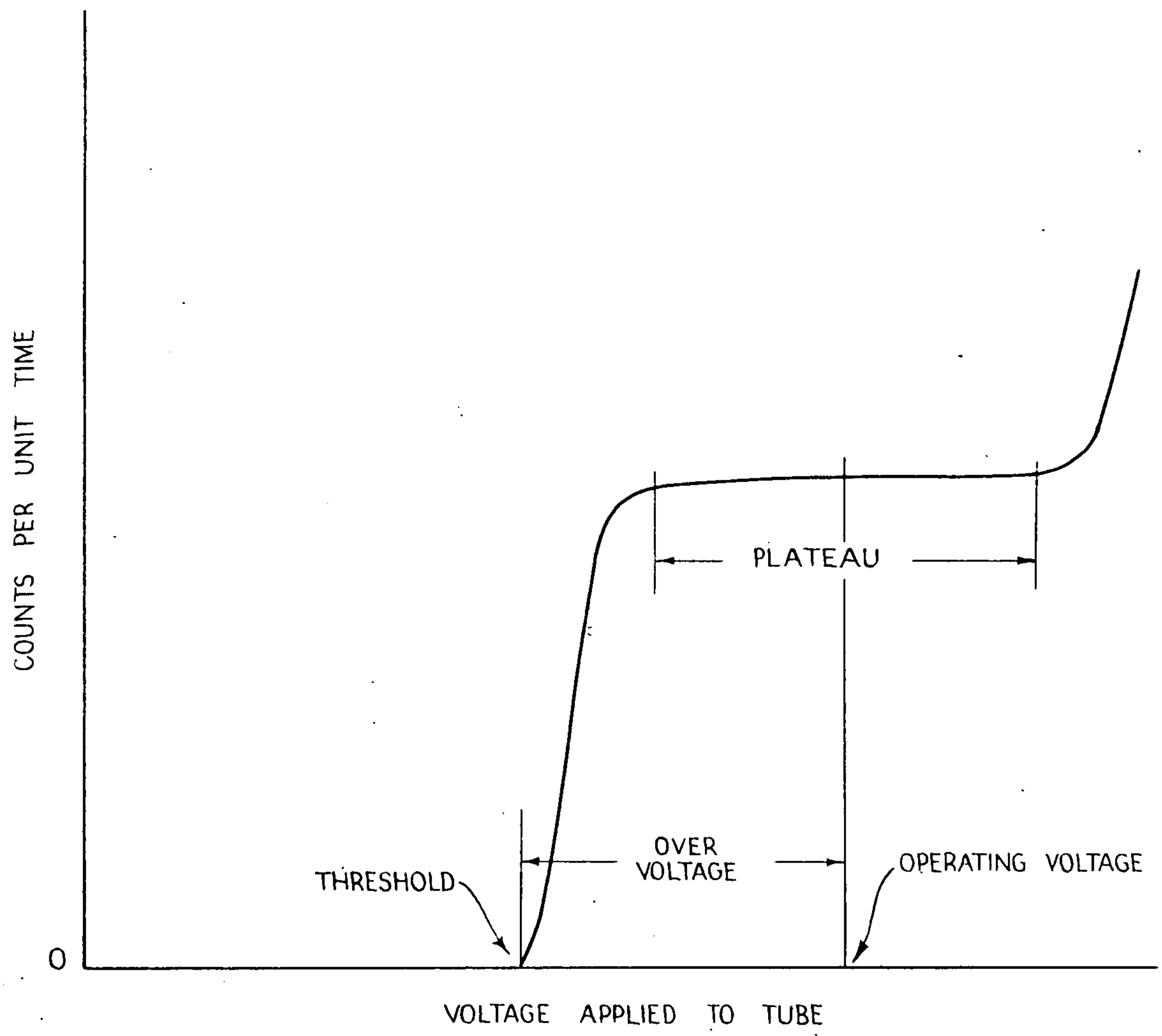
(ii) At high gas amplification, the dependence of the amplification on the applied voltage becomes more and more critical. This imposes severe demands on the stability of the applied voltage.

A detector using a gas amplification of up to 10^3 is called a "proportional counter," and provides output pulses whose amplitude may be of the order of millivolts.

At still higher voltages, ionisation by collision and similar processes becomes the main factor in the functioning of the detector. The original ionising particle acts merely as a trigger to set the process going, the final result being a gas discharge between the electrodes. Assuming that this discharge is stopped after a very short time, by one of the methods mentioned below, it produces a pulse at the electrodes, the amplitude of which may be 1 volt or higher. The amplitude of the pulse is determined by the voltage applied to the tube, and is quite independent of the energy of the ionising radiation. Proportionality is therefore entirely lost. A detector operating under these conditions is known as a Geiger tube, and the voltage range over which the tube operates is called the "Geiger region."

The behaviour of a Geiger tube, exposed to a steady flux of ionising radiation, working into a circuit capable of recording pulses of amplitude of the order of a volt, is shown in Plate 1. Until the voltage reaches a certain minimum value, known as the "threshold," no counts are recorded. As the voltage increases above the threshold value, the count rate increases rapidly to a value which is maintained relatively constant over a range of voltage, known as the "plateau." The length of the plateau is generally 100-200 volts. Further increase of voltage causes a rapid and erratic increase in count rate, and finally the complete breakdown of the tube. Geiger tubes are invariably used on the plateau. The amplitude of the pulse produced depends merely on the "overvoltage," which is the difference between the operating voltage and the threshold, and is quite independent of

PLATE I



BEHAVIOUR OF G.M. TUBE IN GEIGER REGION

the energy of the ionising radiation.

