The application of electronic methods to measurements in atmospheric electricity

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THESIS

Presented in candidature for the degree of

DOCTOR OF PHILOSOPHY

of the University of Durham

by

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entitled

THE APPLICATION OF ELECTRONIC METHODS TO MEASUREMENTS IN ATMOSPHERIC ELECTRICITY.

The work was carried out at the Science Laboratories of Durham Colleges in the University of Durham, during the period 1947-1950, under the supervision of J.A. CHALMERS, M.A., B. Sc., Ph. D.

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INTRODUCTION.

GENERAL.

The study of atmospheric electricity is concerned with the observation and explanation, both physical and mathematical, of the electrical conditions in that part of the earth's atmosphere between the earth and the ionosphere. Much greater attention has been given to the lower region extending to an altitude of about 70,000 feet. Generally the phenomena can be classified conveniently according to whether they are associated with fine or stormy weather conditions.

FINE AND STORMY WEATHER PHENOMENA.

In fine weather there is a 'bound' charge of negative sign on the earth's surface which is associated with a positive electric field in the lower regions of the atmosphere and any concentrations of charge which exist in these regions are only small. Thus the electrical state of the atmosphere can be represented by lines of force proceeding upwards from the negative 'bound' charge on the earth and ending on positive charges in the atmosphere or in the ionosphere. The air is always in an ionized state and the existence of the positive electric field gives rise to a vertical conduction current which brings positive charge to the earth and tends to neutralize the 'bound' negative charge. However, it is found that the value of the electric field at ground level remains more or less constant in fine weather so that the 'bound' charge, too, must be sensibly constant. Thus in fine weather the electrical state of the atmosphere is a quasi-stable one.

In stormy weather the situation is altered considerably from that which has been described for fine weather. Higher electric fields which show appreciable fluctuations from time to time are experienced and under certain conditions the direction of the field is reversed. The ionic current flowing towards the earth's surface is sometimes accompanied by a precipitation current due to the charge carried down by rain, snow and hail, while the production of ions by point discharge and lightning discharges may give rise to an appreciable space-charge in the atmosphere. Thus in stormy weather the electrical situation is a complex one and is dynamic in character due to the movements of high concentrations of charge which exist, particularly in clouds.

THE MAINTENANCE OF THE EARTH'S CHARGE.

It has been mentioned that in fine weather the positive conduction current flowing to the earth tends

tends to neutralize the negative 'bound' charge on the earth's surface which is associated with the positive electric field at ground level. Chalmers (1949) has calculated that at Kew, for example, the 'bound' charge would be destroyed in 48 minutes if no agency for replenishing this charge existed. The earth is a conductor and in considering the charge on the surface at any point account must be taken of the net inflow of charge to the whole surface. Wilson (1920) was the first to suggest that the negative charge might be replenished at those parts of the earth which are experiencing stormy weather. Later work has confirmed this idea. By considering the four main processes responsible for the transference of charge to the earth, Wormell (1930) was able to assess, though only approximately, the annual balance of electrical charge for 1 square kilometre of the earth's surface at Cambridge. He gave a value of 40 coulombs of negative charge. Scrase (1938) and Chalmers and Little (1947) have pointed out the considerable variation in the total balance of the electrical charge for a portion of the earth's surface which can occur, if some periods of precipitation are not recorded.

THE SEPARATION OF CHARGE.

From observations of the electricity in thunderclouds it has been established that the typical thundercloud has at least two localized concentrations of charge; a positive one in the upper regions of the cloud and a negative one in the base. In England, some, if not all, thunderstorms have an additional centre of positive charge in the cloud base. Several theories have been advanced to account for this separation of charge, but none of them is wholly adequate in accounting for all the features observed so far. The main theories are:-

(a) Simpson (1909): The breaking of water drops.

(b) C.T.R. Wilson (1929): Ion-capture by water drops.

(c) Simpson and Scrase (1937): Ice friction.

(d) Findeisen (1943): Production of ice-splinters.

(e) Frenkel (1946): Selective ion-capture by water drops.

(f) Workman and Reynolds (1950): Charge separation during freezing of dilute aqueous solutions.

Each theory consists essentially of a process in which water in either the liquid or solid state becomes electrically charged, followed by a separation of the positively and negatively charged particles under the influence of gravity.

THE ORIGIN OF CHARGES ON PRECIPITATION.

Investigations on thunderstorms by Workman and Reynolds (1949) have shown that no significant electrical effects are observed in a cumulonimbus cell until radar has revealed the presence of precipitation elements. Thus it seems that the separation of charge in a cloud is accompanied by precipitation. This view was held by C.T.R. Wilson (1923) who stated that 'clouds other than those associated with precipitation do not in general produce conspicuous effects on the potential gradient at the earth's surface'. Observations of the charge brought down by rain together with simultaneous measurements of the electric field at the earth's surface and the point discharge current should provide information for a critical examination of the theories advanced to account for the separation of charge and the charge carried by precipitation. In addition it may be possible to estimate the part played by the charging processes in the region below cloud.

Chalmers (1949) has discussed the main theories in detail, from the point of view of the charges carried by precipitation. Serious consideration must be given to theories put forward by Findeisen (1943), Frenkel (1946), Dinger and Gunn (1946) and Workman and Reynolds (1950).

Findeisen in a laboratory investigation has shown that a surface on which ice crystals are subliming, produces negatively charged splinters, while positively charged splinters are formed during vaporization. When an electric field is developed between the 'icing' surface and an auxiliary electrode the charged splinters have the polarity which is the inverse of that of the field. He suggests that this phenomenon may account for the charge separation in clouds. According to the theory the charge on precipitation may be either positive or negative, depending on the prevailing thermodynamical conditions.

Frenkel's theory is based on the fact that water drops exhibit a permanent polarization and consequently capture negative ions quite easily; gravitational separation then takes place between the charged cloud particles and the free ions, producing a cloud of positive polarity. He explains that larger drops as they fall earthwards are polarized in the electric field in the cloud and in the atmosphere below, and may capture ions readily. The collection of positive charge is suggested as more probable, because the positive polar conductivity is greater than the negative one.

Dinger and Gunn have conducted a series of experiments on the electrical effects accompanying the change of state of water. Their results show:-

(a) A transient change of contact-potential is associated with the freezing of the surface of pure water.

(b) Ice which contains entrapped gas in the form of bubbles becomes positively charged on melting, due to the removal of negative charge by the escaping gas bubbles.

They suggest that this process will be important in regions where melting hail exists, because of the entrapping of air bubbles during the layer-by-layer formation of the hail.

Workman and Reynolds, as a result of a series of laboratory experiments have reported the discovery of an electrical effect accompanying the orderly freezing of dilute aqueous solutions. Very high potential differences have been observed across the water-ice interface and their results show that the polarity and magnitude of the potential difference and the quantity of charge separated during freezing depend on the nature of the solute and its concentration. Assuming an elementary thunderstorm model they describe an interaction between ice and water which produces a concentration of negative charge between the 0° C and -10° C. isotherms.

Very little progress will be made in trying to understand how the charge on precipitation is acquired until more is known of the microphysics of clouds and the theories of electrification are formulated on a quantitative basis.

THE AIR-EARTH CURRENT.

(i) Measurement.

It is possible to measure the air-earth current by two independent methods. The direct method involves the measurement of the actual charge reaching an isolated portion of the earth's surface in a given time. Alternatively it is possible to record simultaneously the values of the air conductivity and the electric field at ground level and deduce the conduction current from the product of these two quantities.

To measure the air-earth current directly it is necessary to isolate a portion of the earth's surface using a good insulating material and in order that the conditions should be normal, the collecting surface should be placed in the plane of the earth's surface and its electric potential maintained at earth potential or as near to it as possible. This measurement of charge also includes any change in the 'bound' charge on the surface, unless some form of compensation is used to eliminate the effect of the field changes. A field change of 100 volts-metre^{-1} will produce a change of 'bound' charge of 0.87×10^{-13} coulomb-cms^{-2} which is equal to the charge contribution of the air-earth current (1×10^{-16} amp-cms^{-2}) for a period of 10 minutes. Direct measurements of the air-earth current have been carried out by C.T.R. Wilson (1906 and 1916), C.W. Lutz (1911), G.C. Simpson (1910), F.J. Scrase (1933), Nolan and Nolan (1937), and Chalmers and Little (1947).

Wilson used the Universal Portable Electrometer for his measurements, in the following manner. The test-plate was maintained at earth-potential by adjusting the compensating condenser, while the effect of field changes was eliminated by beginning and ending an observation with the plate covered. The charge collecting period was 1 minute. Usually he mounted the instrument on a tripod; a correcting factor was therefore necessary to convert the results to true air-earth values. Replacing the electrometer and compensator by a capillary electrometer, Wilson was able to obtain continuous adjustment of the potential on the plate to that of the earth.

Lutz employed Wilson's Universal Portable Electrometer and each observation lasted 5 minutes.

Simpson's method is unique considering the difficulties under which he laboured. The exposed plate consisted of a wooden frame 17 metres^2 on which canvas was tightly stretched. A covering of brown paper was placed on the canvas and coated with blacklead to produce a conducting surface. Sulphur insulators were used to mount the surface about 15 centimetres above the general ground level. A water-dropping system maintained the potential of the exposed surface at that of the surrounding earth and as the water drops emerged from the nozzle of the dropper they were caught in an insulated vessel which was connected to a Benndorf Electrometer. An electromagnetic relay system actuated the recording of the electrometer deflexion every two minutes, on a moving strip of paper, and after each recording the electrometer was immediately earthed. The potential gradient was recorded simultaneously on a second Benndorf Electrometer. Corrections for changes in the 'bound' charge were made by using the potential gradients at the beginning and end of each 2 minute observation.

Scrase employed a method in which the effects of field changes were eliminated by means of a quadrant electrometer used differentially. The exposed plate was connected to one pair of quadrants while a polonium collector for registering the potential gradient was connected to the other pair via a variable condenser. Thus one pair of quadrants received the charge due to the air-earth current together with any changes in 'bound' charge due to field changes, while simultaneously the polonium collector responded to these field changes and effectively released 'bound' charges on the condenser plate connected to the other pair of quadrants.

By adjusting the capacity of the condenser the effects of any field changes were balanced so that they made no contribution to the deflexion of the electrometer. Unfortunately Scrase found that the response of the polonium collector was too slow and as it was not judicious to reduce this response time he minimized the effect of rapid field changes by placing a wire net over the exposed plate. The wire net was connected to the polonium collector and its height was adjusted so that the field over the exposed plate was always the same as that measured by the collector; consequently at times the field was different from that which would have occurred under natural conditions. The electrometer was earthed for a period of 1 minute at intervals of 10 minutes. When the exposed plate was screened from the electric field in the air by an earthed metal box it was found that the electrometer developed a deflexion. The cause was traced eventually to the contact potential difference between the exposed plate and the lining of the pit. Corrections were applied to the observations to allow for this additional charge. A second correction was made to compensate for insulation leakage.

Nolan and Nolan used Wilson's method with a charge collecting period of 1 minute for their determination of the air-earth current. For each determination of the current and the electric field they made a simultaneous measurement of the concentrations of positive and negative ions; then in a subsidiary set of experiments they deduced the mean mobilities of the ions concerned. By this means they were able to compare the results of air-earth current measurements by the direct and indirect methods. The problem was examined a second time by P.J. Nolan (1940) who this time measured the conductivities (positive and negative) directly, with a form of the Gerdien apparatus for conductivity measurements, whilst making simultaneous measurements of the conduction current by Wilson's method.

Chalmers and Little made observations of the air-earth current at Durham using a method similar to that employed by Simpson. The charge reaching an exposed surface was collected for periods of 10 minutes and then the total charge was measured by discharging it through a ballistic galvanometer. To reduce the quantity of charge lost by leakage a condenser of large capacity was connected between the exposed surface and 'earth', and this arrangement had the added advantage of preventing the potential of the surface from becoming considerably different from that of the earth. No corrections were made for field changes.

Of the methods described, only Simpson's, Scrase's, and that of Chalmers and Little are suitable for the continuous observation of the air-earth current over long periods. None of them has succeeded completely in measuring the true conduction current under strictly natural conditions; the nearest approach to such conditions being achieved only by Scrase. He measured in effect a mean conduction current and then calculated from the recorded values a mean current for each 10 minute period. Undoubtedly the most accurate method is that due to Wilson, but the tedious manipulation involved in taking a large number of observations detracts from its value as an observational method. It is best reserved for calibration experiments.

(ii) The Indirect Method.

Simultaneous measurements of the conductivity of the air and the electric field in the atmosphere are required for the determination of the air-earth current by this method. A form of the apparatus devised by Gerdien (1905) is usually employed for the conductivity measurements. This consists of two concentric metal cylinders between which an electric field is applied. The inner cylinder is connected to an electrometer to record the ion current. An air-stream is drawn between the cylinders at a velocity such that only a fraction of the ions are removed from the air and Ohm's law holds. The unipolar conductivity is then obtained from a knowledge of the ion current, the geometry of the cylindrical electrodes and the electric field. By reversing the field and repeating the experiment the other unipolar conductivity can be measured. The conductivity of the air is determined as the sum of the positive and negative unipolar conductivities. A variety of methods (described by Chalmers (1949)) are available for the measurement of the electric field.

(iii) General Results.

Table 1 shows some of the results obtained by the two methods.

TABLE 1.

Observer	Year	Station	Current Amp-cms^{-2} x 10^{-16}	
			Direct	Indirect
Wilson	1906, 1916.	Edinburgh	2.22	-
Gerdien	1907	Gottingen	-	2.7
Simpson	1910	Simla	1.8	-
Lutz	1911	Munich	1.0	-
Kahler	1912	Potsdam	-	2.4
Mauchly	1926	Oceans	-	3.2
Scrase	1933	Kew	1.12	-
Nolan and Nolan	1937	Glencree	2.5	-
Chalmers and Little	1947	Durham	2.2	-

The diurnal variation of the conduction current at Kew shows different forms at different times of the year. The winter variation exhibits a maximum at 0600 hours G.M.T. and a minimum at 2100 hours G.M.T. In summer, however, there is a less marked maximum at midnight and a minimum at 1300 hours G.M.T. Generally there is an inverse relationship between the electric field variation and the current variation.

In foggy weather Scrase found that the air-earth current is reduced to a fraction of its normal value and sometimes he observed a negative current, often with a positive electric field. The negative current tended to occur only in 'wet' fogs and was attributed to the 'settling out' of small droplets. The decrease in the current is considered to be due to an increase in the resistance of the atmosphere brought about by the capture of small ions by the fog droplets. At Durham, Chalmers and Little (1947) observed negative fields with negative currents during periods of misty weather. On these occasions the conductivity was almost normal.

(iv) <u>Comparison of the Direct and Indirect Methods.</u>

The direct method measures the conduction current entering the earth while the indirect method measures the current at a certain height above the ground. The form of the two currents is different; the former is unipolar (positive ions) whereas the latter is dipolar. Thus fundamentally the two methods do not measure the same event. At one time it was considered that the indirect method gave values of the current equal to about twice those obtained by the direct method and experimental results seemed to support this idea. Observational results had shown that the electric field was constant in the first few metres above ground and the positive and negative conductivities were equal. Thus, if the positive conductivity did not vary with height the factor 2 was easily accounted for, but this assumption implied the existence of a convection current equal to the product of the electric field and the negative conductivity. Watson (1929), however, had shown that at Kew there was no space-charge within the first metre above the ground and so the existence of a convection current was considered to be doubtful. The results obtained by Nolan and Nolan (1937) at Glencree showed that the convection current was insignificant. Then Hogg (1939) gave further support to the identity of the results of the direct and indirect methods by showing that the positive conductivity at ground level is equal to the dipolar conductivity at a height of 1 metre, and that the positive conductivity decreases with height. Theoretical work by Chalmers (1946), in which he assumes a reasonable relationship for the variation of ionization with height, indicates the possibility of a state of equilibrium of ionization in which the total space-charge is not large enough to produce any significant change of field with height.

PRECIPITATION CURRENTS.

(i) Measurement.

Two methods are available, using either a collector shielded from the electric field or a fully-exposed one. The former method is generally employed for investigations on the charge carried by precipitation, while the latter is more suited for studying the function of precipitation in the maintenance of the earth's charge. The fully exposed collector measures the actual transfer of charge to the earth and includes any secondary effects which may be produced by the splashing of the rain. Any significant increase in the conduction current which may occur in wet weather is also recorded by this type of collector. The shielded collector measures only the charge on rain and in addition the results may not be truly representative of the rain, for driving rain cannot enter the receiving vessel.

The shielded collector is designed so that any charges produced inside it by the Lenard effect are not lost in the splashing process. An electrometer is generally used as the recording instrument. Elster and Geitel (1888), Kahler (1909), Schindelhauer (1913), Baldit (1911), (1912), and Simpson (1909) have made observations on the charge brought down by rain with this type of experimental arrangement. The recording periods were usually of the order of a few minutes. M'Clelland and Nolan (1912), M'Clelland and Gilmour (1920), Miss Marwick (1930), and Scrase (1938) have used a modified system in order to determine the charge carried by a definite quantity of rain. The rain was caught in a small bucket which was shielded from the electric field and also protected from the effects of splashing. When the bucket was full it automatically ejected its contents and simultaneously the electrometer was earthed, thus completing the record for that quantity of rain. Schindelhauer, Simpson and Scrase are among the few who have made continuous measurements; the last two named employed photographic recording.

The completely exposed collector has been used by a number of workers, the first of whom was Weiss (1906). He used a wire brush to catch the raindrops, but unfortunately his results were affected by charge collection due to point discharge.

Herath (1914) used a large area of cloth suspended by insulators and connected to earth via a galvanometer, the deflexion of the latter being recorded photographically. The cloth exposure did not represent natural conditions at all, thus it is possible that the results he obtained were seriously influenced by the effects of splashing.

Wilson (1916) used a system in which complete compensation for the effects of splashing was achieved by having a guard ring around the collector and making their surfaces as natural as possible. He made only a limited number of observations.

Schonland (1928) and Chalmers and Little (1947) have also used the compensated collecting system. The latter collected the charge received during periods of 10 minutes and then discharged it through a galvanometer, the deflexion being recorded photographically.

(ii) <u>General Results.</u>

It seems probable that the electricity of precipitation is positive, but more world-wide continuous measurements are necessary before any definite conclusion can be reached. The results for continuous rain show a positive excess of charge which is more evident than in other types of rain. On many occasions continuous rain has been observed to bring down positive charge for long periods. Shower rain usually exhibits an excess of negative charge, while thunderstorm rain shows a positive excess.

It has generally been found that periods during which there is positive rain are longer than those during which the rain is negatively charged. Often this ratio is greater than the ratio of the total quantities of charge, showing that the periods of negative charge yield more highly charged rain than periods of positive charge.

The charges per unit volume of water measured by different observers in different types of rain vary from 0.01 E.S.U./cc. to 22 E.S.U./cc. For continuous rain 1 E.S.U./cc. is an average value, while 2 E.S.U./cc. is a reasonable average for showers and storms.

Simpson (1909) and Schindelhauer (1913) found very light rain to be highly charged, while Scrase (1938) found it to be otherwise.

Rain current measurements provide values ranging from 10^{-16} amp-cms.$^{-2}$ to 10^{-14} amp-cms.$^{-2}$ for continuous rain, and up to 10^{-12} amp-cms.$^{-2}$ for showers.

Baldit (1911, 1912) has observed the polarity of the rain charge to change a number of times within a period of 2 minutes.