In the Geiger tube as described so far, there is no provision for stopping the discharge once it has been started. In the earlier types of tube, this had to be done externally, by some means which dropped the voltage below the threshold value for a short period. This can be done by connecting the voltage supply to the tube through a very high resistance (of the order of 10^9 ohms or higher). When the tube fires, the passage of the discharge current through the resistor causes a voltage drop sufficient to reduce the applied voltage below the threshold value. This introduces a long time constant into the circuit, so that the tube cannot be used for rapid counting. Alternatively, an electronic means of dropping the voltage may be used. The one-shot multivibrator is very convenient for this purpose. (For notes on the functioning of the multivibrator see Appendix 1). The multivibrator is designed to be triggered by the pulse from the Geiger tube and the large negative pulse developed at the plate of the "off" tube is applied to the Geiger tube, causing the voltage to drop below the threshold value for a time determined by the constants of the multivibrator. The Geiger tube is thus made inoperative for a time which is accurately known, and a correction for this "dead time" can be applied to the observed count rate if necessary.

Most Geiger tubes now incorporate a quenching medium in the gas filling, usually consisting of a small amount of a heavy organic gas. This quenches the discharge very rapidly. Such tubes are known as "self quenching," and may be used with series resistances as low as 100,000 ohms, which makes them capable of rapid counting. They are subject to certain minor disadvantages, which may become apparent in very precise work. In such cases, the use of a multivibrator quenching stage as described above may be preferable.

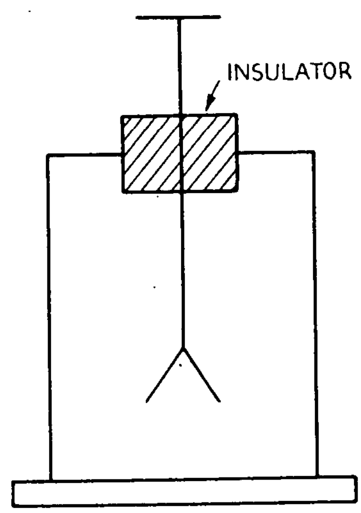
3. EQUIPMENT FOR MEASURING IONISATION CURRENTS

The oldest and most familiar instrument for the measurement of ionisation currents is the electroscope. The equivalent circuit for this instrument is shown in Plate 2. It consists essentially of an ionisation chamber, the centre electrode of which is charged electrically to a high potential. The leaves act as an electrostatic voltmeter, which measures the potential of the electrode. This potential will fall gradually due to leakage of the charge from the electrode across the surface of the insulator. However, if the gas in the chamber is ionised, the rate of leakage of charge will be increased, due to the ionisation current. Measurement of the rate of fall of the leaves will show the total rate of leakage of charge and, provided the natural leak is small compared with that due to ionisation current, accurate current measurements are possible.

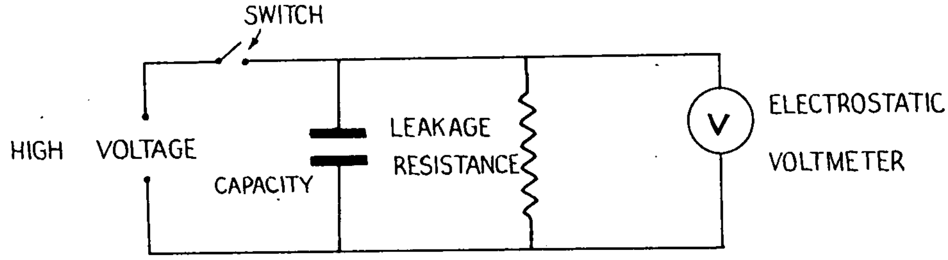
In the hands of a skilled experimenter, the electroscope is capable of results of high accuracy and, in fact, was used in many classical experiments on radio-activity. It is essentially a laboratory instrument, and has largely been superseded by more flexible equipment.

Equipment generally used for measuring ionisation currents is shown schematically in Plate 3. The current through the ionisation chamber is passed through a very high resistance of about 10^{11} ohms, and the resulting voltage drop is applied to a D.C. amplifier. The amplified current is measured on an ordinary current meter.