The relationship between rain charge and the electric field has received considerable attention. In storms and showers there appears to be no general relation, though Simpson (1909) found that there was usually an excess of positive rain and negative field. Later work by Simpson (1949) has shown that the relationship between the electricity on rain and the electric field is entirely different for field values greater than $\pm$ 20 volt-cms^{-1}, from what it is for gradients less than $\pm$ 10 volt-cms^{-1}. In the former case Simpson found that the relation between the rain current i, the point discharge current through a single point I and the rate of rainfall R' could be expressed equally well in any one of the three following ways:

$$\frac{i}{I} = 2.0 \times 10^{-8} (R')^{0.57}$$

$$\frac{i}{I} = \frac{1}{5.5 \times 10^{6}} \left(1 - e^{-0.058 R'}\right)$$

$$\frac{i}{I} = \frac{R'}{4 \times 10^{6} (R' + 20)}$$

From the observations he deduced that the rain current collects its charge from the normal point discharge current, and during very heavy rain the rain current would become equal to the point discharge current, due to the capture of all the ions produced in the discharge. For the smaller fields, it was found that the observations were satisfied by the empirical relationship

$$q = -0.0145(P-4)$$

where q is the charge per unit volume of rain in E.S.U./cc and P is the field strength in Volt-cms^{-1}. During periods of steady snowfall the field was between zero and + 4 volt-cms.$^{-1}$, and the charge was negative, whereas for rain it was positive. Simpson was unable to offer any satisfactory interpretation of the results in terms of the theories advanced to account for the charge on precipitation.

Observations on the charge on snow have shown that there may be either a positive or negative excess, depending on the prevailing conditions. Sleet and hail are usually positively charged, but Chalmers and Little (1937) recorded very large negative currents.

CHAPTER I.

AN APPARATUS FOR RECORDING AIR-EARTH AND PRECIPITATION CURRENTS.

1.1 PRELIMINARY CONSIDERATIONS.

For investigating any of the physical characteristics of the earth's atmosphere it is essential to use an apparatus which will record the observations automatically during every hour of the day and for every day of the year. Only under such conditions is it possible to give an unreserved interpretation of the results.

Two methods of recording are available for most types of observation, the photographic method and the more direct method of using a pen-recorder. The latter system has several advantages. It is easy to set up, and in the long run is more economical than the photographic system. Furthermore, with the pen-recorder the recordings can be examined as the events occur. This is an advantage which must not be overlooked when studying phenomena which recur very infrequently. In fact, it was the determining factor in the selection of the method of measurement to be outlined in this chapter.

Apparatus used for making continuous observations should need as little supervision and maintenance as possible. Also it should be sufficiently robust to withstand the heavy wear and tear of continuous operation. Economy, too, is an important consideration in the design of large-scale apparatus.

1.2 THE APPARATUS.

It was decided to design an electronic measuring system which could be used with a temporary photographic recording unit. Later it would be a simple matter to change to an electromagnetic pen-recording system.

The complete apparatus is shown schematically in Figure I.

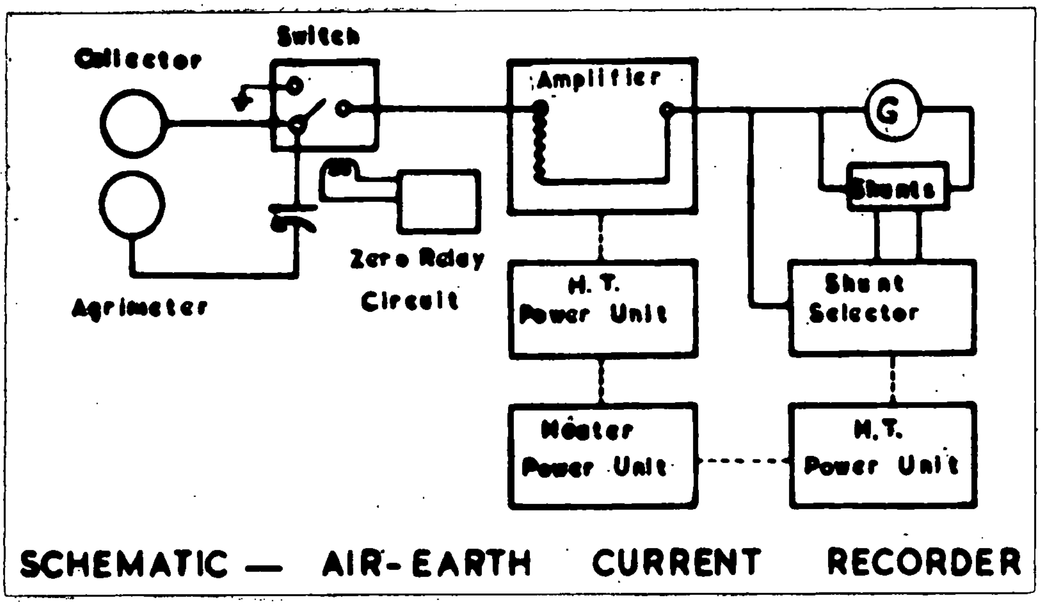


FIGURE 1.

It consists of an insulated surface connected to an amplifier for measuring the small currents reaching the surface. A mirror galvanometer is used to record the measurements, and its sensitivity is controlled automatically according to the magnitude of the atmospheric electric currents by a shunt-selector unit. A switch inserted between the collector and the amplifier is operated from a relay circuit, and enables a record of the amplifier zero to be obtained periodically. The agrimeter is used in other research work to measure the electric field at ground level. It was used in this research in an attempt to annul the effects of field changes in the manner described by Scrase (1933). Power supplies are obtained from the A.C. mains supply and are well stabilized.

The individual units of the apparatus are discussed in detail in the next chapters.

CHAPTER II.

THE COLLECTOR.

2.1 CHARACTERISTICS.

To measure the air-earth current it is necessary to use a surface which is well exposed to the atmosphere, whereas for rain-current measurements, as discussed on page 17, two types of collector are available. At the outset it was decided to use a fully-exposed collector for both the air-earth and rain-current measurements, as this is the simplest arrangement which can be obtained. The area of the exposed surface was determined so that the minimum current to be measured was of the order of 10^{-13} ampere. A high resistance of magnitude 10^{11} ohms was adopted for converting this current into a voltage of a magnitude which can be measured easily. Thus, for reliable measurements, it is necessary to keep the leakage resistance of the supporting insulators of the collector above a value of 10^{12} ohms and the choice of insulating materials is important. The method of compensation for the effects of the splashing of rain suggested by Wilson (1916) should be used for a fully-exposed collector.

2.2 INSULATION.

Polystyrene and perspex are the two materials which were considered for use in the construction of supporting insulators for the collector. Both materials are easily machined and have good mechanical properties. Perspex was eventually rejected in favour of polystyrene because it unfortunately absorbs moisture. The high frequency concentric cable with a solid polyethylene insulation was selected to serve as the electrical connexion between the collector and the amplifier. The resistivities of polystyrene and polyethylene are given in the following table.

Material	Volume Resistivity ohms-cm^{-3}	Surface Resistivity ohms-cm^{-2}
Polystyrene	$10^{17} - 10^{19}$	$10^{16} - 10^{18}$
Polyethylene	10^{17}	$> 10^{16}$

A study of the insulating properties of these materials in damp weather was made using the arrangement shown in Figure 2.

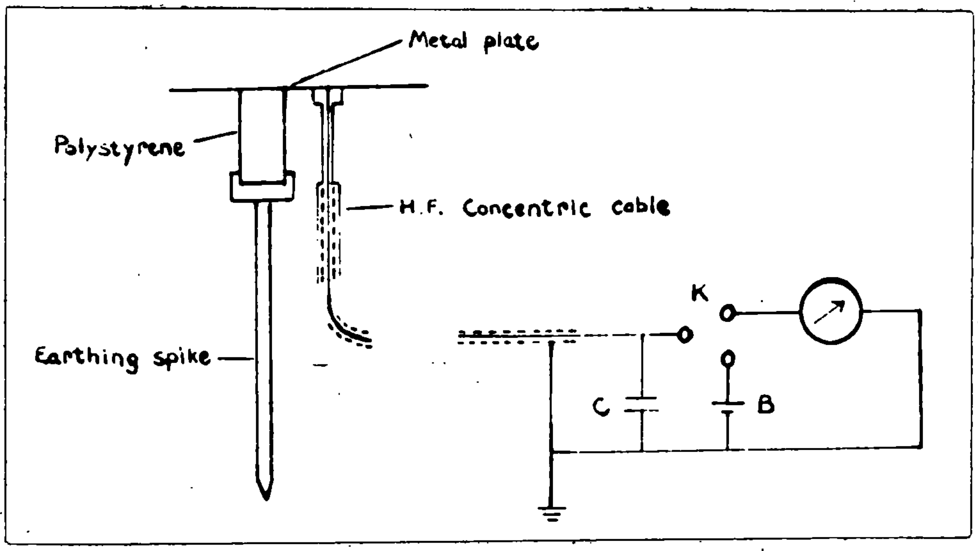


FIGURE 2.

The insulated metal plate was mounted in a hole in the ground with the plate at surface level. A long length of screened cable connected the plate to the measuring equipment in the laboratory. A length of polyethylene about 6 inches long was exposed at the plate end of the cable by removing the polyvinyl chloride cover and the braided sheath. Both ends of the cable were sealed with paraffin wax to prevent moisture from penetrating between the braided sheath and the polyethylene insulation. The plate was left out of doors for about a fortnight and each morning the leakage resistance of the system was measured in the following manner:

A mica condenser, C, of capacitance 0.02 microfarads and leakage resistance greater than 10^{11} ohms was charged to a potential of 3 volts and immediately discharged through the ballistic galvanometer, the deflexion, d_1 being noted. The condenser was then recharged to the same potential and allowed to discharge naturally for 10 minutes before being discharged through the galvanometer. This deflexion, d_2, was observed. The leakage resistance, R, of the condenser was deduced from the relation:

$$\frac{d_2}{d_1} = e^{-\frac{t}{RC}} \qquad (2.01)$$

where t is the time of natural discharge and C the capacitance of the condenser. The cable was next connected in parallel with the condenser and the leakage resistance of the combination was determined in the same manner. From these two results it was a simple matter to deduce the leakage resistance of the metal plate and connecting cable. The capacitance of the cable was of the order of a few hundred micromicrofarads and could be neglected in the calculations. Several observations were always made and a mean value deduced from them. The effect of electrical heating was also studied. The results are summarized in the following table:

Conditions.	Leakage Resistance Ohms.
Electrically heated, all weathers	$> 10^{12}$
Fair weather, low humidity	$10^{12} - 10^{11}$
High humidity, damp ground	$10^{11} - 10^{10}$
After night dew or during light rain	$10^{10} - 10^{9}$
Heavy rain, snow	$10^{9} - 10^{8}$

In addition to the above results, it was observed that the paraffin wax successfully prevented moisture from entering the cable, and so it was never necessary to heat the main body of the cable.

Thus it was evident that satisfactory insulation conditions could be achieved by employing electrical heating and shielding the polystyrene insulators from dust and rain.

2.3 ELECTRIFICATION OF THE INSULATORS.

During preliminary tests with the complete apparatus shown in Figure 1 it was observed that there were rather large fluctuations in the galvanometer deflexion which persisted when the collector was screened from the atmosphere, though to a lesser degree. These fluctuations arose from two independent causes. They were:-

(a) <u>Instability of the amplifier.</u> The large capacitance between the input grid and earth altered the feedback conditions in the amplifier.

(b) <u>Frictional charges on the insulators.</u> These were produced whenever the polyethylene insulation of the cable or the polystyrene supporting insulator was subject to strains of any kind.

It is worth noting that when the collector is exposed to the atmosphere there is an additional contribution from field changes.

The first cause was eliminated by inserting the resistance R9 in the amplifier circuit (Figure 14.). It was then possible to observe the fluctuations due to the frictional charges alone. The insertion of the resistance R9 in some measure reduced the apparent magnitude of the fluctuations, but this is explained in Section 4.8. The connecting cable was now buried in the soil to prevent it being disturbed by wind, but even this did not eliminate the fluctuations completely. The cable was now susceptible to changes in pressure on the soil, and the vertical portion enclosed in the vertical support for the collector tended to respond to any slight movement of the collector. A complete solution to the problem was found by enclosing the cable inside conduit pipe which is supported and fixed in such a manner as to prevent the whole structure from executing large vibrations. The vertical portion of the cable is supported by a paraffin wax filling inside the supporting stem for the collector. As a further measure, the surface of the collector is about 1½ inches below ground level in order to shield it from the wind. Violent action is now necessary to produce frictional charges which can be observed with the galvanometer.

2.4 CONTACT POTENTIAL DIFFERENCES.

During tests to ascertain whether periodic isolation of the amplifier from the collector would provide a zero datum line for the current measurements, it was found that this 'zero' did not coincide with the 'zero' obtained by screening the collector from the atmosphere. The latter 'zero' corresponded to a positive current of 10^{-16} ampere-cms^{-2} in relation to the former. If the screened collector was disconnected from the amplifier for a short period and then reconnected a large impulse was delivered to the galvanometer, and after several observations it was noted that the magnitude of the impulse was proportional to the time during which the collector remained insulated. It was now deduced that the collector was receiving ions from the air in the pit, and it was presumed that this ionic current arose because of contact potential differences between the collector and the surrounding soil. Scrase (1933) had observed an effect similar to this one. Methods to eliminate the effect were considered. They were:-

(a) Introduction of an 'artificial' electric field in the pit to produce a counterbalancing ionic current.

(b) Covering the outer surface of the collector with a thin layer of soil (Wilson 1916).

(c) Lining the pit with the same material as the collector.

(d) Covering the outer surface of the collector and the lining of the pit with the same material.

The first method was tried and proved to be successful. An insulated copper plate was mounted underneath the collector and the negative potential applied to it was varied until the collector showed no sign of charging-up when it was disconnected from the amplifier. The method was not put into operation because it was considered that the variations of moisture content in the soil would produce a variable contact potential difference, thus necessitating continuous adjustment of the compensating potential applied to the plate.

Attempts were made to place a coating of soil on a metal plate, but they met with little success. Furthermore, it was foreseen that this coating would have to be renewed from time to time due to the effects of weathering, and so no further attention was given to method (b).

Method (c) was considered to be a more practical method, but the quantity of copper sheet required indicated that it would be an expensive one. In the interests of economy the method was modified, and method (d) was the outcome. The pit was lined with iron sheet and aluminium 'metallic' paint was applied to the inner surface of this sheet and the outer surface of the collector. Paint was also applied to the underside of the screening plate and the exposed surface of the collector. This method has been adopted and has functioned satisfactorily. Trace B of Plate I on page shows a zero datum level covering a period of 16 hours with the collector screened and connected to the amplifier. A second datum line corresponding to the 5 minute periods at 2 hour intervals when the amplifier was disconnected from the collector can also be seen. It will be observed that a slight discrepancy between the datum lines still remains, but this is only equivalent to a

The Collector.

FIGURE 3.

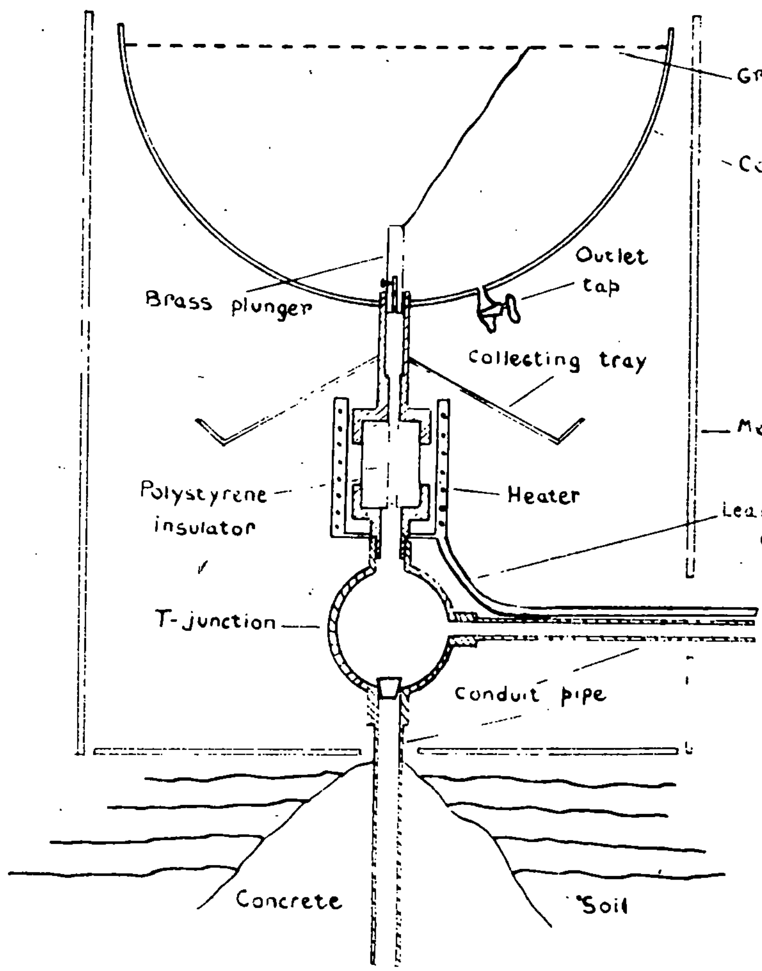
current of 2×10^{-17} ampere-cms^{-2}. This current is probably due to ions reaching the collector in a convection current which can arise in the pit.

2.5 THE COLLECTOR.

The collector is set up in a pit which is about 3 feet deep and 2 feet in diameter. A side-bay is provided to facilitate maintenance. The pit is located approximately 15 feet from the laboratory. A circular brick wall has been built inside the hole to support the surrounding soil. Figure 3. shows the installation.

The design of the collector itself is illustrated in Figure 4. (on page 36).

The hemispherical shape was chosen to minimize the effects due to rain striking the outer surface of the collector and then falling to the ground. The bowl has a diameter of 20 inches and the area of the exposed surface is approximately 2000 cms^2. A thin layer of soil can be placed on the grid in the bowl so that the exposed surface is physically the same as the surrounding surface. In this way complete compensation for the effects of the splashing of rain is obtained. The air gap between the collector and the guard ring is about an inch wide. The conical-shaped collecting tray underneath the collector is used to catch any drops of rain which drip off the outer surface of the collector.



THE COLLECTOR

FIGURE 4.

The polystyrene insulator is about 3 inches in diameter and the exposed surface is about an inch long. A firm support has been obtained by bolting the insulator to the brass cups which hold it at each end. A hole ½ inch in diameter has been drilled down the axis of the insulator so that the connecting cable can pass through it and up to the copper bowl. The polystyrene has been polished with jewellers' rouge in oil and then washed with soap and water. The bowl with the insulator attached is screwed into the top of the T-junction, and at the same time it holds the screened heating coil in place. The heater has a resistance of 20 ohms and the current it carries is regulated by means of a rheostat. It is never allowed to dissipate more than 40 watts, otherwise the polystyrene shows signs of overheating. In addition to preventing the condensation of moisture on the insulator, the heater protects it from rain, dust and stray electric fields. An 'earth' terminal is mounted on the vertical support below the T-junction. The iron sheet lining and a connecting wire from the laboratory are connected to this terminal. The connecting screened cable is carried in conduit pipe from the laboratory to the collector. The portion of cable which projects above the T-junction has been stripped of the polyvinyl chloride cover and braided sheath.

Paraffin wax completely fills the T-junction to prevent movement of the cable at this point, and also seals off this end of the cable from the atmosphere. The inner conductor of the cable is secured inside the brass plunger by means of a bolt, while the braided sheath is connected to earth at the amplifier end. The joint between the plunger and the collector is sealed with paraffin wax to prevent the penetration of water. An iron plate can be supported on the iron sheet lining to screen the collector when necessary.

During foggy weather it was found that moisture condensed in the tube immediately below the plunger and then it dripped down into the top of the T-junction and caused a serious drop in the leakage resistance of the collector. To counter this effect the tube was blocked with paraffin wax just below the plunger, so that any moisture which condensed on the cold metal surface could not reach the insulator.

To discourage spiders from building webs across the gap separating the collector from the guard ring, D.D.T. powder is spread liberally around the collector and some is placed in the bottom of the pit. In damp weather the webs reduce the leakage resistance and sometimes individual fibres are difficult to detect.

The brick and iron sheet linings keep the equipment in the pit in a very clean condition which is essential for this type of work.

CHAPTER III.

THE MEASUREMENT OF SMALL DIRECT CURRENTS.

3.1 GENERAL METHODS.

Three types of instrument are available for measuring small direct currents. They are the electrometer, the galvanometer and the thermionic valve.

Galvanometers are only suitable for measuring currents greater than 10^{-10} amperes. A typical moving coil instrument has a sensitivity of 12,000 mm/micro-ampere, while the moving magnet type can have a sensitivity about ten times this value. They are ideal for photographic recording provided care is taken to avoid thermal E.M.F's and contact potential differences.

Electrometers have a very high charge sensitivity; for the Hoffman electrometer it is of the order of 10×10^{14} mm/coulomb. Their zero drift is determined by changes in contact potential and by non-elastic strain in the suspension. The mirror-types are convenient for photographic recording. Usually the more sensitive instruments are very difficult to handle.

Instruments employing thermionic valves can be used to measure currents greater than 10^{-17} ampere.

The sensitivity is limited by thermal agitation and shot noise in the input circuit. Zero drift is dependent on the stability of the power supplies and the constancy of contact potential differences between the input electrodes. Usually if great care is exercised the drift can be reduced to negligible proportions. Such instruments can be adapted for either photographic or electromagnetic pen-recording, and generally they are reliable in operation as well as being easy to use.

3.2 THE ELECTROMETER VALVE.

A current of the order of 10^{-8} ampere is found to flow between grid and cathode when ordinary thermionic amplifying valves are operated with a negative grid potential. Thus the smallest current which can be measured with such a valve is of that order, and the accuracy of measurement naturally depends on the magnitude of the variation of the grid current. An ordinary valve consequently has no advantage over a sensitive galvanometer.

As a result of a systematic study of the sources of current flowing to the grid and methods of eliminating or reducing them, undertaken by Metcalf and Thompson (1930), special triode and tetrode valves having grid currents in the range of 10^{-13} - 10^{-15} ampere were developed. Because of their special application such valves are termed 'electrometer valves'.

3.3 SOURCES OF GRID CURRENT.

The sources contributing to the grid current in a thermionic valve are listed by Warren (1935) as follows:-

(a) Electrons passing from the cathode to the grid.

(b) Positive ions produced in the residual gas.

(c) Positive ions produced on the surface of the anode by electron bombardment.

(d) Positive ions from the anode.

(e) Poor insulation between the grid and other electrodes.

(f) Primary electron emission from the grid.

(g) Positive ions from the cathode.

(h) Photoelectric emission from the grid.

(j) Secondary emission from the grid, due to positive ion bombardment.

(k) Relatively high-velocity secondary electrons from the cathode due to positive ion bombardment.

The first source can be eliminated by operating the grid at a potential which is sufficiently negative to repel all electrons travelling from the cathode. The effects of positive ions in the valve will be reduced considerably if the anode is operated at a potential which is lower than the ionization potential of the residual gas and simultaneously the secondary emission from the grid, listed as (j) and (k) will become unimportant too. Source (f) may be eliminated if the grid is designed to operate at a low temperature. The use of a dull emitting filament or the introduction of an extra grid, the space-charge grid, immediately around the cathode, which is maintained at a positive potential relative to the cathode will avoid the collection of positive ions from the cathode, source (g). Photo-electric emission can be eliminated by the use of a dull emitting filament and by excluding all external light from the valve. By selecting suitable insulating materials and keeping the valve in an evacuated enclosure, leakage currents may be avoided.

If the above precautions are observed the grid current can be kept to a value below 10^{-15} ampere.

3.4 USE OF THE ELECTROMETER VALVE.

There are four distinct ways of employing the electrometer valve and each will be considered in turn.

(a) Direct Deflexion Method.

The current to be measured is made to develop a voltage across a high resistance, connected between the grid and the cathode of the valve. Generally, the steady anode current is 'backed-off' and the change in this current is indicated by a sensitive galvanometer. Power supplies for the valve are usually obtained from batteries and the stability of such circuits is affected by small changes in the E.M.F's of these batteries. In some cases the zero-drift of the galvanometer may be appreciable. Such circuits are not suitable for long period measurements.

Attempts have been made to improve the stability of these circuits by taking the valve supplies from a single battery using a network of resistances. The values of these resistances are calculated in terms of the operating conditions and the valve characteristics, so that the electrodes have the desired potentials, and the galvanometer current is zero and remains so for variations in the filament current. A number of suitable arrangements have been devised and Penick (1935) discusses several of them.

(b) Null Method.

An auxiliary potential is applied to the grid of the electrometer valve and its magnitude is adjusted until the anode current returns to its original value. This is usually achieved by including a standard variable resistance in the filament circuit and using the voltage developed across it to 'back-off' the applied signal voltage.

(c) Rate of Drift Method.

The grid of the valve is charged to a negative potential with respect to the filament, then the current to be measured is allowed to reduce the negative potential on the grid. Observations of the rate of change of anode current are used to determine the rate of change of grid potential from calibration results. Precautions must be taken to avoid random variations and drift due to changes in battery voltage. Bridge circuits using matched valves can be used to avoid battery fluctuations. The method is usually reserved for measuring currents less than 10^{-15} ampere.

(d) D.C. Amplifiers.

An amplifier is essential when the recording instrument is a milliammeter, an electromagnetic pen recorder or a cathode ray oscillograph. The electrometer valve may be used successfully as the input stage of a D.C. amplifier provided the amplifier is designed carefully to restrict zero-drift. A more stable amplifier can be obtained by employing total negative feedback; this also makes calibration easier and produces a shorter response time. Either batteries or stabilized A.C. operated power supplies are suitable for these amplifiers. The following summary of the characteristics of three D.C. feedback amplifiers indicates the sensitivity and stability which can be anticipated for this type of amplifier.

Roberts (1939) describes a two stage feedback micromicroammeter using a 6C6 as an electrometer valve. High tension and low tension supplies are obtained from an A.C. power unit. No estimate of the stability of the circuit is given.

Graham, Harkness and Thode (1947) have designed a D.C. feedback amplifier capable of measuring ionization currents in the range $2 \times 10^{-10} - 4 \times 10^{-13}$ ampere with an accuracy of 0.5%. The short term fluctuations are equivalent to an input current of 10^{-15} ampere, while the long term drift is equivalent to a current variation of 3×10^{-14} ampere per hour. The amplifier uses an R.C.A. 954 acorn pentode as an electrometer valve, followed by two stages of amplification. A low impedance output is obtained by using a cathode-follower. The valves are all heated from the high tension supply by connecting their heaters in series.

Pierson (1950) has produced a negative-feedback D.C. amplifier with a balanced twin-tetrode electrometer valve (Ferranti DBM8A). Over a period of 80 hours the maximum long term drift is of the order of 1 millivolt for a 5 hour-period. The short term fluctuations are equivalent to a variation of

± 0.5 millivolt of the input voltage. The amplifier is mains operated, has a gain of 700 approximately and will give a maximum undistorted output of ± 3½ volts.

3.5 LIMITATIONS TO THE LINEAR AMPLIFICATION OF SMALL DIRECT CURRENTS.

The limitations of D.C. amplifiers are not understood as thoroughly as those for A.C. amplifiers and consequently estimates of their performance are difficult to make and vary from one designer to another. There are two major factors to consider: short period fluctuations and long term zero-drift. It will be an advantage to exclude from the discussion such sources of disturbance as variation of the voltages from the power supplies, variation of the temperature of components, pick-up of stray signals and those arising from mechanical defects. These fluctuations can be avoided or at least their contribution can be made negligible by careful design.

Short period fluctuations arise from the following sources:-

(a) Anode current shot noise and partition noise.

(b) Grid current shot noise.

(c) Flicker noise.

(d) Leakage currents.

MacDonald (1947) has given a valuable summary of the sources of electrical noise. A careful choice of valves will eliminate leakage currents, and will prevent the valve noise from being unduly excessive. The anode current and grid current shot noise can be readily estimated. It is usual to express the fluctuations in terms of the equivalent input signal which will give the same power output as the fluctuations.

The anode current shot noise in the frequency band o-f c/s has a mean square amplitude given by the relationship

$$\overline{\Delta V}^2 = 2eI_a \int_0^f G \frac{(\rho + |Z|)^2}{\mu^2} df. \qquad (3.01)$$

where e is the electronic charge, I_a the anode current, $|Z|$ the magnitude of the anode load, and μ the valve amplification factor. G is a factor, usually between 0.01 and 0.1 which takes account of the screening effect of the space charge.

For tetrodes and pentodes the relationship is modified to account for the increased noise due to the variable partition of the cathode current between the anode and the screen grid. The relationship becomes

$$\overline{\Delta V}^2 = 2eI\left(\frac{GI_a + I_s}{I_a + I_s}\right)\int_0^f |Z|^2 df. \qquad (3.02)$$

The grid current shot noise is given by the formula

$$\overline{\Delta V_g}^2 = 2eI_g \int_0^f |Z_g|^2 df. \qquad (3.03)$$

where $|Z_g|$ is the magnitude of the grid-cathode impedance.

Flicker noise is difficult to assess. Macfarlane

(1947) has derived a mathematical expression for the effect, but at the present moment it cannot be used to deduce the intensity of noise under given conditions, because of the lack of important quantitative information. The mean square amplitude of flicker noise is known to vary inversely with frequency for the range 10 c/s - 1 Kc/s, while above 1 Kc/s it is negligible. Below some low frequency it is assumed to become uniform. The equivalent input for flicker noise is generally of the order of 50 - 100 microvolts (Harris and Bishop 1949).

Long term drift, after the amplifier has attained temperature equilibrium is probably due to a gradual change in the condition of the cathode and grid materials in the input valve, which affects the electrostatic field conditions in the valve. Attempts to minimize it by using matched valves in balanced circuits are not wholly successful. Superimposed on this long term drift there may be a slow fluctuation of the order of several hours duration, due to changing contact potential differences between the valve electrodes as a result of the variation of temperature. For D.C. amplifiers a low rate of drift has a magnitude of 100 microvolts per 30 min. approximately (Harris and Bishop 1950).

3.6 A.C. METHODS.

More stable amplification can be achieved by using

A.C. methods, but to offset this the conversion of a small direct current into an A.C. signal introduces certain difficulties, among which the avoidance of spurious signals is probably the most important. In addition, a phase-sensitive rectifying system must be introduced, to determine the polarity of the D.C. signal. The two types of converter in general use are the electromagnetically operated contact interrupter and the periodically varying capacitance type. The former is used in circuits requiring a low input impedence, while the latter is reserved for high input impedances.

Gunn (1932) was probably the first to design an A.C. amplifying system for the measurement of small charges and direct currents. The method depends upon the periodic variation of a capacitance connected between the input terminal and the grid of the input valve. A condenser of fixed capacitance is connected between the input terminal and 'earth' while a high resistance is connected between the input grid and 'earth'. The alternation of charge between the two condensers as a result of the varying capacitance produces an A.C. voltage drop across the high resistance, which can be amplified easily to any desired level. Synchronous detection is used to derive the polarity of the signal.

Gunn used a mechanical rectifying system connected to the shaft of the motor which varied the capacitance. The amplifier is essentially a band pass system and so high noise level effects and other fluctuations are minimized. No indication of the zero-drift was given.

Palevsky, Swank and Grenchik (1947) describe a more refined instrument in which the background current is less than 10^{-16} ampere. The zero-drift is equivalent to 0.1 millivolt per 24 hours, and this small value has only been achieved by very careful design of the D.C.-A.C. converter, which is either a vibrating reed or diaphragm. To eliminate the effects of contact potential differences between the condenser plates, it was necessary to use an elaborate procedure for gold-plating them, and afterwards they were operated in an inert atmosphere.

3.7 SELECTION OF A SPECIFIC METHOD.

The D.C. feedback amplifier was chosen for this research for the following reasons:-

(a) It was considered possible to design such an amplifier to give the requisite long-term and short-term stability. The A.C. method is superior on this score, but is more complex and much depends on the construction of the condenser plates. Also it is a more expensive method than the method adopted.

(b) Calibration is easy and such amplifiers are capable of handling large input voltages without distortion.

(c) The potential of the collector is automatically maintained at 'earth' potential.

(d) Either photographic or pen-recording can be used.

(e) Maintenance and setting-up is easy to perform.

CHAPTER IV.

A D.C. NEGATIVE FEEDBACK AMPLIFIER.

4.1 DESIGN CONSIDERATIONS.

The use of total negative feedback with a D.C. amplifier offers several advantages.

Consider the amplifier shown in Figure 5.

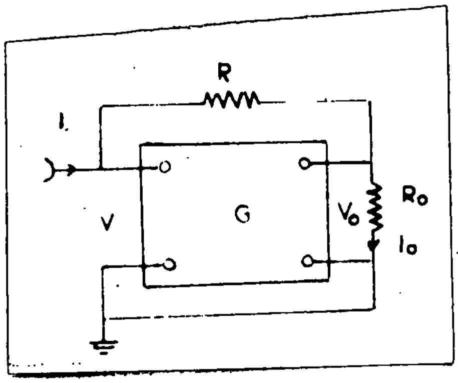


FIGURE 5.

Suppose I , the conduction current from the collector develops an output voltage V_o . Let G be the overall gain of the amplifier without feedback.

The effective input voltage V is given by

$$V = RI - V_o \qquad (4.01)$$

and

$$V_o = GV \qquad (4.02)$$

$$\therefore \quad I = \frac{V_o}{R} \cdot \frac{G+1}{G} \qquad (4.03)$$

$$I = I_o \cdot \frac{R_o}{R} \cdot \frac{G+1}{G} \qquad (4.04)$$

Thus if $G \gg 1$, I_o is directly proportional to I and a linear system is obtained.

The effective input resistance R_e is given by

$$R_e = \frac{V}{I} = R - \frac{V_o}{I} \qquad (4.05)$$

Substituting for I from equation (4.03)

$$R_e = R - \frac{G}{G+1} R \qquad (4.06)$$

$$= \frac{R}{G+1} \qquad (4.07)$$

Thus the input resistance is effectively $R/G+1$ and similarly the time constant of the input circuit is reduced from CR to $CR/G+1$. Calibration is made easier and the amplifier can handle a high input voltage before saturation sets in. Improved stability is obtained and small changes in gain become unimportant. An advantage which is important for the present application is that the ion collector is maintained at a steady potential and it is easy to arrange that the potential is 'earth'. Thus the collector will ideally simulate an actual piece of ground in electrostatic conditions, and there will be no voltage stresses across the supporting insulator.

4.2 THE ELECTROMETER INPUT STAGE.

The smallest current to be measured is of the order

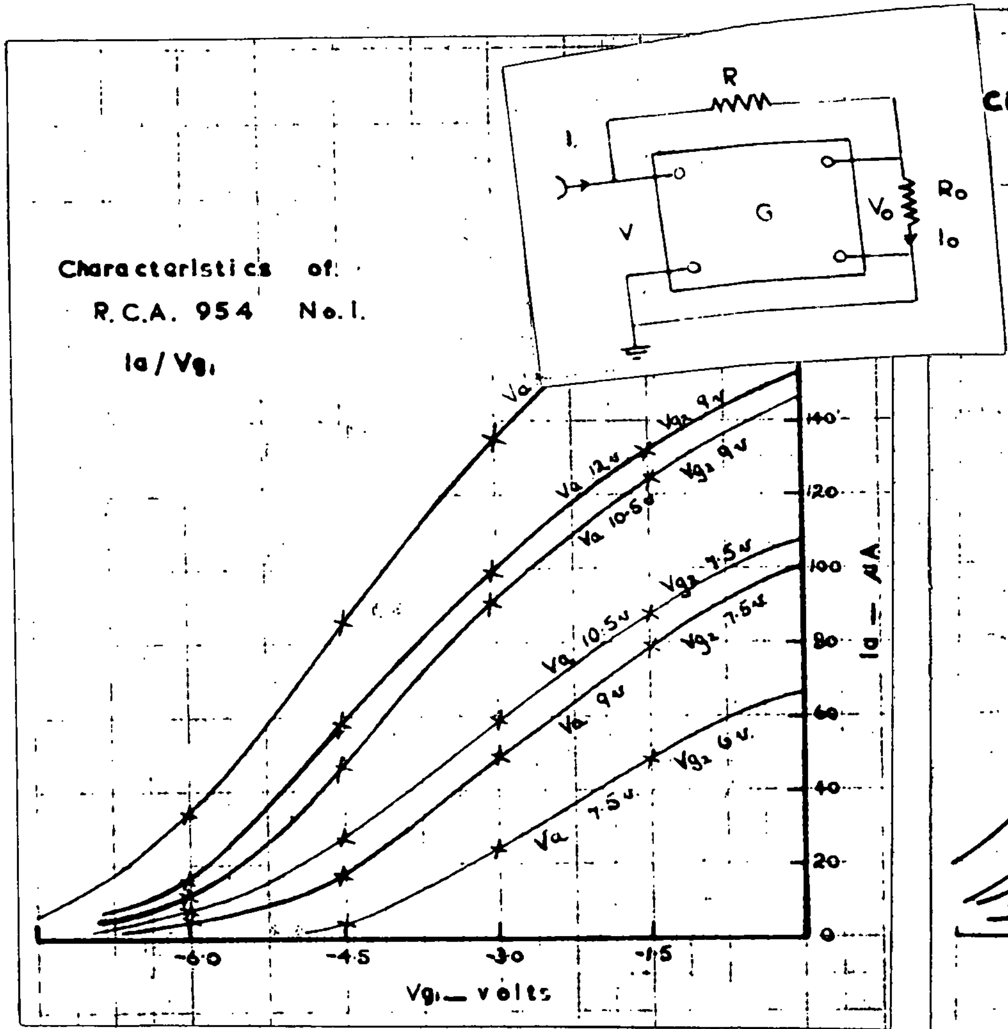


FIGURE 6.

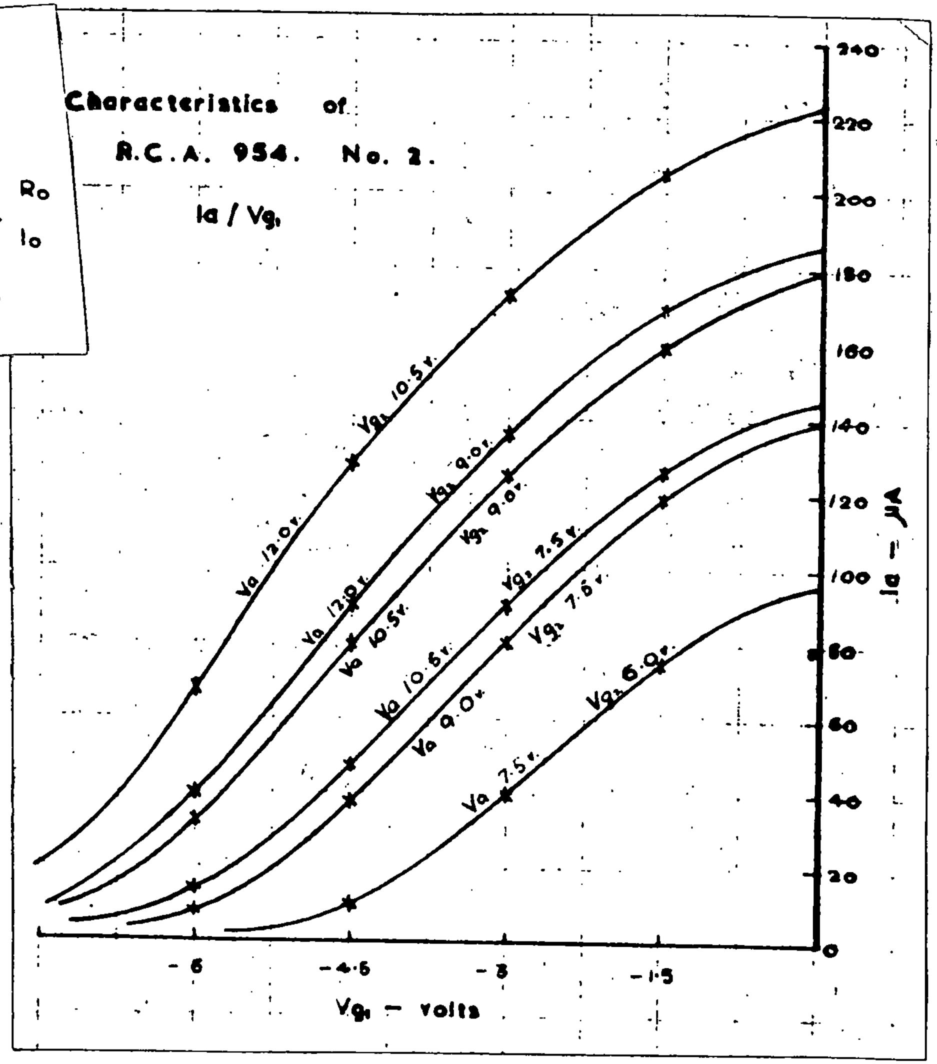


FIGURE 7.

of 10^{-13} ampere, so for a reliable performance it was necessary to use a valve having a grid current no greater than 10^{-14} ampere. Conventional electrometer valves were avoided because of their expense and susceptibility to microphonics. Gabus and Pool (1937) showed that an R.C.A. 954 acorn pentode could be used as an electrometer valve under certain conditions. Later, Nielsen (1947) made a more detailed study and showed that the R.C.A. 959 was also suitable for electrometer work. A '959' was immediately available and was tried first. Unfortunately the valve is directly heated and when heated from a stabilized mains operated supply it was found that the short term fluctuations were too great, consequently the valve was rejected in favour of the 954.