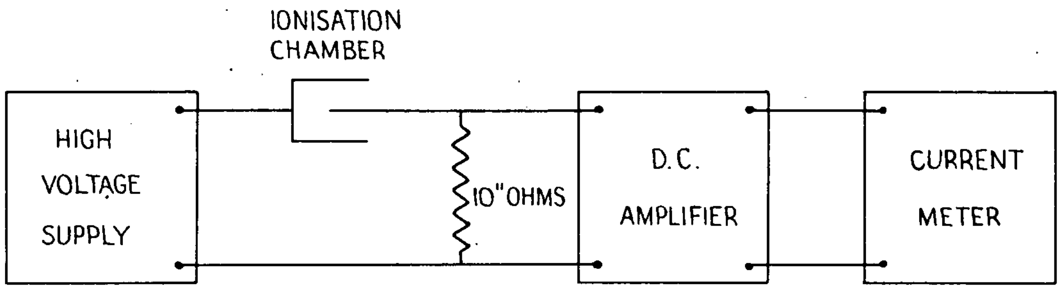
PLATE 2



ELECTROSCOPE



EQUIPMENT CIRCUIT OF ELECTROSCOPE



EQUIPMENT FOR MEASURING IONISATION CURRENTS

It is obvious from the schematic diagram that, in order to obtain accurate current measurements, the input impedance of the D.C. amplifier must be large in comparison with the resistance of 10^{11} ohms. This cannot be obtained by conventional methods because of the grid current that flows in the first stage of the amplifier. This is of the order of 10^{-8} amps in an ordinary tube and gives an input impedance of only 10^{8} ohms. Considerable improvement is obtained by using the tube in the manner shown in Plate 4. Here the suppressor is used as the control grid. The low plate voltage of 6 volts is chosen to prevent the formation of positive ions in the gas of the tube. A potential of about 15 volts is applied to the screen to prevent positive ions formed at the cathode from reaching the plate. Further improvement is obtained by operating the heater at reduced current, by mounting the tube in a light-tight box, and by coating the glass of the tube with insulating wax to cut down surface leakage.

A tube used in this way is known as an "electrometer tube." A number of commercial radio tubes, used in this manner, can have input impedances of the order of 10^{13} ohms. If higher impedances are required, specially constructed electrometer tubes may be used. In such tubes, the input impedance may be as high as 10^{17} ohms.

Electrometer tubes are difficult to use because the steady currents show a tendency to drift and this is often very difficult to remedy. Suitable circuits, and discussions of the precautions necessary, may be found in the standard texts.

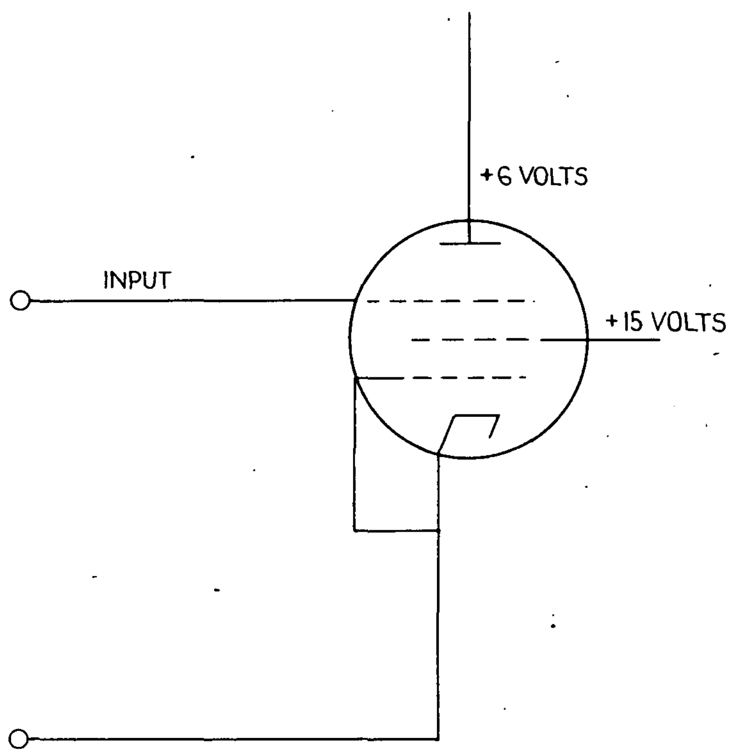
In recent years, a considerable advance in the measurement of small currents has been made with the development of the vibrating reed electrometer. This consists of a condenser, composed of a fixed plate and a vibrating reed which is driven at its resonant frequency by a suitable oscillator. The D.C. voltage developed across the high resistance is applied to this condenser and the resulting A.C. voltage is suitably amplified. The instrument is much less subject to drifts than the ordinary D.C. amplifier using electrometer tubes. The accuracy of measurement is limited only by the accuracy and stability of the high resistance used.

In all apparatus of this type, the greatest care is necessary with insulation. An insulation resistance of 1,000 megohms would virtually short circuit the whole set-up. In order to obtain reliable measurements, the insulation resistance must be high in comparison with the input impedance of the amplifier. To obtain and maintain such resistance of the order of 10^{15} ohms requires the utmost care in the construction and use of the equipment.