The characteristics of two 954 valves were determined under the conditions suitable for electrometer work. They are shown in Figures 6, 7, 9, and 12. Then the valve grid currents were measured, using the rate of drift method. The grid current is given by the relation

$$I_g = C_g \frac{\partial E_g}{\partial t} = C_g \frac{\partial I_a}{\partial t} \cdot \frac{\partial E_g}{\partial I_a} \qquad (4.08)$$

where I, C and E refer to current, capacity and voltage respectively and the subscript letters 'a' and 'g' to anode and grid respectively. After the valve had

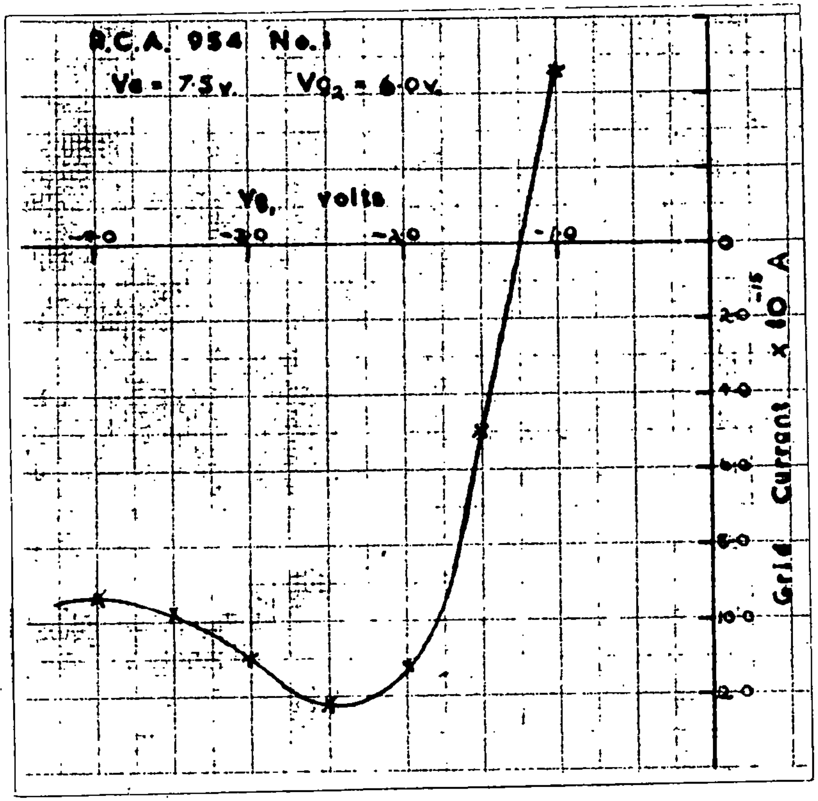


FIGURE 8.

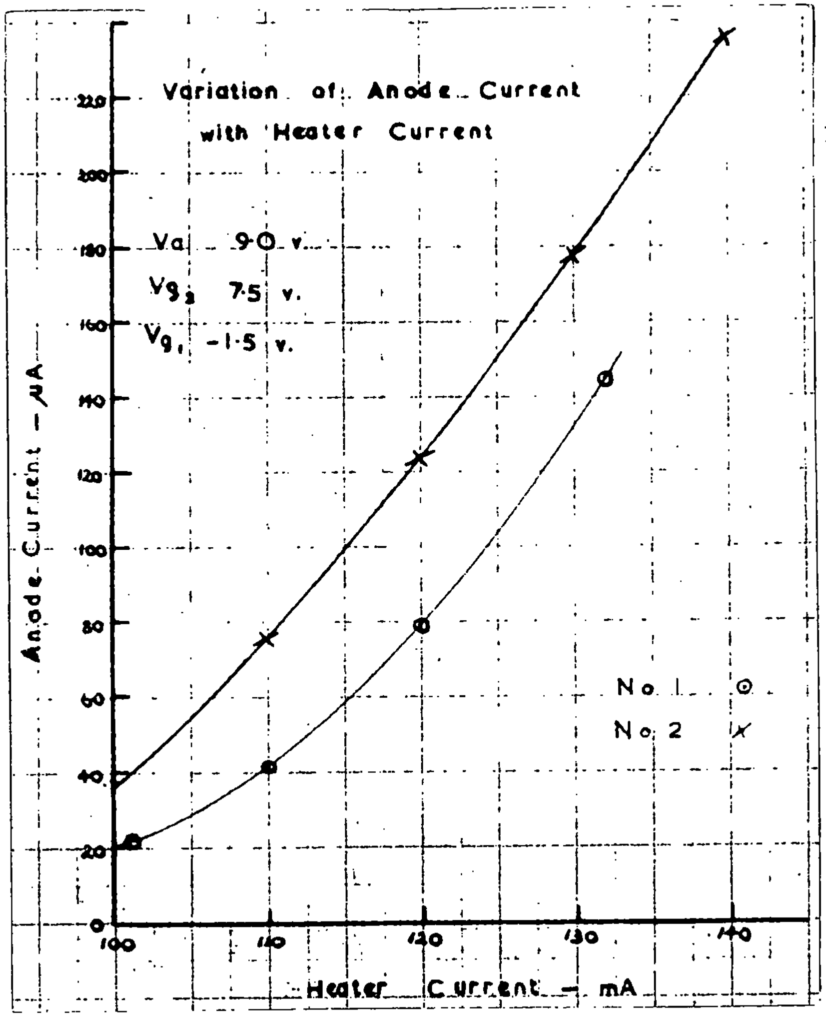
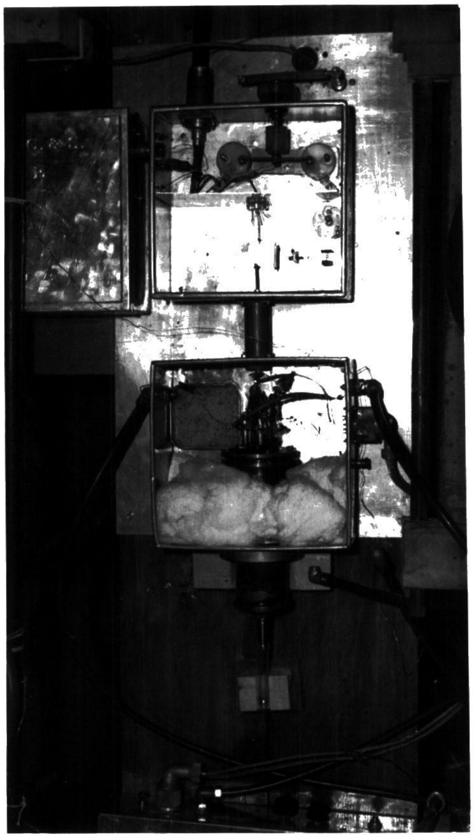


FIGURE 9.

been scrupulously cleaned with a swab soaked in 95% ethyl alcohol it was mounted in a light-proof tin box. Connexion to each valve pin was made with a tiny barrel connector, and the connecting wires were stout enough to give the valve a rigid suspension. A short length of concentric screened cable with polyethylene insulation was used as the control grid lead. The capacity of the grid circuit was determined by a bridge method. Valve No. 1 was found to be more suitable for electrometer work and its grid current characteristic is given in Figure 8. .

To minimize leakage effects the electrometer valve has been mounted in a brass vacuum chamber (Figure 11.) in the manner described in the preceding paragraph. The heater, space-charge grid and cathode leads are taken through a metal-glass seal, while polystyrene insulation is used for the anode, control grid and feedback leads. The polystyrene insulators are screwed firmly into the end-plate of the chamber and all the joints are sealed with Apiezon 'W' vacuum wax. To avoid damaging the surfaces of the insulators with heat the first layers of wax were deposited from a solution in benzene. Later, more wax was added using heat. The 10^{11} and 10^{10} ohm resistors are situated inside the chamber, which is mounted inside a tin box so that the



The Electrometer Stage.

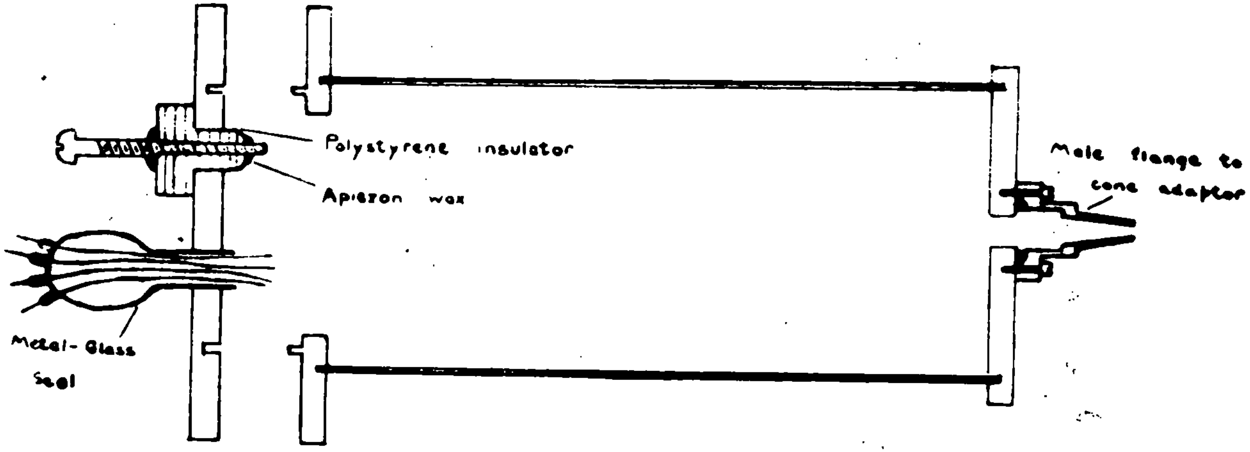
FIGURE 10.

input leads have complete electrical shielding. Sorbo rubber is used to give a shock-proof mounting. Several layers of cotton wool surround the chamber to provide adequate heat insulation, and the glass tube leading from the chamber to the vacuum pump is also covered to prevent light from entering the chamber at the evacuation point. A weekly evacuation is adequate for maintaining a good vacuum.

The disposition of the electrometer valve V_3 in the amplifier circuit is shown in Figure 14. The anode and screen voltages are 10 volts and 9 volts respectively, while the cathode resistor develops a bias of 2 volts. The heater supply of 120 milliamperes is taken from the 225 volt H.T. supply, adjustments being made by varying the rheostats R.25 and R.26. Also the minimum potential on the heater is maintained at a volt above the cathode potential to prevent electrons from the heater reaching the control grid.

The valve grid current under the operating conditions stated above is approximately 10^{-14} ampere, and the grid resistance is of the order of 5×10^{14} ohms. It is now possible to estimate the equivalent noise voltages in the input circuit using relations (3.01) and 3.03) and the following values for the circuit constants:

$$C_g = 800\,\mu\mu F, \quad R_g = 10^{11}\,\Omega, \quad R = 2M\Omega,$$



VACUUM CHAMBER

FIGURE 11.

$\rho = 150 K\Omega$, $\mu = 2.7$, $I_a = 50 \mu A$, $I_g = 10^{-14}$ ampere, $e = 1.6 \times 10^{-19}$ coulomb, and the bandwidth of the anode circuit f = 20 Kc/s.

Anode current shot noise

$$\overline{\Delta V}^2 = \frac{2eI_a}{\mu^2}\int_0^f (\rho+R)^2 df$$

$$= \quad 2 \times 10^{-8} \text{ volt}^2$$

Grid current shot noise

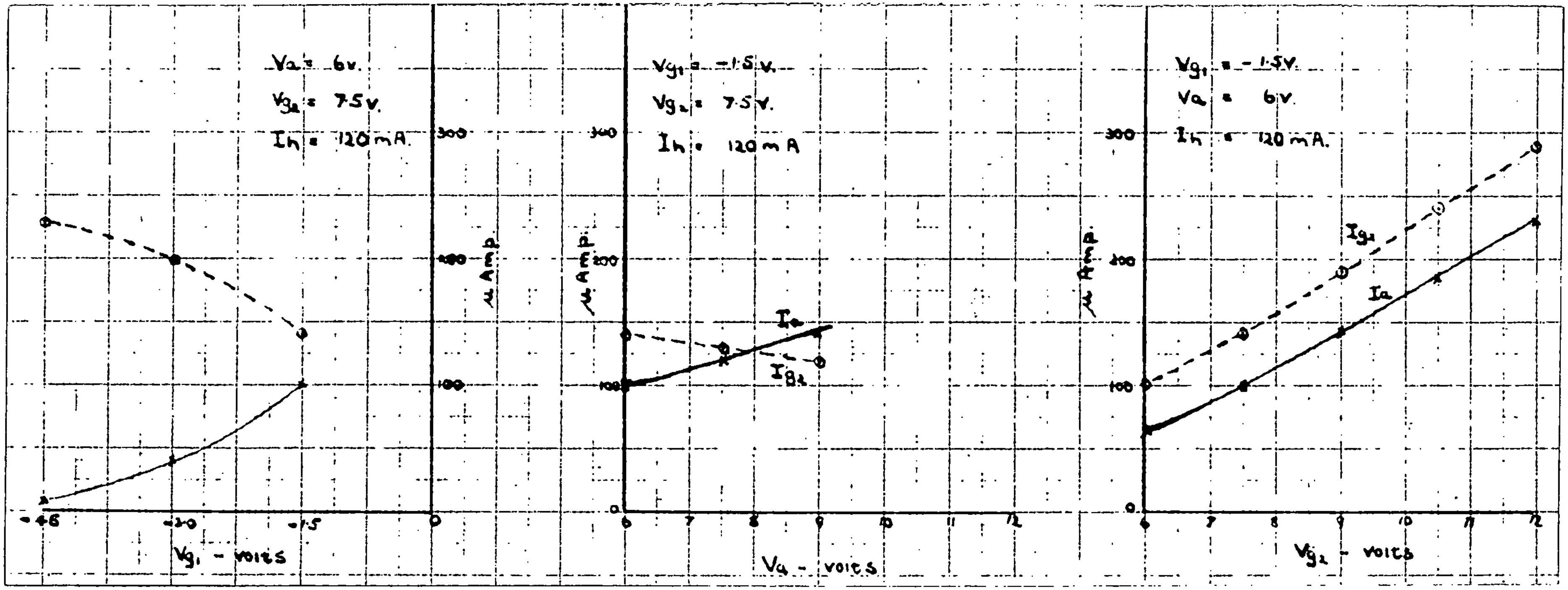
$$\overline{\Delta V}^2 = \frac{eI_gR_g}{2C}$$

$$= \quad 1 \times 10^{-13} \text{ volt}^2$$

The anode current shot noise makes the largest contribution, and if the equivalent input for flicker noise is assumed to be 100 microvolts, the total noise input will be equal to 240 microvolts approximately. Thus the noise disturbances are well below the smallest input signal of 2 - 4 millivolts.

4.3 ZERO-DRIFT COMPENSATION.

Early experiments with an amplifier almost identical with that described by Graham et al (1947) showed that the minimum value of long term zero-drift which could be obtained was equivalent to a change of current referred to the input of 3×10^{-14} ampere per hour. This value was unsatisfactory for the long period recording which was required. To improve the performance of the amplifier the following method was devised.



Va = 6v.
Vg2 = 7.5v.
Ih = 120mA.
Vg1 - volts
μAmp
Vg1 = -1.5v.
Vg2 = 7.5v.
Ih = 120mA
Ia
Ig2
Va - volts
Vg1 = -1.5v.
Va = 6v.
Ih = 120mA.
Ig2
Ia
Vg2 - volts

FIGURE 12

A second R.C.A. 954, V_2 of Figure 14. is used to minimize zero-drift. The anode voltage of 20 volts approximately for V_1 (Figure 14.) is obtained from a V.R.150/30, using a voltage divider resistor chain. The valve is mounted inside a tin box on the main amplifier chassis. To minimize temperature changes the box is lagged with asbestos.

When the amplifier is set up to give zero output for zero input, both input and output potentials will be at 'earth'. The input grid should remain at this potential even when the amplifier is recording conduction currents, but any voltage drift in the succeeding stages of the amplifier will cause the potential to deviate from 'earth'. Thus to minimize drift, it is necessary to maintain the input potential at 'earth'. E. Williams (1944) has shown that a cathode-coupled double triode amplifying stage will give an output voltage proportional to the potential difference between the grids under certain conditions. If this output is fed back in the correct phase it can be used to reduce the potential difference between the grids to zero. An examination of the characteristics for the two 954's shows that they can be made to have almost identical operating conditions. The resistance R_{27} in Figure 14. is used to reduce the anode current of valve No. 2 so that it is approximately equal to the anode current of valve No. 1 over the heater current range 115 - 120 milliamperes. For a change in grid voltage the total cathode current of a '954' remains practically constant so that it is necessary to achieve additional coupling between the valves. From Figure 12. it will be seen that the space-charge grid current decreases at the same rate as the anode current increases with control grid voltage. It is thus possible to obtain adequate coupling between the valves by using both the space-charge grid and the cathode of each valve. The control grid of the 'balancing' valve was connected to earth, and examination of the amplifier circuit together with the following analysis shows that the feedback is degenerative for zero-drift too.

Consider the simplified arrangement of the input stage as shown overleaf:-

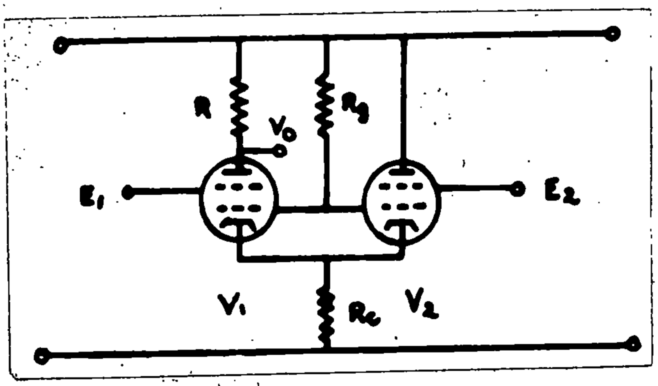


FIGURE 13.

Suppose potentials E_1 and E_2 are applied to the grids of V_1 and V_2 respectively.

The change in anode current in each valve can be represented by the equation:-

$$\Delta I_a = k \Delta V_a + p \Delta V_s + q \Delta V_g \qquad (4.09)$$

where the parameters k, p and q are defined as follows:-

$$k = \left(\frac{\partial I_a}{\Delta V_a}\right)_{s,g}, \quad p = \left(\frac{\partial I_a}{\Delta V_s}\right)_{g,a}, \quad q = \left(\frac{\partial I_a}{\partial V_g}\right)_{a,s.} \qquad (4.10)$$

and the suffixes 'a', 's' and 'g' refer to anode, space-charge grid and control grid respectively. Similarly the change in space-charge grid current can be represented by the equation:-

$$\Delta I_s = l \Delta V_a + m \Delta V_s + n \Delta V_g \tag{4.11}$$

where

$$l = \left(\frac{\Delta I_s}{\Delta V_a}\right)_{s,g}, \quad m = \left(\frac{\partial I_s}{\partial V_s}\right)_{g,a}, \quad n = \left(\frac{\partial I_s}{\partial V_g}\right)_{a,s} \tag{4.12}$$

From Figure 12. it is reasonable to assume that $n = -q$, $m = p$ and $l = -k$, and so

$$\Delta I_s = -k \Delta V_a + p \Delta V_s - q \Delta V_g \tag{4.13}$$

For the circuit of Figure the following equations hold:

$$\Delta I_{a_1} = k \Delta V_{a_1} + p \Delta V_s + q \Delta V_{g_1} \tag{4.14}$$

$$\Delta I_{a_2} = k \Delta V_{a_2} + p \Delta V_s + q \Delta V_{g_2} \tag{4.15}$$

$$\Delta I_{s_1} = -k \Delta V_{a_1} + p \Delta V_s - q \Delta V_{g_1} \tag{4.16}$$

$$\Delta I_{s_2} = -k \Delta V_{a_2} + p \Delta V_s - q \Delta V_{g_2} \tag{4.17}$$

$$4p . \Delta V_s = \Delta I_{s_{1+2}} + \Delta I_{a_{1+2}} \tag{4.18}$$

$$\Delta V_{a_1} = -R \Delta I_{a_1} - 4p . R_c \Delta V_s \tag{4.19}$$

$$\Delta V_{a_2} = - 4p . R_c \Delta V_s \tag{4.20}$$

$$\Delta V_s = -R_g(\Delta I_{s_1} + \Delta I_{s_2}) - 4p . R_c \Delta V_s \tag{4.21}$$

$$\Delta V_{g_1} = E_1 - 4p . R_c \Delta V_s \tag{4.22}$$

$$\Delta V_{g_2} = E_2 - 4p . R_c \Delta V_s \tag{4.23}$$

From equations (4.16), (4.17), (4.19), (4.20), (4.21), (4.22) and (4.23)

$$\Delta V_s (1 + 4pR_c + 2pR_g + 8kpR_cR_g + 8pqR_cR_g) = -kRR_g \Delta I_{a_1} + qR_g(E_1 + E_2) \tag{4.24}$$

Equation (4.14) can be written as

$$\Delta I_{a_1}(1+kR) = \Delta V_S(p-4kpR_c-4pqR_c) + qE_1 \tag{4.25}$$

Then on combining equations (4.24) and (4.25)

$$\Delta I_{a_1}(1+kR)A = [qR_g(E_1+E_2) - kRR_g\Delta I_{a_1}](p-4kpR_c-4pqR_c) + qAE_1 \tag{4.26}$$

where

$$A = 1+4pR_c+2pR_g+8kpR_cR_g+8pqR_cR_g \tag{4.27}$$

$$\therefore \Delta I_{a_1}[(1+kR)A + kRR_g(p-4kpR_c-4pqR_c)] = qR_g(p-4kpR_c-4pqR_c)(E_1+E_2) + qAE_1 \tag{4.28}$$

$$\Delta I_{a_1} = \frac{4pqR_cR_g(k+q)(E_1-E_2) + q(1+3pR_g+4pR_c)E_1 + pqR_gE_2}{(1+kR)A + kRR_g(p-4kpR_c-4pqR_c)}$$

or

$$\Delta I_{a_1} = \frac{4pqR_cR_g\left[(k+q)(E_1-E_2) + \frac{1+3pR_g+4pR_c}{4pR_cR_g}E_1 + \frac{E_2}{4R_c}\right]}{4pR_cR_g(k+q)(2+kR) + (1+kR)(1+4pR_c) + pR_g(2+3kR)} \tag{4.29}$$

Now the parameters k, p and q are each of the order of $20\mu A$ /volt, while R and R_g are in the range 0.1 - 2 megohms. Consequently equation (4.29) can be reduced to the approximate form:-

$$\Delta I_{a_1} = \frac{q(E_1 - E_2)}{2 + kR} \tag{4.30}$$

provided R_c has a reasonably large value.

The output voltage V_0 across the anode load of V_1 is given by the relation

$$V_0 = -R\Delta I_{a_1}$$

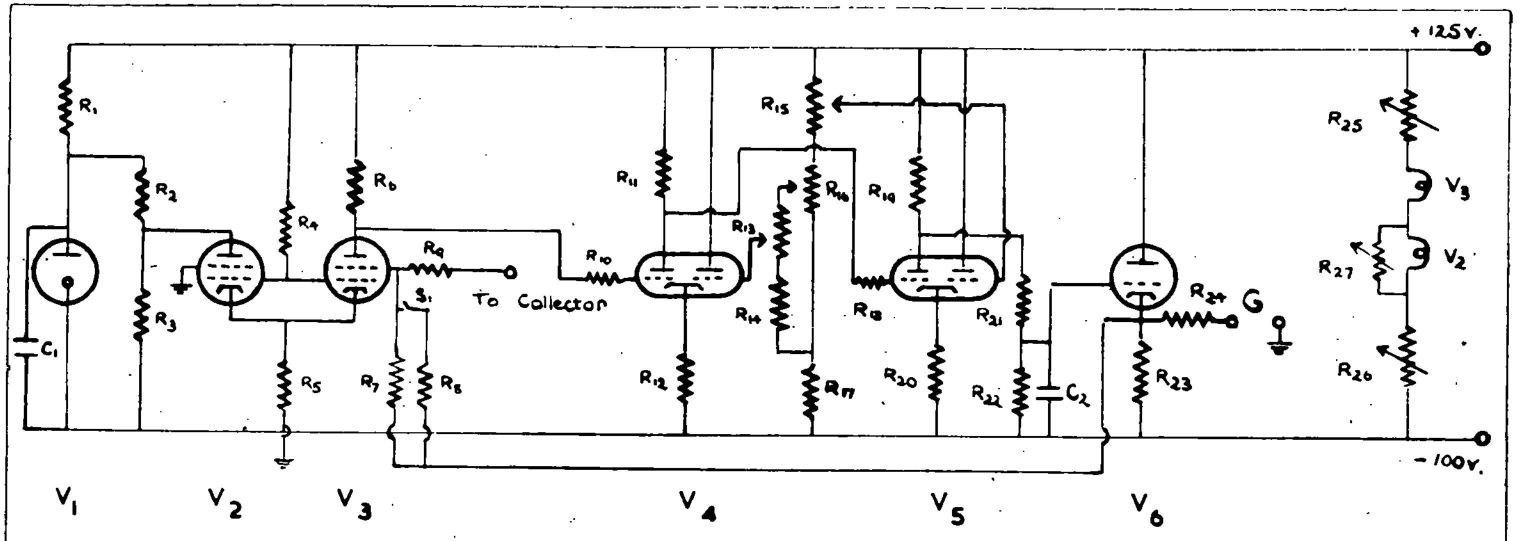
$$= -\frac{q}{k}(E_1 - E_2) \tag{4.31}$$

provided $kR \gg 2$.

Thus any change of voltage between the grids of the two valves produces an output voltage proportional to the voltage difference between the grids and phase-reversed with respect to the grid of V_1, provided R and R_g are very large. R_c must have a sufficiently large value to justify the approximation in equation (4.30).

4.4 THE MAIN SECTION OF THE AMPLIFIER.

The electrometer input stage is followed by two stages of amplification using 6 SC 7 double triodes. E. Williams (1944) has commented on the stability and



R1 — 50 KΩ	R11 — 500 KΩ		R21 — 3 MΩ			V1 —	VR 150/30
R2 — 20 KΩ	R12 — 250 KΩ		R22 — 3 MΩ			V2,3 —	R.C.A. 954
R3 — 100 KΩ	R13 — 10 KΩ	pot. w.w.	R23 — 25 KΩ	w.w.		V4,5 —	6SC7
R4 — 200 KΩ	R14 — 20 KΩ	w.w.	R24 — 50 KΩ	w.w.		V6 —	6J5
R5 — 10 KΩ	R15 — 50 KΩ	pot. w.w.	R25 — 1200 Ω	w.w.			
R6 — 2 MΩ	R16 — 5 KΩ	pot. w.w.	R26 — 1200 Ω	w.w.		S1 —	Relay Switch
R7 — 10^{11} Ω	R17 — 50 KΩ	w.w.	R27 — 800 Ω	w.w.			
R8 — 10^{10} Ω	R18 — 10 KΩ						
R9 — 10^{9} Ω	R19 — 330 KΩ		C1 — ·006 μF				
R10 — 10 KΩ	R20 — 300 KΩ		C2 — ·05 μF				

D. C. AMPLIFIER

FIGURE 14.

compensation for current drifts due to variations of cathode temperature, which can be obtained by using this class of valve. The second amplifying stage is followed by the cathode-follower output stage and a resistor chain is used to couple the valves. Such an arrangement reduces the overall gain by a factor of 2, but it was considered to offer greater stability as a coupling device than the use of a gas-discharge valve (Graham et al (1947)). The condenser C_2 is essential for adjusting the feedback so that oscillations are avoided. R_{15} is preset while the other potentiometers R_{16} and R_{13} are used as coarse and fine zero controls respectively. All resistors have high wattage ratings and in important parts of the circuit wire wound types are used. Without feedback the amplifier has a gain of approximately 500, and it can handle an input of 20 volts before saturating.

4.5 THE RECORDING APPARATUS.

The recording instrument is a sensitive Cambridge mirror-galvanometer used in conjunction with a drum camera. The galvanometer has a period of 24 seconds, and is used in an over-critically damped condition. An advantage is obtained by using a sensitive galvanometer. The shunt resistances are extremely small in magnitude compared with the damping resistance, thus if they are shorted out in operation the damping condition will remain unchanged. The drum camera will function at two speeds, namely 1 revolution per hour (resolution 39.2 cms/hour) and 1 revolution per 24 hours (resolution 1.7 cms/hour). The overall width of the photographic paper is 12 cms. and the maximum sensitivity of the galvanometer has been adjusted so that 0.5 cm. deflexion represents an output of 0.02 volt from the amplifier.

4.6 CALIBRATION AND 'ZEROING'.

The 10^{11} ohm and 10^{10} ohm resistors were calibrated by the leakage method described in Section 2.2.

The galvanometer circuit was calibrated in terms of voltage by using a normal potentiometer method. The individual resistances used in the shunt circuit were calibrated using a bridge-megger.

A resistance of the order of 6×10^{11} ohms is used for calibrating the amplifier regularly in order to check the sensitivity. The resistance was calibrated in terms of the 10^{11} ohm resistor by connecting it in series with a 1.5 volts dry cell and applying a potential to the input grid of the amplifier. The calibration was checked later using a quadrant electrometer with the rate of drift method.

As indicated in Section 2.4, a zero datum line is obtained by periodically disconnecting the amplifier from the collector for a short interval. The more

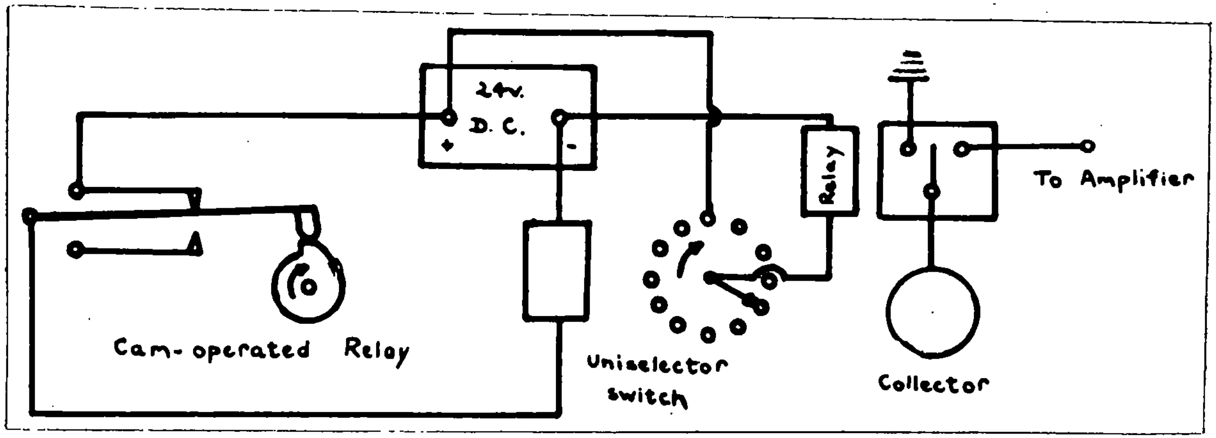

24v.
D. C.
+
-
Relay
To Amplifier
Cam- operated Relay
Uniselector
switch
Collector

FIGURE 15.

conventional method of screening the collector could not be used because of the great mechanical difficulties and power requirements necessary for moving a large iron plate at regular intervals.

A see-saw type switch with polystyrene insulation is used for disconnecting the amplifier from the collector and simulteneously it 'earths' the collector. The switch box is shown in Figure 10. The contacts of the switch are tipped with platinum so that contact potential troubles are avoided. The plunger-type relay which operates the switch can be energized for a period of 5 minutes at either half-hourly or hourly intervals as desired, using the relay system shown in Figure 15. The cam is made to perform one revolution in 5 minutes by a synchronous motor with a suitable gear train. The moving contact arm on the uniselector switch is thus moved on to the next contact after 5 minutes and the zero-switch relay is connected to suitable contacts in the uniselector so that it is energized at either half-hourly or hourly intervals. The method has proved very successful in operation.

As pointed out in Section 2.4, a small current of the order of 2×10^{-17} amp.cms^{-2} is recorded when the collector is screened and a correction is made for this.

4.7 PERFORMANCE.

Trace A of Plate I shows a typical record for the zero stability of the amplifier over a period of approximately 16 hours. The fluctuations at the beginning of the trace are those obtained when the collector was connected to the amplifier. The long-term drift is due in part to the effect of temperature changes on the galvanometer shunt circuit. In warm weather the room temperature increases rapidly because of the heat generated by the valves in a small room with inadequate ventilation. Usually the drift is equivalent to a current variation of 10^{-14} ampere per hour referred to the input.

Short-term fluctuations never exceed the equivalent current variation of 4×10^{-14} ampere. Such fluctuations only occur when there are serious changes in the mains supply.

The stability of the amplifier with the screened collector attached is shown in trace B of Plate I. The short-term stability depends on how well the collector is screened from wind and dust. To obtain this record the cover plate had to be buried under a thick layer of soil to seal the pit effectively.

The three most important factors governing the stability were found to be:-

(1) Bad contacts in the heater circuit of the electrometer valve.

Trouble from this source was experienced during the early stages of the work due to the employment of well-worn rheostats in the heater circuit. Variable resistances with an adjustable screw-clip are to be preferred to the type employing a 'wiping-arm'.

(2) Temperature effects.

This effect can only be minimized by lagging the amplifier with thermal insulating material.

(3) Light.

It was found that a small amount of light was leaking into the vacuum chamber via the glass-tap and the evacuation orifice and much of the long-term drift was attributed to the variations produced by large changes in intensity of the light in the laboratory. The remedy, fortunately, was simple. The glass apparatus was screened from all light.

Since the operational model of the amplifier was set up no serious troubles or breakdowns have occurred, and every record taken has been satisfactory.

4.8 RESPONSE OF THE AMPLIFIER TO 'IMPULSES'.

The following analysis was carried out to determine to what extent 'impulsive currents' produced by field changes could be smoothed out.

Consider the equivalent amplifier circuit shown in Figure 16. :-

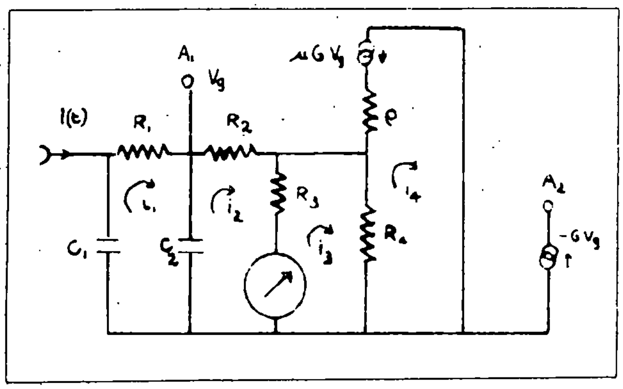


FIGURE 16.

The concentric cable in the input circuit is represented by the lumped capacitances C_1 and C_2. A_1 denotes the signal grid of the electrometer valve. The portion of the circuit to the right of R_2 is essentially the equivalent circuit of the cathode-follower output stage. It is assumed that the amplifier gain without feedback G, is a real quantity; in other words, that the feedback is inverse at all frequencies.

Furthermore, to simplify the equations the galvanometer is considered as a pure resistance of low value.

The Laplace transform (Carslaw and Jaeger (1947), Jaegar (1946)) is used throughout the analysis.