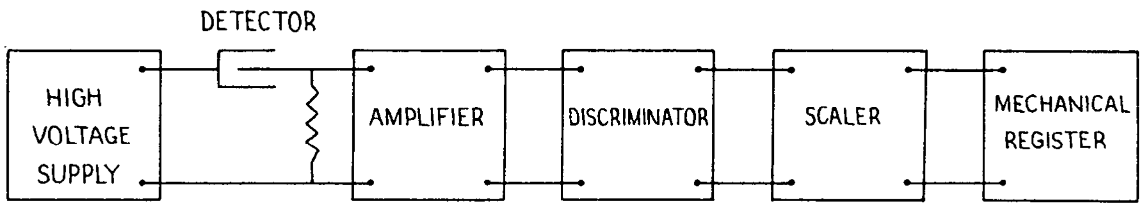
4. EQUIPMENT FOR REGISTRATION OF PULSES

Most radio-active measurements are performed using equipment which registers voltage pulses caused by individual ionising particles. Two types of equipment may be used, and these are shown schematically on Plate 5. The detector may be an ionisation chamber, a proportional counter or a Geiger tube, depending on the type of information required. The choice of detector is governed by the properties of the various types, which may be summarised as follow :-

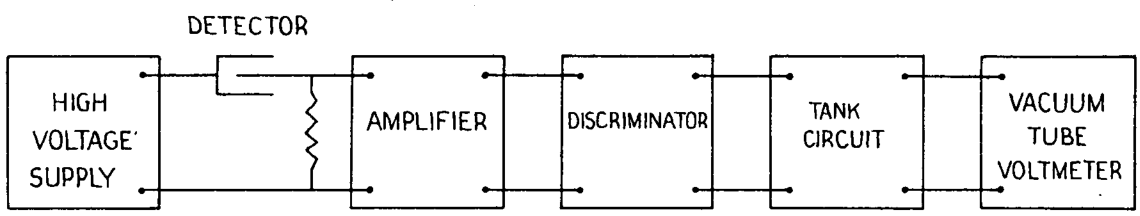
PLATE 4



TYPICAL OPERATING CONDITIONS FOR ELECTROMETER TUBE



COUNTER



RATEMETER

EQUIPMENT FOR REGISTRATION OF PULSES

	Voltage Required	Gain of Amplifier Required	Proportionality	Speed
Ionisation Chamber	Low	Very high	Good	Fast
Proportional Counter	Moderate; highly stable	High	Good	Fast
Geiger Counter	High	Low	Nil	Limited

Where discrimination between ionising particles of different energies is required, either an ionisation chamber or a proportional counter must be used. The great disadvantage of either of these detectors, however, is the high gain amplifier required. This confines their use to the laboratory.

The Geiger counter, although at a disadvantage to the other detectors in most respects, has the major advantage that it requires very little amplification. It is used in all portable equipment, and largely in the laboratory. Briefly, the general practice is to use Geiger tubes whenever possible, and to have recourse to proportional counters or ionisation chambers only when the properties of the Geiger tube make it unsuitable for a particular application.

The various circuit elements shown on Plate 5 are discussed in more detail below.

(a) High Voltage Supplies.

High voltage supplies ranging from a few hundred to two thousand volts are required for various types of detectors. The current drawn is infinitesimal in each case.

The voltage may be supplied from dry batteries. This has various disadvantages. Dry batteries are expensive and bulky. Also, the current drawn is so small that the life of the batteries is limited only by their shelf life, and their actual capacity is not used.

Various electronic devices are successfully used for supplying high voltages. For laboratory use, the most convenient is to generate the voltage by an oscillator at radio frequency and use an R.F. transformer to obtain the necessary voltage level. This R.F. voltage is then rectified and filtered. The voltage can be readily controlled over a wide range by detuning the oscillator, or by using the ordinary voltage divider.

A method which has been used in compact portable equipment makes use of the properties of the free-running multivibrator (see Appendix 1). It is well known that if a current I be passed through an inductance L, the voltage developed across the inductance is L dI/dt (in consistent units). It is a fundamental property of the multivibrator that the change-over between tubes occurs almost instantaneously, so that dI/dt is very large. It is found that a practicable supply giving a high voltage may be obtained by using a free-running multivibrator, with a small choke as the plate load of one tube. The voltage developed across the choke is rectified and filtered. A disadvantage of this circuit is that the voltage is not easily controlled, so that the supply has to be designed to cover a relatively small voltage range.

For methods of stabilising such voltage supplies reference should be made to the standard texts.

(b) Amplifiers.

The pulse as furnished by the detector must be amplified to a voltage level sufficient to trigger the discriminator. The functioning of the discriminator is described below; at present, it is sufficient to state that it requires a pulse of a few volts to trigger it. For rough comparison purposes, this figure may be taken as 10 volts. In any particular experiment, sufficient amplification must be provided to raise the level of the minimum pulse to be detected to at least this figure.

The limit to the amount of amplification that can be used is fixed by noise in the tubes of the amplifier, which cannot be completely eliminated. The amount of noise varies from amplifier to amplifier, but for an amplifier designed and constructed with maximum precautions, noise equivalent to about 3.5 microvolts R.M.S. at the first grid has been observed. This is equivalent to a peak amplitude of about 10 microvolts. It follows that a pulse of amplitude less than 10 microvolts cannot be detected, no matter how much gain is used, as it cannot be distinguished from the noise. Also, it is undesirable that the noise pulses be amplified to a level sufficient to trigger the discriminator. The maximum useful gain may therefore be taken as the gain which would raise a signal of 10 microvolts to 10 volts; i.e., a voltage gain of 10^6. Provision is always made for adjusting the gain by means of attenuators.