The ion-current to be measured is represented as a function of time $I(t)$. Employing the circulating currents shown in the diagram and applying Kirchhoff's Laws, the following subsidiary equations are obtained:-

$$\left(\frac{1}{pC_1} + \frac{1}{pC_2} + R_1\right)\bar{i}_1 = \frac{1}{pC_2}\bar{i}_2 + \frac{1}{pC_1} I(t) \qquad (4.32)$$

$$\left(\frac{1}{pC_2} + R_2 + Z\right)\bar{i}_2 = Z\bar{i}_3 + \frac{1}{pC_2}\bar{i}_1 \qquad (4.33)$$

$$Z(\bar{i}_3 - \bar{i}_2) = Y(\bar{i}_4 - \bar{i}_3) \qquad (4.34)$$

$$(\mu+1)Y(\bar{i}_4 - \bar{i}_3) + \rho\bar{i}_4 = \mu G\frac{1}{pC_2}(\bar{i}_1 - \bar{i}_2) \qquad (4.35)$$

If $\mu \gg 1$, equation (4.35) reduces to:-

$$Y(\bar{i}_4 - \bar{i}_3) + \frac{\bar{i}_4}{g_m} = \frac{G}{pC_2}(\bar{i}_1 - \bar{i}_2) \qquad (4.36)$$

where

$$g_m = \mu/\rho$$

From equations (4.34) and (4.36)

$$\bar{i}_3\left\{Z+\frac{Z+Y}{Yg_m}\right\} = \bar{i}_2\left\{Z+\frac{Z}{Yg_m}-\frac{G}{pC_2}\right\}+\frac{G}{pC_2}\bar{i}_1 \qquad (4.37)$$

Equation (4.33) is multiplied throughout by G and is then subtracted from equation (4.37) giving

$$\bar{i}_3\left[(G+1)Z+\frac{Z+Y}{Yg_m}\right] = \bar{i}_2\left[(G+1)Z+GR_2+\frac{Z}{Yg_m}\right] \qquad (4.38)$$

From equations (4.32) and (4.33)

$$\bar{i}_2\left[A(1+pC_2R_2+pC_2Z)-pC_1\right] = \bar{i}_3\,pC_2ZA+pC_2\,\bar{I}(t) \qquad (4.39)$$

Where $\quad A = pC_2+pC_1+p^2C_1C_2R_1$

and combining equation (4.38) with equation (4.39)

$$\bar{i}_3-\bar{i}_2 = \bar{\Delta i} = \frac{\left(GR_2-\frac{1}{g_m}\right)\bar{I}(t)}{Bp^2+Dp+E} \qquad (4.40)$$

where

$$B = C_1C_2R_1R_2\left(Z+\frac{Z+Y}{Yg_m}\right)$$

$$D = GZC_1R_1+\left(Z+\frac{Z+Y}{Yg_m}\right)\left(C_1R_1+C_2R_2+C_1R_2\right)$$

$$E = (G+1)Z+\frac{Z+Y}{Yg_m}$$

First of all consider equation (4.40) under the following conditions:-

$$R_1 = 0 \quad , \quad C_1 + C_2 = C$$

$$\overline{\Delta i} = \frac{\left(GR_2 - \frac{1}{g_m}\right)\bar{I}(t)}{pCR_2\left(Z + \frac{Z+Y}{Yg_m}\right) + (G+1)Z + \frac{Z+Y}{Yg_m}} \qquad (4.41)$$

Now suppose $I(t) = Q[1 - H(t-a)]$, that is a rectangular-shaped current pulse of amplitude Q and duration 'a' seconds is applied to the circuit under the conditions stated above.

$$\bar{I}(t) = \frac{Q}{p}\left(1 - e^{-ap}\right) \qquad (4.42)$$

$$\therefore \quad \overline{\Delta i} = \frac{Q\left(GR_2 - \frac{1}{g_m}\right)\left(1 - e^{-ap}\right)}{p\left[pCR_2\left(Z + \frac{Z+Y}{Yg_m}\right) + (G+1)Z + \frac{Z+Y}{Yg_m}\right]} \qquad (4.43)$$

Assuming $GR_2 \gg \frac{1}{g_m}$, $G \gg 1$ and $Z \gg \frac{Z+Y}{Yg_m}$, equation (4.43) reduces to

$$\overline{\Delta i} = \frac{Q.GR_2\left(1 - e^{-ap}\right)}{CR_2 Z\, p\left(p + \frac{G}{CR_2}\right)} \qquad (4.44)$$

$$\therefore \Delta i = Q.\frac{R_2}{Z}\left(1 - e^{-\frac{G}{CR_2}t}\right) - Q.\frac{R_2}{Z}.H(t-a)\left[1 - e^{-\frac{G}{CR_2}(t-a)}\right] \qquad (4.45)$$

If $R_2 = 10^{11}\Omega$, $C = 725\mu\mu F$, and $G = 500$ the time constant $\frac{CR_2}{G}$ is 145 milliseconds. Figure 17. shows the form of Δi when a = 50 milliseconds (A) and a = 1 second (B)

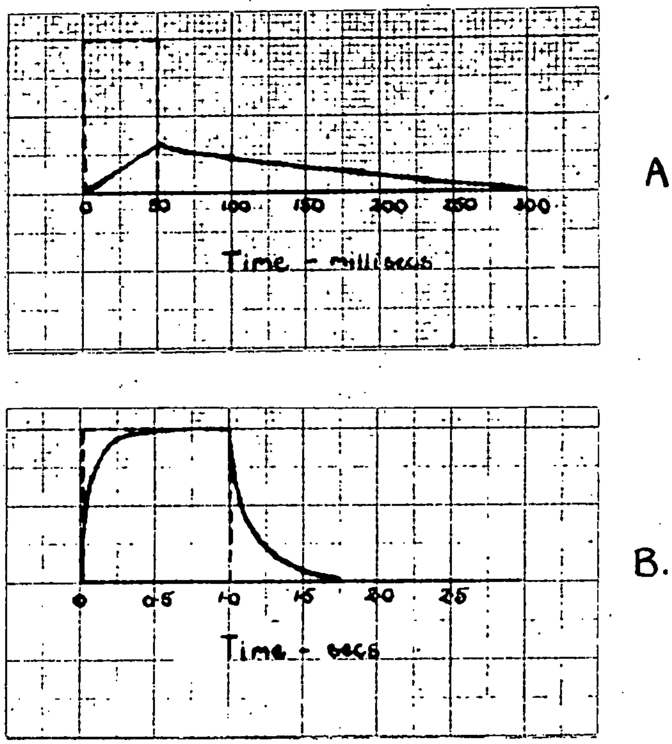


FIGURE 17.

Now consider the effect of introducing R_1.

It is assumed that $G \gg 1$, $Z \gg \frac{Z+Y}{Y g_m}$ and $(C_1+C_2)R_2 \ll GC_1R_1$

Equation (4.40) then becomes:-

$$\overline{\Delta i} = \frac{G R_2 \bar{I}(t)}{GC_2R_1R_2Z\left(p^2 + p.\frac{G}{C_2R_2} + \frac{G}{C_1C_2R_1R_2}\right)} \qquad (4.46)$$

If $$I(t) = Q[1 - H(t-a)]$$

$$\overline{\Delta i} = \frac{Q.\, GR_2\left(1 - e^{-ap}\right)}{C_1C_2R_1R_2Z\, p\left(p^2 + p\frac{G}{C_2R_2} + \frac{G}{C_1C_2R_1R_2}\right)} \qquad (4.47)$$

Substituting in equation (4.47) the following numerical values: $C_1 = 700\,\mu\mu F$, $C_2 = 25\,\mu\mu F$, $R_1 = 1\times10^9\,\Omega$ $R_2 = 1\times10^{11}\,\Omega$, $Z = 20\,K\Omega$, $G = 500$ produces the equation:

$$\overline{\Delta i} = Q\cdot\frac{10^{10}}{7}\cdot\frac{\left(1 - e^{-ap}\right)}{p\left(p^2 + 200p + 285\cdot7\right)} \qquad (4.48)$$

$$\therefore \quad \Delta i = 5\times10^6\cdot Q[1 - H(t-a)] +$$

$$3\cdot7\times10^4\cdot Q\left[e^{-198\cdot5t} - H(t-a)\,e^{-198\cdot5(t-a)}\right] -$$

$$4\cdot85\times10^6\cdot Q\left[e^{-1\cdot5t} - H(t-a)\,e^{-1\cdot5(t-a)}\right] \qquad (4.49)$$

Comparing equation (4.49) with equation (4.45) it is observed that an additional time-constant of 2/3 second has been introduced. Furthermore, the short time-constant term has been reduced in amplitude approximately 130 fold and so will have little influence on the form of the output pulse. Figure 18. shows the form of Δi when a = 50 milliseconds (A) and a = 1 second (B).

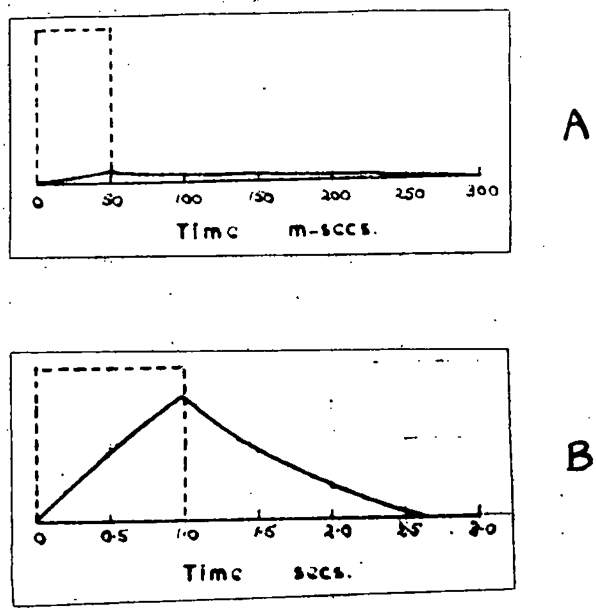


FIGURE 18.

Thus with the introduction of R_1 between C_1 and C_2, impulses of short duration have little effect on the input circuit of the amplifier; consequently the effects of rapid field changes are suppressed. The effective time-constant of the amplifier is now 2/3 second.
It is not expedient to increase R_1 too much otherwise it will alter the potential of the collector considerably when large currents are received.

The conditions of the galvanometer (long period and heavy damping) are such that the response to rapid variations in the input signal to the amplifier is also small.

CHAPTER V.

STABILIZED POWER SUPPLIES.

5.1 CHARACTERISTICS.

To obtain maximum stability in a D.C. amplifier it is essential for both heater current and high tension supplies to be taken from highly stable sources. Batteries of very high current capacity are suitable, but their operating period is strictly limited and duplicate supplies are necessary for continuous operation. A more convenient arrangement is to use an A.C. operated power unit which incorporates an electronic device for maintaining a constant output voltage level. The essential elements in the regulating circuit for a stabilized power unit are a regulated component, an error detecting device and an amplifier. The regulated component usually consists of one or more power valves connected in parallel, and it may be operated in series or in shunt with the unregulated power supply. A series regulating circuit is generally adopted for use with power units supplying currents up to 0.5 ampere.

The chief requirements for a stabilized power supply are:-

(a) No change in output voltage when the supply voltage varies; namely, a good regulation factor.

(b) No change in output voltage as the load current varies; in other words, zero output impedance. Sometimes too, it is essential for this impedance to be zero or at least very low over a wide range of frequencies.

(c) No drifting of the output voltage with time. This factor depends on the characterixtics of the voltage control standard.

5.2 GENERAL DESIGN CONSIDERATIONS.

Consider the basic series-regulating circuit shown in Figure 19. :-

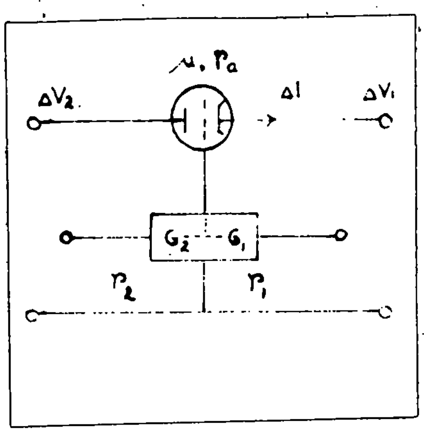


FIGURE 19.

Suppose a change ΔV_2 in the unstabilized supply produces a change ΔV_1 in the stabilized supply. It is assumed that ΔV_1 and ΔV_2 are both either increments or decrements in voltage.

Let r_1 and r_2 be the fractions of the stabilized and unstabilized voltages respectively, applied to the amplifier, and suppose G_1 and G_2 are the respective voltage gains of the two sections of the amplifier.

Then the control voltage applied to the series valve:-

$$V_g = r_2 G_2 \Delta V_2 + r_1 G_1 \Delta V_1 \tag{5.01}$$

and the voltage drop across the valve changes by

$$(\Delta V_2 - \Delta V_1)$$

If ΔI is the change in load current, the operation of the series valve is expressed by the equation:

$$[\Delta V_2 - \Delta V_1] + \mu V_g = r_a \Delta I \tag{5.02}$$

$$\Delta V_2 (1 + \mu r_2 G_2) - \Delta V_1 (1 - \mu r_1 G_1) = r_a \Delta I \tag{5.03}$$

$$\therefore \quad \frac{\Delta V_1}{\Delta V_2} = \frac{1 + \mu r_2 G_2 - r_a \frac{\Delta I}{\Delta V_2}}{1 - \mu r_1 G_1} \tag{5.04}$$

For $\Delta V_1 / \Delta V_2$ to be zero,

$$1 + \mu r_2 G_2 - r_a \frac{\Delta I}{\Delta V_2} = 0 \tag{5.05}$$

$$r_2 = - \frac{1 - r_a \, \Delta I / \Delta V_2}{\mu G_2} \tag{5.06}$$

It is important to realize that $\Delta I / \Delta V_2$ is usually a negative quantity.

Another relationship can be obtained from equation (5.03), namely:-

$$\frac{\Delta V_1}{\Delta I} = \frac{\frac{\Delta V_2}{\Delta I}\left(1 + r_2 G_2 \mu\right) - r_a}{1 - r_1 G_1 \mu} \qquad (5.07)$$

If equation (5.06) is satisfied $\Delta V_1 / \Delta I = 0$, thus equation (5.06) specifies the condition for both zero regulation factor and zero output impedance.

5.3 EARLIER WORK.

Miller (1941) describes a power supply in which the short term variations are of the order of 2 parts in a million. A gas-discharge regulator valve type VR 105/30 is used as the reference voltage, and the voltage is applied via an R.C. smoothing network to one of the grids of a double triode valve; the first valve of a 2-stage shunt amplifier. A portion of the unstabilized supply is fed back to one of the grids of the second amplifying stage to compensate for variations in the unstabilized supply. The heaters of the two valves composing the shunt amplifier are connected in series and the current is taken from the stabilized supply.

Hill (1945) has made a general analysis of the operation of stabilized power units together with a detailed study of one or two specific circuits. None of these circuits shows any remarkable characteristics.

Graham, Harkness and Thode (1947) have developed a circuit of high stability. A single stage shunt amplifier is used. The voltage standard, a V.R.105 gas-discharge regulator valve is connected in the cathode circuit of the shunt valve. This arrangement suffers from the disadvantage that the varying cathode current of the amplifying valve must pass through the V.R.105 valve and so reduces the stability of the standard voltage developed.

Harris (1948) and Attree (1948) both describe circuits employing a single stage shunt amplifier which is heated from an A.C. supply. Neither circuit has been designed to give a very high performance.

5.4 GAS-DISCHARGE REGULATOR VALVES.

The most important characteristics to be considered in the selection of a gas-discharge regulator valve for use as a reference voltage are:-

(a) Reproduction of the voltage after each firing at the same load current.

(b) Temperature coefficient of voltage drift.

(c) Spontaneous changes of voltage.

(d) Dynamic resistance.

Kirkpatrick (1947) has studied the VR series of regulator valves and finds that the type VR 75 gives the better performance with respect to the characteristics listed above.

Titterton (1949) has examined some of the valves in common use, and reports that the voltage-current characteristics are complex; several discontinuities being usually observed in the operating range. Another disturbing feature revealed in his experiments is the poor performance of the valves at low audio frequencies when the load current is varied.

Benson, Cain and Clucas (1949) have investigated the characteristics of the types 7475 (CV 1070) and 85A1 and have shown that the latter has good characteristics.

The characteristics of several of the gas-discharge regulator valves are given in the following table.

Type	Temperature Coefficient. mV - $^{o}C^{-1}$	Repetition of Striking Voltage volts.	Variation of Running Voltage with Time.
85A1	Max. - 7 Mean - 3	2	Little change. Max. 0.9%
7475 CV1070	Max - 27 Mean - 6.7	3.5	Small variations up to 1000 per hour followed by large variations.
VR75	- 30	.02	0.25% (17 hrs.)
VR105	Erratic	1.57	0.06% (53 hrs.)
VR150	+ 39	.65	0.22 (25 hrs.)

To obtain a good voltage standard for a stabilized power supply, careful selection of particular valves from a batch of the type showing the most suitable characteristics is essential. The valve should be shielded, electrically to reduce the effects of stray electric fields, and thermally to minimize the fluctuations in the ambient temperature. The load current for the valve should be obtained from the stabilized supply and the operating range should be chosen with reference to the discontinuities in the voltage current characteristic. It is also important to use as low a value of load current as possible.

High tension batteries can be used successfully as voltage standards, provided that the current drawn from them is extremely small. This means that they must be connected in the grid circuit of the amplifying valve.

5.5 ANALYSIS OF THE CIRCUIT.

A power supply of the type described by Miller (1941) was considered to be essential for meeting the long and short term stability requirements in the amplifier. An analysis of the circuit was undertaken to see if any improvement in performance could be obtained. The basic circuit is given in Figure 20 :-

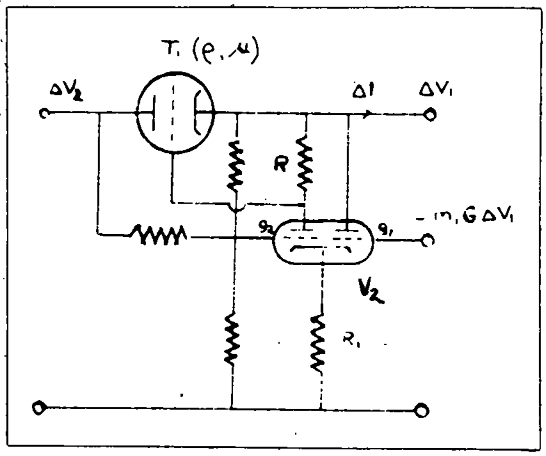


FIGURE 20.

The following notation is to be used:

m_1, m_2 are the fractions of the voltage of the stabilized supply applied to the grid of the first amplifier valve, V_1 , and the grid g_2 of V_2 respectively.

m_3 the fraction of the voltage of the unstabilized section applied to the grid g_2 of V_2 .

G the voltage gain of V_1 .

r, η the valve anode resistance and amplification factor respectively of V_2 .

ρ, μ the valve anode resistance and amplification factor respectively, of T_1 , the series regulated valve.

Suppose a change ΔV_2 in the unstabilized supply voltage causes a change ΔV_1 in the voltage of the stabilized section and a change ΔI in the load current. It is assumed that ΔV_1 and ΔV_2 are in phase, that is, they have the same sign.

Consider the voltages applied to the grids of V_2

On g_1 the voltage is $-m_1 G \Delta V_1$

and on g_2 it is $m_3 \Delta V_2 + m_2 \Delta V_1$

Using the relationship for the output voltage from a cathode-coupled double triode amplifying stage (E. Williams 1944), the controlling voltage V_{g_1} applied to the grid of the series valve T_1 is obtained

$$V_{g_1} = -\frac{\eta R(m_3\Delta V_2 + m_2\Delta V_1 + m_1 G\Delta V_1)}{2r + R} - \Delta V_1 \qquad (5.08)$$

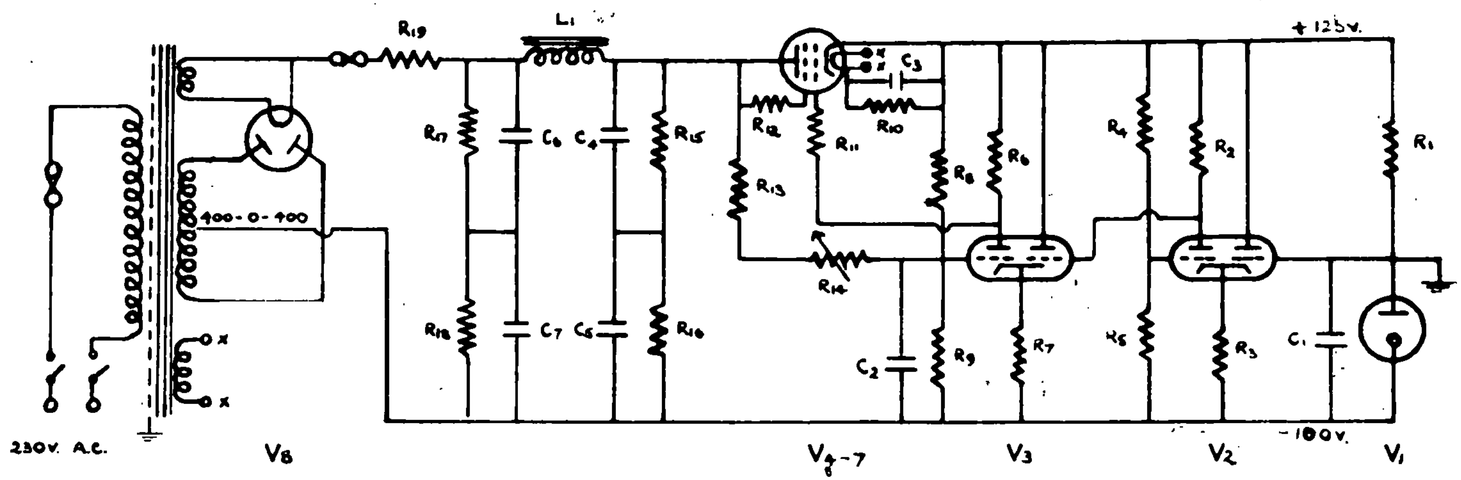
The change in the voltage drop across T_1 is $\Delta V_2 - \Delta V_1$ thus the operation of T_1 is given by the equation

$$(\Delta V_2 - \Delta V_1) + \mu V_{g_1} = \rho\,\Delta I \qquad (5.09)$$

$$\therefore\ \Delta V_2 - \Delta V_1 - \frac{\mu\eta R(m_3\Delta V_2 + m_2\Delta V_1 + m_1 G\Delta V_1)}{2r+R} - \mu\Delta V_1 = \rho\,\Delta I \qquad (5.10)$$

$$\Delta V_2(2r + R - \mu\eta m_3 R) - \Delta V_1\left[(2r+R)(1+\mu) + \mu\eta m_2 R + \mu\eta m_1 G R\right]$$
$$= (2r+R)\rho\,\Delta I. \qquad (5.11)$$

$$\therefore\ \frac{\Delta V_1}{\Delta V_2} = \frac{(2r+R-\mu\eta m_3 R) - (2r+R)\rho\frac{\Delta I}{\Delta V_2}}{(2r+R)(1+\mu) + \mu\eta R(m_2 + m_1 G)} \qquad (5.12)$$



R1 — 50KΩ W.W.	R11 — 10KΩ	C1 — ·006 μF	V1 — VR 105/30
R2 — 500KΩ	R12 — 100Ω	C2 — ·01 μF	V2,3 — 6SC7
R3 — 100KΩ	R13 — 10MΩ	C3 — ·05 μF	V4-7 — 6L6
R4 — 100KΩ W.W.	R14 — 2MΩ pot	C4 — 10 μF	V8 — 5U4G
R5 — 70KΩ W.W.	R15 — 10MΩ	C5 — 10 μF	
R6 — 220KΩ	R16 — 10MΩ	C6 — 10 μF	
R7 — 300KΩ	R17 — 10MΩ	C7 — 10 μF	
R8 — 12KΩ W.W.	R18 — 10MΩ	L1 — 20 H	
R9 — 25KΩ W.W.	R19 — 35Ω W.W.		
R10 — 100KΩ			

H. T. POWER UNIT

FIGURE 21.