As well as having sufficient gain, an amplifier for use with an ionisation chamber must fulfil several other requirements. It should be capable of delivering output signals of a fairly wide range of amplitude. An upper limit of fifty volts may be taken as a not unreasonable figure. Over this range the amplitude of the output signal must be accurately proportional to that of the input at all settings of the gain control, if full use is to be made of the proportional characteristic of the detector. The gain must be very stable. Furthermore, the amplifier should preserve the sharpness of the detector pulses. In other words, it should be sensitive to frequencies as high as possible. An upper, half-power frequency of 1 megacycle is desirable. The low frequency response is generally limited by the insertion of a coupling with a short time constant at the input to one stage, to prevent the amplifier being overloaded by relatively slow variations in the detector output voltage.

The design and construction of an amplifier having all the above properties is an extremely difficult matter. When used with a proportional counter, the extreme gain of 10^6 is unnecessary, a gain of 10^4 being usually sufficient. However, an amplifier with a gain of 10^4, satisfying the other requirements mentioned, is still a high grade amplifier. This is the main difficulty in the use of ionisation chambers and proportional counters.

With the Geiger tube, this difficulty does not arise. The output pulse is of the order of a volt, and as there is no proportionality and the tube is not capable of very high counting speeds, no particular care is necessary with regard to gain stability or high frequency response. Some amplification is usually desirable. This can be provided readily by means of a single pentode stage giving a voltage gain of about 50.

(c) Discriminators.

A discriminator is a circuit which, on receipt of an input pulse of suitable amplitude, provides an output pulse of amplitude and wave form depending only on its own circuit constants. Discriminators are invariably based on some form of the "one shot" multivibrator (see Appendix 1). When this circuit has adjustable bias, it performs the following two functions :-

(i) Discrimination - The circuit can be triggered only by pulses of amplitude greater than a certain voltage, which depends on the applied bias. By varying this bias, a "spectrum" of the amplitudes and relative frequencies of the pulses from the detector may be obtained.

(ii) Pulse Shaping - Any input pulse which triggers the discriminator appears at the output as a pulse of standard wave form and amplitude, quite independent of the shape of the input pulse.

In different applications, emphasis may be laid on one of these functions to the exclusion of the other. Thus, in the counter set-up shown on Plate 5, discrimination is the main requirement, since the requirements for triggering the scaler are not critical. In fact, when a Geiger tube is used as detector in this set-up, the discriminator section is not required. In the ratemeter set-up, both functions are essential, except when a Geiger tube is used. Then the pulse shaping function is the essential one, as there is no proportionality in a Geiger tube, and therefore no possibility of discrimination.

(d) Scalers and Mechanical Registers.

The most convenient way of recording pulses is by means of a mechanical register. However, these are limited in the rate at which they can record pulses. Available registers vary widely in resolving time. Great improvements have been made in recent years, and a number of registers now constructed will count 50 random pulses per second, with negligible losses. In fact, some registers are known which will count 100 random pulses per second quite reliably. The mechanical design of such instruments need not be discussed in detail here. Increased resolving power may be obtained in them by lightening the working parts, so as to reduce inertia, or by using a relatively robust movement, and supplying more driving power. Both these methods have limited possibilities. If the movement is made very light, the instrument becomes difficult to adjust, and subject to wear. On the other hand, the power demands cannot be made too high, otherwise the design of the driver stage becomes difficult.

A register which counts 100 pulses per second is still quite inadequate, even for a relatively slow detector such as a Geiger tube, which may have a resolving time of some hundreds of microseconds. To meet this situation, a scaling circuit is used between the discriminator and the register. Scaling circuits are based on the "scale of 2" flip-flop multivibrator (see Appendix 1). The fundamental property of this circuit is that, when pulses are applied to the input, half the number of pulses appear at the output. Thus, if n such stages are used in series, the number of pulses appearing at the output of the last stage is $\frac{1}{2^n}$ of the number at the input. It is therefore a simple matter to calculate the number of scaling circuits required to reduce the maximum rate of input pulses to a figure within the capacity of the register used.

Such scaling circuits, having a resolution time of 5 microseconds, can be readily constructed and are quite reliable in use. It is found, however, that it is very difficult to obtain resolution times shorter than this. Scaling circuits with resolution times of about a microsecond have been constructed, but they must be carefully set up, and operated by a skilled technician.

The fundamental "scale of 2" circuit can be used as the basis of a "scale of 10" counter, with a little extra complication. Details of this circuit are given in the standard works.

(e) Tank Circuits.

The fundamental tank circuit is shown in Plate 6. The theory of the circuit is discussed in the standard works. Provided certain restrictions on the size of the components are satisfied, it may be shown that -

(i) The average voltage appearing across C_2 is proportional to the product C_1R. It is thus convenient to set the sensitivity of the instrument by altering the value of R.