For the regulation factor $\Delta V_1/\Delta V_2$ to be zero

$$2r + R - \mu\eta m_3 R = (2r + R)\rho\, \Delta I/\Delta V_2 \qquad (5.13)$$

$$\therefore \quad m_3 = \frac{(2r+R)\left(\frac{\Delta V_2}{\Delta I} - \rho\right)}{\mu\eta R \;\Delta V_2/\Delta I} \qquad (5.14)$$

From equation (5.11)

$$\frac{\Delta V_1}{\Delta I} = \frac{\Delta V_2/\Delta I\,(2r + R - \mu\eta m_3 R) - \rho(2r+R)}{(2r+R)(1+\mu) + \mu\eta R(m_2 + m_1 G)} \qquad (5.15)$$

If equation (5.14) is satisfied $\Delta V_1/\Delta I$ is zero, and so the output impedance is also zero.

5.6 CIRCUIT DETAILS OF THE HIGH TENSION SUPPLY.

The circuit of the unit providing the H.T. supply for the amplifier and heater power unit is shown in Figure 21. . It will deliver a current of 200 milliamperes at 225 volts.

The unstabilized section of the unit is of conventional design and employs a π-type filter. Each capacitative section of the filter consists of two condensers connected in series to reduce the chances of failure in the unit and a resistance of 10 megohms is connected across the terminals of each condenser to distribute the voltage stress equally. Measurement of the voltage-current characteristic showed that the value of $\Delta V_2/\Delta I$ was - 1000 ohms.

A VR 105/30 gas-discharge regulator valve is used as the voltage standard, and to minimize the effect of variations in the ambient temperature the valve has been placed in a screening can which has an external thick coating of asbestos paper. The regulating shunt amplifier has two stages employing 6 SC 7 double triodes, while the regulated section consists of four 6 L 6 power valves connected in shunt. 'Grid-stoppers' are connected in the control grid leads of the power valves to prevent parasitic oscillations. Wire-wound resistors of high wattage rating are used in the control parts of the circuit only. The condensers C_1 and C_2 are essential for stability. The heaters of the valves V_2 and V_3 are connected in series and are fed from the heater power unit.

Using the values of the circuit constants it is possible to deduce a value for m_3, the fraction of the unstabilized supply fed to the regulating amplifier, using equation (5.14). The following values are used

$m_1 = 3/7$	$G = 30$	$r = 100\,K\Omega$
$m_2 = 2/3$	$\rho = 300\,\Omega$	$R = 220\,K\Omega$
$\frac{\Delta V_2}{\Delta I} = -1000\,\Omega$	$\mu = 11$	$\eta = 60$

$$m_3 = \frac{(2r+R)\left(\frac{\Delta V_2}{\Delta I} - \rho\right)}{\mu \eta R \frac{\Delta V_2}{\Delta I}}$$

$$= \frac{420{,}000 \times 1700}{11 \times 60 \times 220{,}000 \times 1000}$$

$$= \frac{1}{270}$$

It has been found more convenient to use a value of the order of $\frac{1}{400}$ for m_3, in order to reduce the hum content too.

From equation (5.15) the value of $\Delta V_1/\Delta I$ can be deduced.

$$\frac{\Delta V_1}{\Delta I} = \frac{\frac{\Delta V_2}{\Delta I}\left(2r+R-\mu\eta m_3 R\right) - e\left(2r+R\right)}{(2r+R)(1+\mu) + \mu\eta R\left(m_2+m_1 G\right)}$$

$$= \frac{-1000\left(420,000 - 60\times 11\times 220,000\right) - 300\times 420,000}{(420,000\times 12) + (60\times 11\times 220,000)\left(\frac{2}{3}+\frac{90}{7}\right)}$$

$$= \underline{-0.106\,\Omega} \quad \text{approx.}$$

5.7 PERFORMANCE.

The voltage-current characteristic of the stabilized unit was measured using the circuit shown in Figure 22. The measuring instrument was a sensitive Pye-table galvanometer.

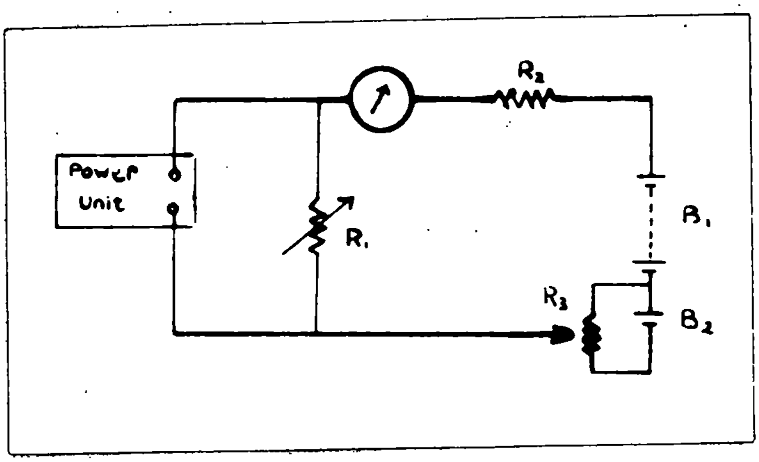


FIGURE 22.

The curve obtained is shown in Figure 23.

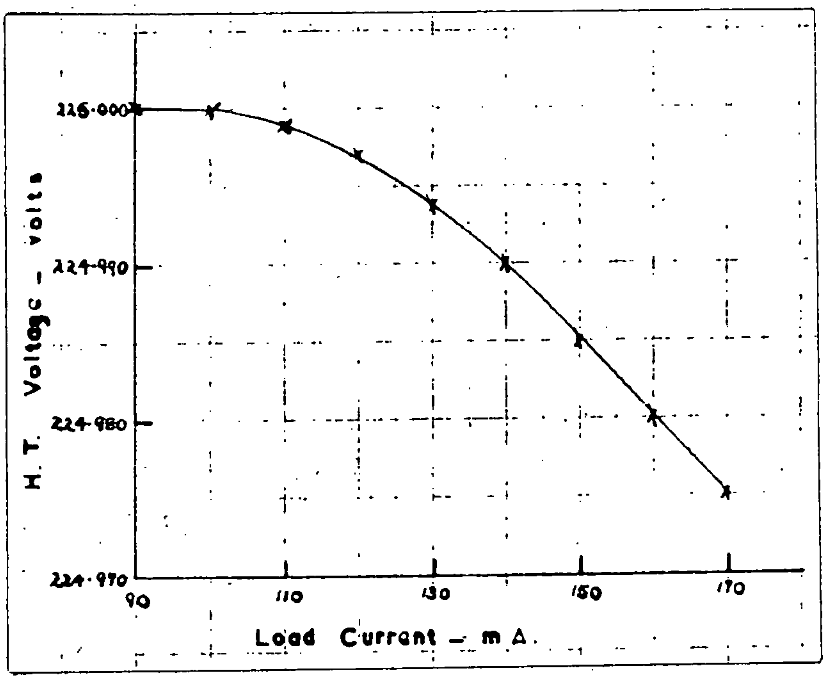


FIGURE 23.

The characteristic is perfectly flat for the current range 90 - 100 milliamperes, and then it develops into a linear fall of voltage with increasing load current. The maximum value of $\Delta V_1 / \Delta I$ is - 0.5 ohm while for the current range 90 - 110 milliamperes the measured value does not exceed the one calculated.

Using a similar circuit to that shown in Figure 22, it was possible to observe the stability of the gas-discharge regulator valve over a period of 2 hours using a mirror galvanometer and a photographic recording camera. Figure 24. shows the record obtained.

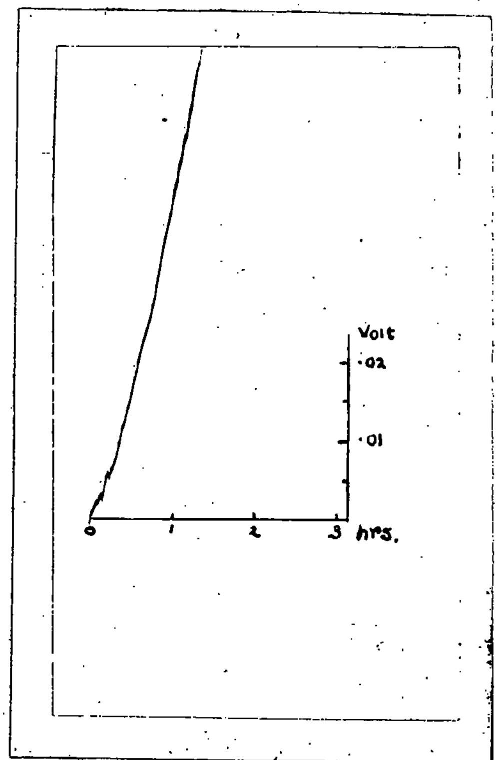
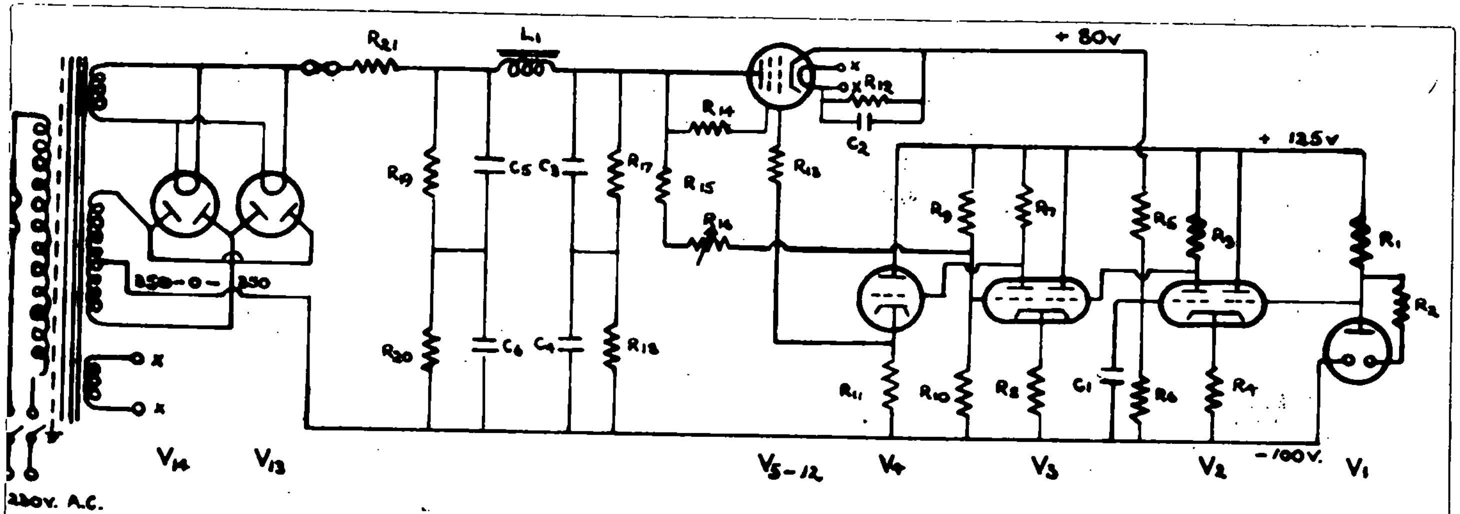


FIGURE 24.

The largest spontaneous changes in voltage are of the order of 1 millivolt. Unfortunately, the H.T. battery used to back-off most of the voltage developed by the regulator valve was in a poor condition and showed a considerable drift in voltage, so the test was discontinued after 2 hours. The same valve has been constantly in service since July 1948 and still functions as a reliable voltage standard.



R1 — 50KΩ W.W.
R2 — 5MΩ
R3 — 500KΩ
R4 — 50KΩ
R5 — 75KΩ W.W.
R6 — 60KΩ W.W.
R7 — 500KΩ
R8 — 100KΩ
R9 — 25KΩ
R10 — 25KΩ
R11 — 500KΩ

R12 — 100KΩ
R13 — 10KΩ
R14 — 100Ω
R15 — 10MΩ
R16 — 2MΩ pot
R17 — 10MΩ
R18 — 10MΩ
R19 — 10MΩ
R20 — 10MΩ
R21 — 25Ω W.W.

C1 — ·05μF
C2 — ·05μF
C3 — 8μF
C4 — 8μF
C5 — 8μF
C6 — 8μF
L1 — 20 H

V1 — S.T.C. 4313 C
V2,3 — 6SC7
V4 — 6J5
V5-12 — 6L6
V13,14 — 5U4G

HEATER POWER UNIT

FIGURE 25.

A 10 per cent change in mains voltage produces a change in the output voltage of 10 millivolts. The short term fluctuations observed over periods of 1 hour duration are of the order of 1 millivolt. The hum content is less than 1 millivolt peak to peak.

5.8 ADDITIONAL HIGH TENSION SUPPLY.

A power unit, similar in design to that described in Section 5.6, was constructed to supply power to the shunt selector unit. It can supply a current of 200 milliamperes at 300 volts. A V R 150/30 valve is used as the voltage standard.

5.9 HEATER POWER UNIT.

This power unit is designed to supply the heater current to all the '6.3 volts - 0.3 ampere' type valves used in the complete system. It will deliver a current of 300 milliamperes at a voltage of 180 volts. The circuit is shown in Figure 25. .

The unstabilized mains supply is unconventional in that two 5 U 4 G rectifier valves are operated in shunt in order to produce the required load current comfortably. The unit is lightly fused so that if one of the rectifier valves fails the other is never allowed to pass the full load current.

The regulated section of the amplifier consists of eight 6 L 6 power valves connected in parallel. This arrangement was adopted to restrict the 'heating-up' of each valve and to achieve a long 'life' for the valves. The shunt amplifier is similar to that described in Section 5.6 except that it has, in addition, a cathode-follower output to drive the eight power valves. This amplifier is operated from the 225 volt power supply. An S.T.C. 4313C gas-discharge regulator valve is used as the voltage standard. Normally the load current is adjusted to 280 milliamperes to minimize the dissipation of heat in the unit.

A change of load current of 15 milliamperes produces a change in the amplifier zero equivalent to an input of 4 millivolts.

CHAPTER VI.

THE AUTOMATIC SHUNT SELECTING UNIT.

6.1 SPECIFICATION.

The smallest current to be measured is of the order of 2×10^{-13} amperes while the largest may approach a value of 1×10^{-8} amperes. Chalmers and Little (1949) recorded a current of $- 7.3 \times 10^{-12}$ amperes-cms in a shower of soft hail. With an input resistance of 10^{11} ohms the amplifier can cope with a maximum current of 2×10^{-10} amperes, so that for the rare occasions when this value is exceeded the 10^{11} ohms and 10^{10} ohms resistors can be used in shunt.

On the highest sensitivity range the galvanometer has been adjusted to give a deflexion of 0.5 cms. on the photographic camera drum at a distance of 1 metre, for a current of 2×10^{-13} amperes referred to the input of the amplifier. The half-width of the photographic paper is 5+ cms. so the different sensitivity ranges for photographic recording, expressed in terms of the input voltage across the high resistance are:-

Sensitivity	Voltage Range
High	0 - ± 0.2 volt
Medium 1	± 0.2 - ± 2.0 volt
Medium 2	± 2.0 - ±20 volt
Low	±20 - ±200 volt

Thus, either three or six trigger-operated relays are necessary for changing the value of the galvanometer shunt, depending on whether the circuit will function with both a positive and negative signal or only a unidirectional one.

6.2 EARLIER WORK.

Smith, Lozier, Smith and Bleakney (1937) used a mirror galvanometer with photographic recording. A very wide paper was used to cover the required range of measurement.

Washburn, Wiley and Rock (1943) employed four galvanometers which recorded simultaneously at four different sensitivity levels.

Hipple, Grove and Hickman (1945) used a system with a speedomax recorder in which the sensitivity was reduced as the deflexion increased. An approximately logarithmic scale was achieved by connecting a suitable network of resistances to a potentiometer shunting the input to the recorder. The movable contact of this potentiometer was coupled to the motor which controlled the writing pen. A limit switching device was also incorporated to ensure that the peaks of all signals were recorded.

Lossing, Shield and Thode (1947) describe an electronic shunt selector using thyratrons which were adjusted to fire at certain voltages. The thyratrons operated relays which adjusted the shunt system in the Speedomax recorder. When the pen returned to the zero signal line after retracing a peak it closed a limit switch which extinguished the thyratrons and set the recorder at maximum sensitivity again.

It is worth indicating that the systems described above were employed in mass-spectrographic analyses where the signal variation is a controlled one, that is it depends on the scanning of the magnetic field. Greater difficulties are experienced when the signal variation is more or less random.

6.3 AN ELECTRONIC TRIGGER CIRCUIT.

Limit switching using photoelectric cells or other devices is not a very satisfactory procedure for automatic recording, because the recording instrument has usually reached its peak before the sensitivity is lowered. In this type of system the switching-relay is controlled by the recording instrument which may bring it into action by means of a photoelectric cell arrangement or simply by the making of an electrical contact. The response of the recording instrument usually lags well behind that of the amplifier and the electrical signal will have almost reached its peak before the sensitivity is changed. This type of action may result in the beheading of many peaks or the production of artificial ones. For mass-spectrometer analyses this may be tolerable, but in the present application it would lead to some confusion. For good recording, change of sensitivity should occur before the galvanometer or pen-writer deflexion has reached a maximum. Thus it is apparent that the switching-device should respond directly to the signal voltage rather than be controlled from the recording instrument.

As triggering devices for precision work, thyratrons and cold cathode gas-filled valves are unsatisfactory. They do not restrike at the same voltage and after striking they must be extinguished by some external source.

A hard-valve trigger unit seemed to be most desirable for precision work and a modified version of Schmitt's trigger circuit (1938) was adopted as a switching unit. The operation of the circuit is discussed in some detail by Williams (1946). Figure 26. illustrates the circuit.