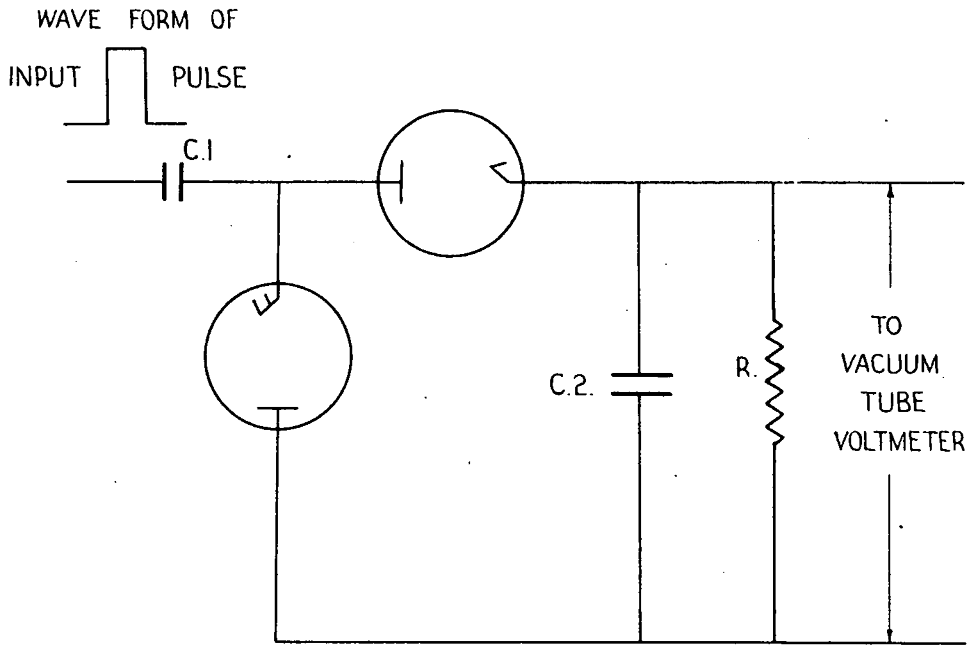
(ii) The accuracy of the instrument (measured by the steadiness of the reading) is proportional to $\sqrt{C_2}$. It is convenient to adjust the accuracy of the reading by altering the value of C_2. For rough work, a lower value may be used, and a rough reading obtained rapidly. For accurate work, a large value must be used, with consequent increase in the time required to obtain the reading.

(iii) The time required for the reading to be obtained is proportional to the time constant RC_2.

5. CRYSTAL AND SCINTILLATION COUNTERS

It has long been known that alpha particles cause scintillations when they impinge upon screens coated with certain crystalline materials, and many of the classical experiments on radio-active materials were performed using such screens as detectors. It has been found recently that crystals of certain organic materials also are sensitive to gamma radiation. Originally, the scintillations were observed by eye. This is a tedious and rather inaccurate process. A much wider field of use for these methods has arisen due to the recent development of the photomultiplier tube. A tube of this type is effectively an amplifier of extremely high gain, which converts the scintillations into voltage pulses of considerable amplitude.

For many purposes, scintillation instruments have great advantages over other types of detectors. They are proportional and are capable of extremely fast counting. It is probable that electronic techniques are not yet sufficiently advanced to take full advantage of the counting speeds available from a scintillation counter. Gamma ray scintillation counters are much more



RATEMETER TANK CIRCUIT

efficient than Geiger tubes (i.e., for the same flux of gamma radiation, the scintillation counter records many times more counts than a Geiger tube of comparable size). This is a great advantage in airborne equipment, where a ratemeter with a very short time constant must be used.

However, certain major difficulties are encountered in the use of scintillation counters. The photomultiplier tube requires a high voltage (usually 1,000 to 1,500 volts). The tube itself produces a background of noise, which increases rapidly with increasing voltage. It is therefore essential that the voltage supply be very well stabilised. The tubes are expensive, and easily damaged by incorrect operation. Also, it is found that the characteristics of the tubes vary widely from tube to tube, so that recalibration of the equipment is necessary if a tube has to be changed.

For these reasons, the use of scintillation counters is practically confined to the laboratory. A portable instrument has recently been put on the market. It is considerably dearer than a portable Geiger counter, and it is doubtful whether its extra gamma counting efficiency justifies the extra expense except in very special cases. It has been found that the sensitivity of the Geiger counter is more than adequate for use in prospecting for radio-active minerals.

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January, 1953.

APPENDIX I.

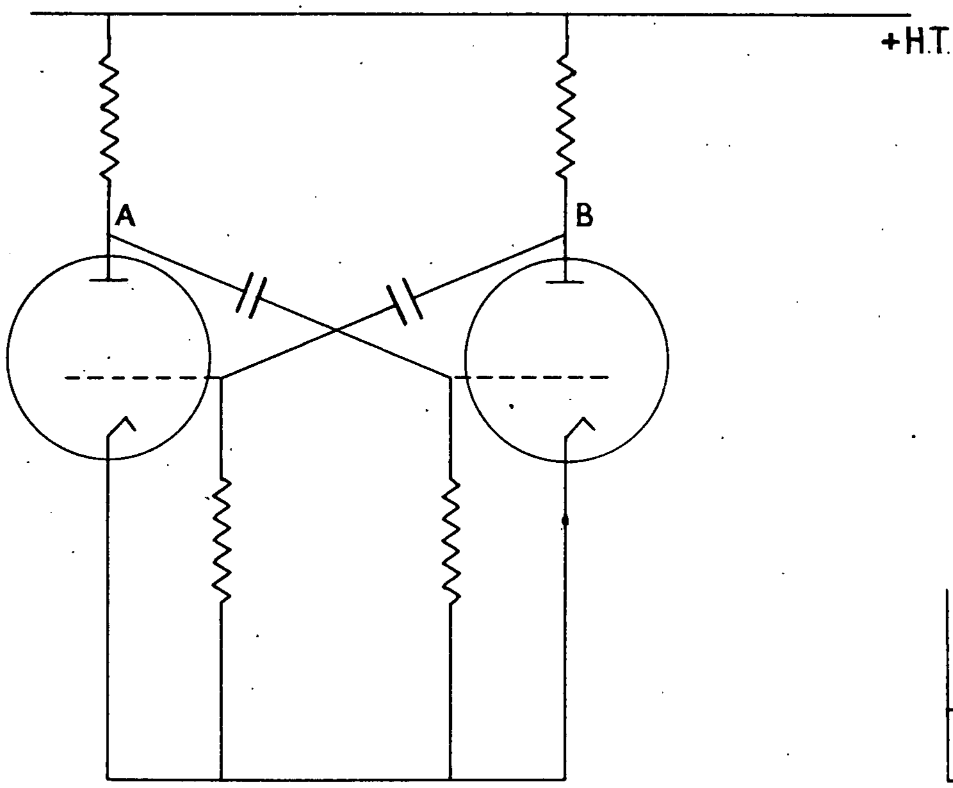
NOTES ON THE MULTIVIBRATOR.

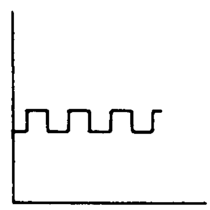
The following notes are intended to describe briefly the functioning of the multivibrator, which in one form or another, is an essential part of most instruments for the detection of ionising radiation. The detailed design of these circuits requires great skill and experience.

(a) The "free running" multivibrator is shown in Plate 7. This circuit has no stable state. It has two extreme states, in one of which tube A is conducting and tube B non-conducting, while in the other, the reverse condition holds. The circuit oscillates between these states, at a frequency which depends on the circuit constants. The change-over occurs almost instantaneously, so that the wave form is roughly rectangular.

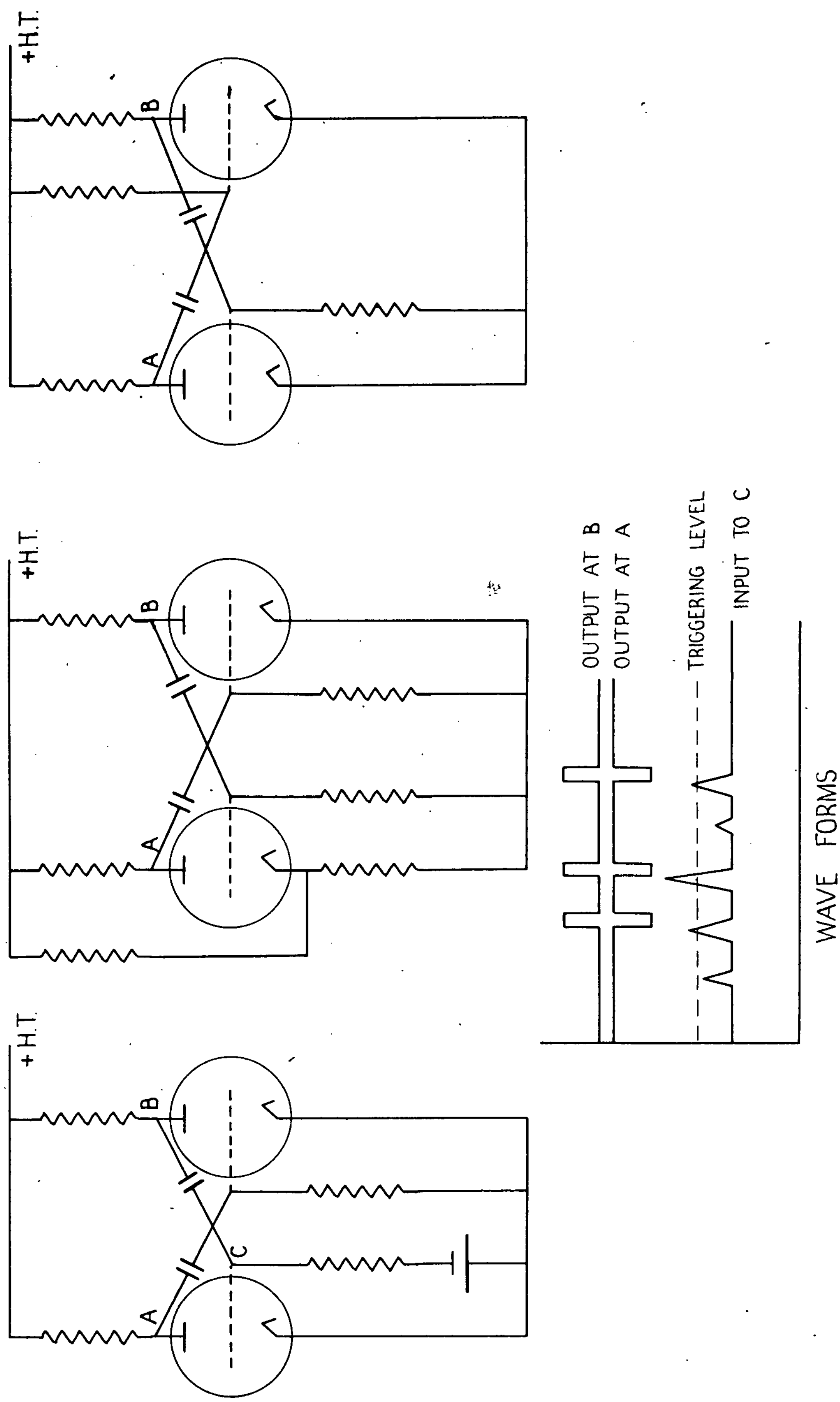
(b) The "one shot" multivibrator is shown in Plate 8. Three forms of the circuit are shown, which are identical in operation. The circuit consists essentially of a multivibrator in which a bias is applied to one tube. The circuit then has a stable state, in which, in the circuits shown, tube A is "off" (non-conducting) and tube B is "on" (conducting). If, however, a positive pulse of sufficient amplitude is applied to the grid of tube A, the bias is overcome, and the tube "runs free" for one cycle. The output wave form at the plates of tubes A and B is shown in the diagram. By adjustment of the amount of bias, the level of the pulse needed to trigger the circuit may be varied. The output pulse depends only on the circuit constants, and not at all on the shape of the input pulse (within certain limits). It must be remembered, however, that the triggering mechanism of such a circuit is not as simple as it sounds. Reference should be made to the standard works for details of practical discriminator circuits.

(c) The "flip flop", which is the basis of most scaling circuits, is shown in Plate 9. The circuit has two stable states, in which one tube is "off" and the other "on." It will rest in either of these states, until the arrival of a suitable triggering pulse. This causes the circuit to change over to the other state, in which it will remain, until the next input pulse arrives. The wave forms are shown on the diagram, from which it is obvious that the number of pulses appearing at A or B is half the number of input pulses received. For details of the functioning of the circuit, and methods of applying input pulses, reference should be made to the standard works.

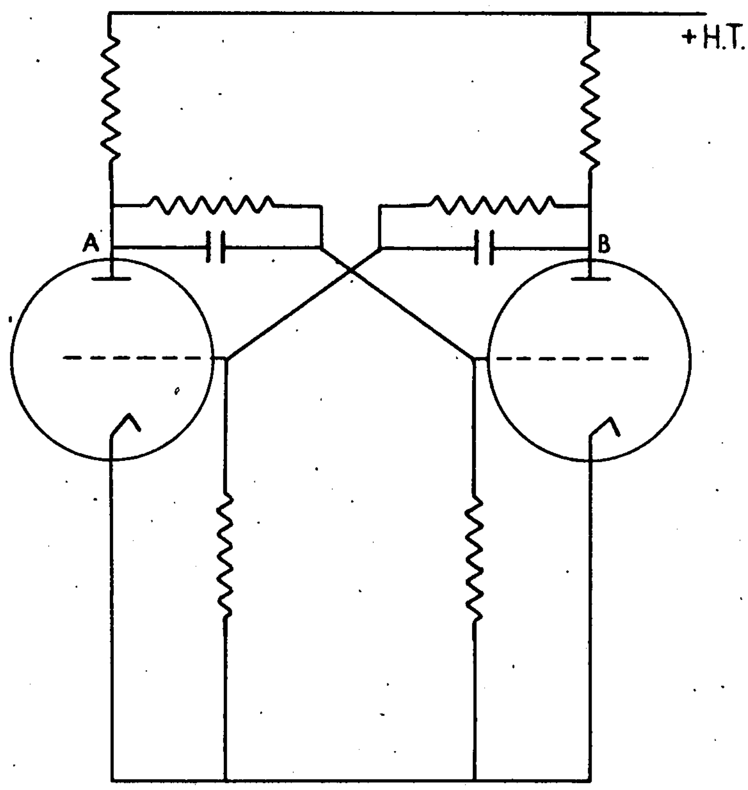


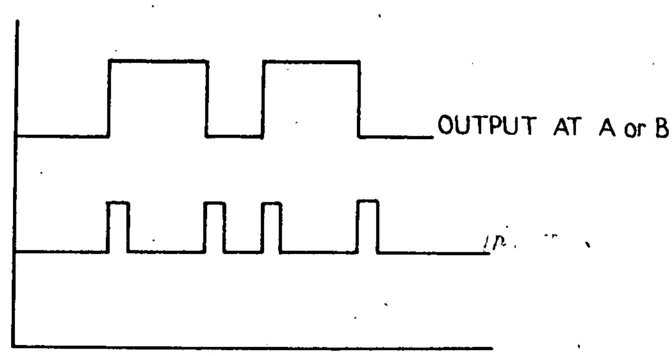

WAVE FORM AT A and B

CIRCUIT DIAGRAM OF FREE RUNNING MULTIVIBRATOR



CIRCUIT DIAGRAM OF ONE SHOT MULTIVIBRATOR





WAVE FORMS

CIRCUIT DIAGRAM OF FLIPFLOP

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A complete bibliography on the subjects treated in these notes would probably include thousands of titles. However, the standard works mentioned below summarise the state of modern knowledge sufficiently for all purposes except those of the research physicist.

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