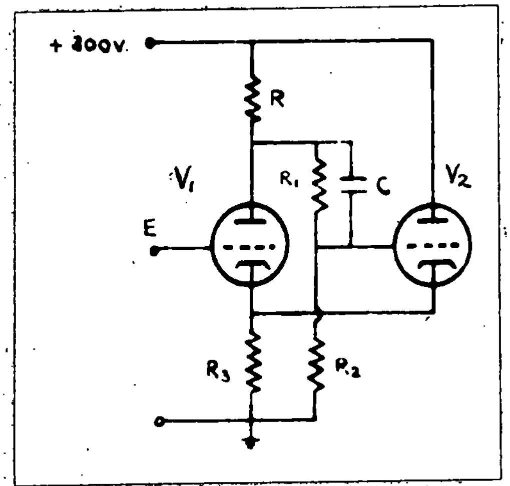
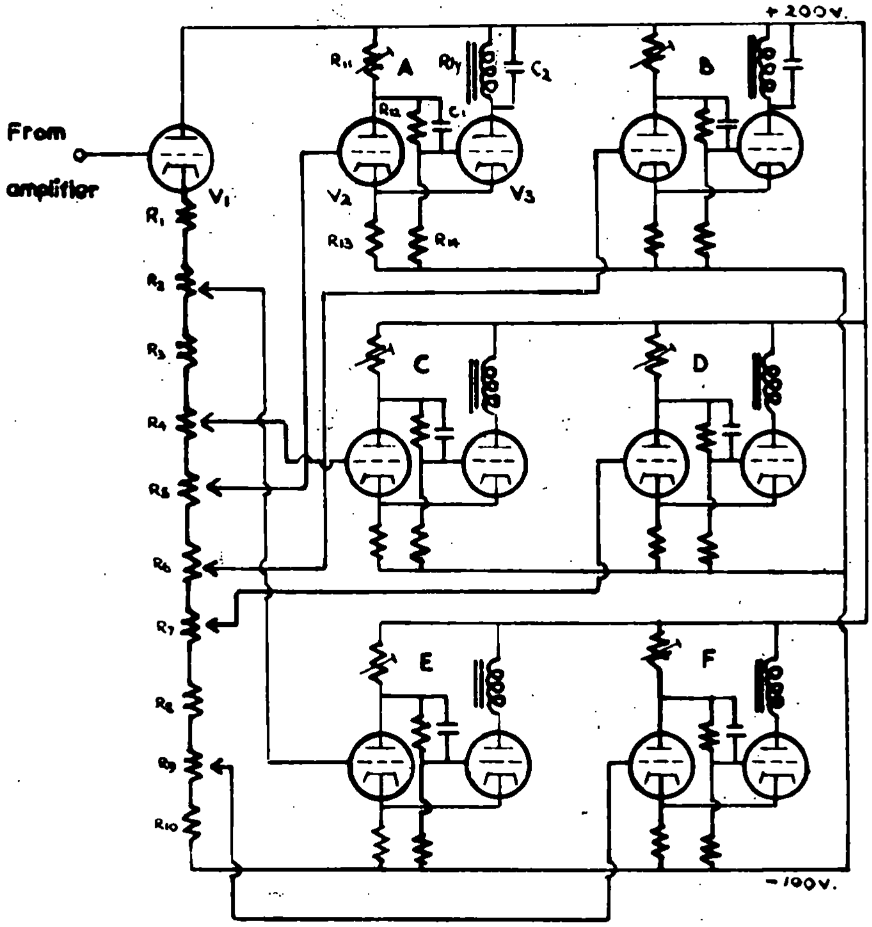


FIGURE 26.

When the potential E on the grid of V_1 is zero V_1 is cut off and V_2 functions as a cathode-follower stage. The potential on the cathode will be approximately $\frac{R_2}{R_1+R}$ x 300 volts = e volts say, provided both R_1 and R_2 are much greater than R. If the potential E is now increased, then current will begin to flow in V_1 as soon as E becomes close to e volts. The grid potential of V_2 now begins to fall, thus assisting the transfer of current from V_2 to V_1 and promoting a trigger action. The speed of the trigger action depends on the value of R and the optimum value is given by the relation

$$R = 4/g \qquad (6.1)$$

where g is the mean mutual conductance of each valve.



Units ABCDEF are identical.

R_1 — 2·5 KΩ		w.w	R_{11} — 10 KΩ	pot	V_1 — 6J6
R_2 — 1 KΩ	pot	w.w.	R_{12} — 300 KΩ		V_2 — EF50
R_3 — 3·5 KΩ		w.w.	R_{13} — 16 KΩ		V_3 — EF50
R_4 — 500 Ω	pot.	w.w.	R_{14} — 100 KΩ		
R_5 — 200 Ω	pot	w.w.			
R_6 — 200 Ω	pot	w.w.	C_1 — 10 μμF		
R_7 — 500 Ω	pot	w.w.	C_2 — 0·1 μF		
R_8 — 1 KΩ		w.w			
R_9 — 1 KΩ	pot	w.w.	Rly — High speed relay		
R_{10} — 12 KΩ		w.w.			

SHUNT SELECTOR I.

FIGURE 27.

If R is less than this value, the change-over is a slow process, whereas a larger value of R introduces a 'backlash' effect. After the circuit has triggered at the predetermined potential it is found that it will only return to its original state when the potential on the controlling grid is a little below this potential. The minimum 'backlash' which can usually be obtained is about 0.1 volt. The condenser C reduces the effect of stray capacitance at the grid of V_2. A relay inserted in the anode circuit of V_2 can be operated by controlling the potential on the grid of V_1.

6.4 SHUNT SELECTOR 1.

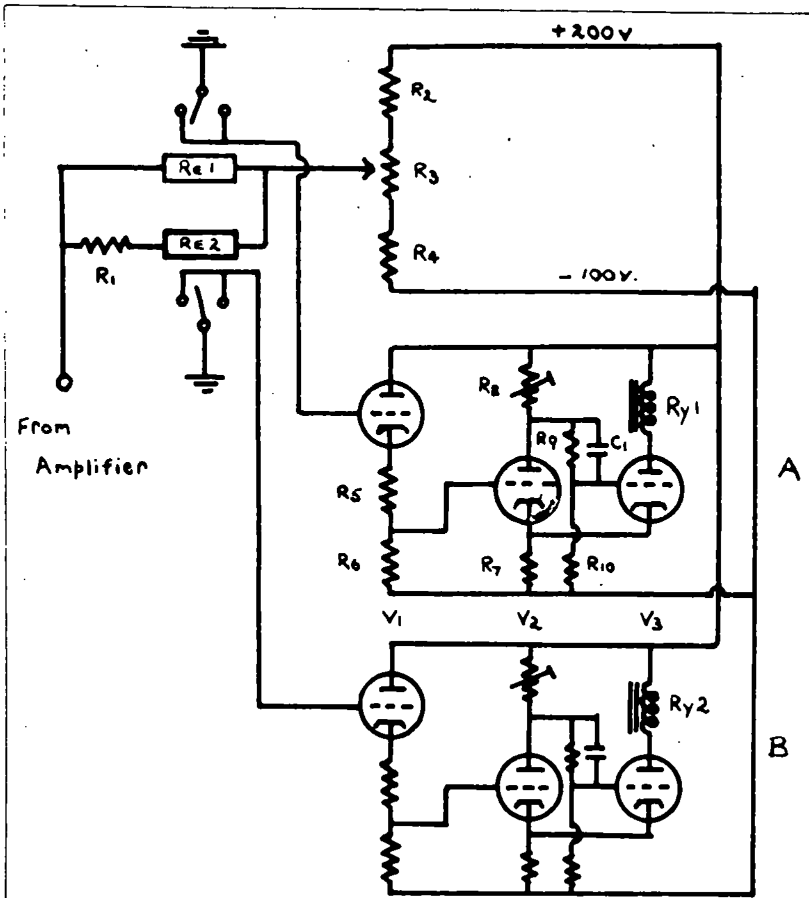
The first circuit which was tried is shown in Figure 27. Six trigger units were used and each one was adjusted to operate when the potential on the controlling grid was - 30 volts with respect to 'earth'. E.F. 50's triode connected, were used because there was a good supply of them available and they supplied enough current to operate the high speed relays. A current of 3 milliamperes would just operate these relays. The signal from the amplifier was fed to a cathode-follower V_1 and the triggering potentials for the trigger units were taken from a resistor chain in the cathode circuit. The tappings on the resistor chain were calculated so that when the grid potential was at a change-over level the potential at the tapping point for the associated trigger unit was - 30 volts. The units were set to trigger at the following potentials referred to the grid of

A	- 0.2 volt	B	+ 0.2 volt
C	- 2.0 volts	D	+ 2.0 volts
E	-20 volts	F	+20 volts.

It was intended that units A, B, C and D should control two shunts in the galvanometer circuit, while E and F would alter the input resistance in the electrometer grid circuit from 10^{11} ohms to 10^{10} ohms.

The effect of 'backlash' on units A and B was too important to be neglected, for a 0.1 volt difference would cause a mid-scale change-over. The use of the condenser C_2 across the relay coil reduced the 'backlash' to the order of .02 volt by bringing the circuit almost to an oscillating condition. For units E and F advantage was taken of the 'backlash'. The preset potentiometers were set so that a 'backlash' of 18 volts was obtained. The 10^{11} ohm resistor would then be shunted by the 10^{10} ohm resistor at an input voltage level of 20 volts and restored to the normal condition at 2 volts.

Preliminary tests revealed the following defects:-



Units A & B are identical

R_1 —	5KΩ		C_1 —	10 μμF.	
R_2 —	6 KΩ	W.W	Re —	Minature relay	
R_3 —	1 KΩ	W.W.	Ry. —	High speed relay	
R_4 —	3 KΩ	W.W.			
R_5 —	20 KΩ	W.W.	V_1 —	6J5	
R_6 —	35 KΩ	W.W.	V_2 —	EF 50	
R_7 —	16 KΩ		V_3 —	EF 50	
R_8 —	10 KΩ	pot.			
R_9 —	300 KΩ.				
R_{10} —	100 KΩ				

SHUNT SELECTOR 2.

FIGURE 28.

(a) Long term stability of units A and B could not be obtained. The triggering potentials varied from time to time and occasionally the relays faltered.

(b) The setting-up of the experimental circuit was not easy and a more elaborate system of jackpoints and meters was necessary to make handling easier. The development of an operational model would take some time.

(c) The full circuit could not be operated for some of the relays were found to be faulty and no replacements were available.

Rather than proceed to develop this system further, a simpler system using limit switching was examined.

6.5 SHUNT SELECTOR 2.

During tests with the previous circuit it was found that by operating each trigger unit from a cathode-follower stage a more reliable and stable switching system could be obtained. Circuits A and B of Figure 28. illustrate this type of system. The control grid of the cathode-follower stage is allowed to 'float' and the trigger action is initiated by connecting the grid to 'earth'. The circuit has the advantage that a good electrical contact is not essential, but the contact resistance should not be greater than 1000 ohms for reliable operation. Such a system can be operated with either positive or negative signals using a centre-indicating device as a limit-switch.

Preliminary tests were carried out using a centre-reading milliammeter as a limit-switch. The light aluminium pointer was allowed to move in a gap between two brass contacts which were electrically connected. The ends of the contacts were ground to sharp conical points. The pointer was 'earthed' while the contacts were connected to the control grid of the cathode-follower. At first it was found difficult to trigger the relay circuit by this method. Satisfactory contact could not be obtained because of the oxide-layer on the pointer and the small pressure exerted by the pointer when moving steadily. An impulsive motion of the pointer was usually adequate, however. To overcome this contact difficulty both the pointer and the brass contacts were silver plated electrolytically and satisfactory contact was now obtained during operation. However, with constant use the silver layer on the pointer soon deteriorated and this difficulty could not be overcome. Furthermore, occasionally bad contacts were caused by dust settling on the brass contacts. It was found that relays manufactured by Messrs Elliot

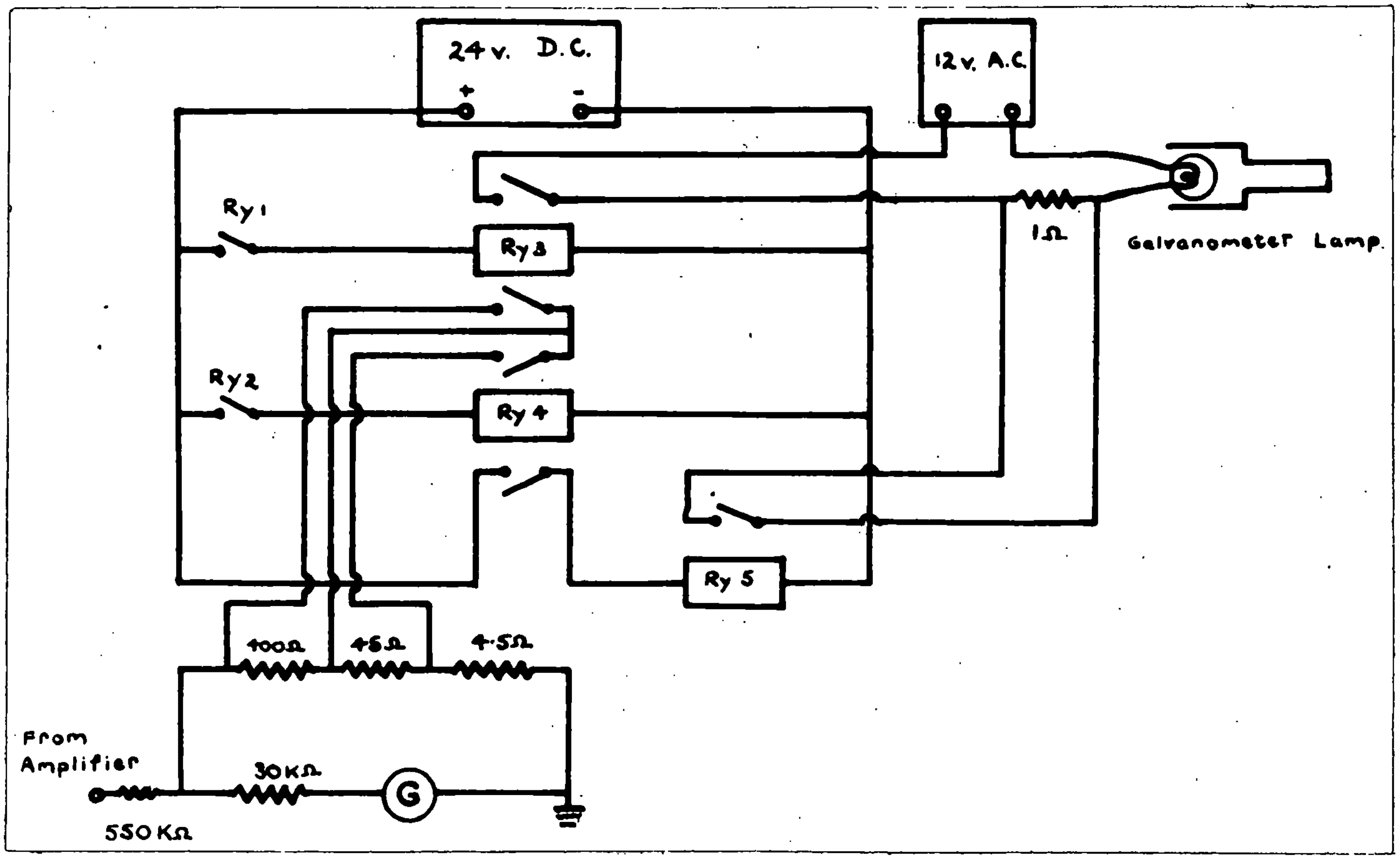

24 v. D.C.
+
-
12 v. A.C.
Ry 1
Ry 3
Ry 2
Ry 4
Ry 5
1 Ω
Galvanometer Lamp.
100Ω
45Ω
4·5Ω
From Amplifier
30 KΩ
G
550 KΩ

FIGURE 29.

Brothers Limited were suitable for this type of limit-switch and some were purchased.

The experimental selector circuit shown in Figure was built up using the miniature relays as limit-switches. It was not possible to connect the relays between the amplifier output and 'earth' because the 'earth' connection would upset the stability of the power unit supplying the amplifier. The resistance of each relay is 700 ohms, so that large rain currents would produce large current changes in the gas-discharge regulator valve V_1 (Figure 21.). Accordingly an 'earth' connexion was tapped from the resistor chain R_2 , R_3 , R_4. R_{E1} operates when the amplifier output voltage is ± 0.2 volts and R_{E2} when it is ± 2.0 volts.

The complete relay circuit is shown in Figure 29. . It will be observed that the shunt resistances are very small compared with the resistance in series with the galvanometer, and so the damping of the galvanometer is unaffected when they are short circuited. The sensitivity changes are indicated on the side of the photographic paper by means of the additional galvanometer lamp. The beam of light from the slit in the lamp is reflected back to the camera drum by a plane mirror set up a metre away from the lamp. The angle of the lamp was adjusted so that the spot of light is in the same horizontal plane on the photographic paper as the galvanometer spot, in order to obtain time synchronization. The sensitivities are indicated as follows:

High	H. S.	No side trace.
Medium 1	M. S. 1	Faint side trace
Medium 2	M. S. 2	Dark side trace (obtained by short circuiting the 1Ω resistance.)
Low	L. S.	

The circuit of Figure 28. has been tested several times and has given a satisfactory performance. It cannot be used with the 24 hour record because of the poor resolution obtained when there are rapid fluctuations.

To complete the shunt selector circuit, units E and F of selector 1 need to be added to introduce the low sensitivity scale. Also for protective purposes a resistance of 5000 ohms should be connected in series with R_{E1} and controlled by the operation of R_{E2}. In setting-up the circuit adjustments should be made so that when units E and F trigger at the 2 volt level, they do so before R_{E2}.

For operational use the circuit should be rebuilt.

CHAPTER VII.

OPERATIONAL TESTS WITH THE APPARATUS.

7.1 INTRODUCTION.

Measurements of atmospheric currents have been carried out since the beginning of March 1950, but not with any regularity. From time to time it was necessary to interrupt the systematic recording in order to carry out tests. Usually it was possible to make the test between 9 a.m. and 4 p.m. and then a long period record was obtained between 4 p.m. and 9 a.m. on the following morning. Measurements of the electric field strength were obtained from the agrimeter. This is essentially an electrostatic generating voltmeter of the type described by Workman and Holzer (1939). It generates an output voltage which is proportional to the electric field strength and of opposite polarity. A Dolezalek electrometer records the output voltage.

7.2 FLUCTUATIONS IN FINE WEATHER.

Fluctuations may be caused by:-

(a) Field changes: The magnitude of the fluctuation is a function of the rate of change of the electric field.

(b) The effect of wind: This may be twofold. It may cause minor field changes in the region of the exposed collecting surface due to the transport of groups of ions, as well as producing a varying ionic current at the collector as a result of the arrival of the ions in gusts, in the same way in which rain reaches the collector in windy weather. To resolve the two effects is almost an impossibility.

(c) Vertical convection currents: Such a convection current with a gusty component would produce field changes and varying ionic-currents in the same way as wind.

A deflection which crosses the zero datum line would indicate a field change rather than a change in polarity of the current because of the predominance of positive ions near the ground.

Observations have shown the influence of the above three factors.

Plate 2 shows the correlation between some rather large field changes and the fluctuations on the air-earth current record. The field changes are of the order of 100 volt-metres^{-1}, and the fluctuations are equivalent to a current of 10^{-15} amp.-cms.$^{-2}$, thus a fluctuation of the order of 10^{-16} amp.-cms.$^{-2}$ could be produced by a field change of 10 volt-metres^{-1} which would have an amplitude of .07 cms. on the field record. The field records were consequently of very little assistance in studying the more frequently occurring fluctuations of the order of 0 - 4 x 10^{-16} amp.-$cms.^{-2}$.

The results suggest that the current may vary naturally and that it would be wrong to assume that the record of the current should show smooth variations of long period as is suggested by Scrase's records (1933). A closer examination of Scrase's records shows that the rate of charging-up of the electrometer varies during the 9 minute intervals, and so the current is not constant during that interval.

On cloudless days when the wind has been of moderate strength large fluctuations with amplitudes reaching 6 x 10^{-16} amp.-$cms.^{-2}$ have been observed, while on similar days when calm conditions have prevailed the fluctuations have been no greater than 2 x 10^{-16} amp.-$cms.^{-2}$. Traces B and C of Plate 3 are typical records for calm conditions with no cloud. Traces C and D of Plate 1 are interesting. The former was obtained on a windy day using a metal plate above the collector while the latter was taken on a calm day using a wire net of 1 inch mesh instead of the plate. The fluctuations of C have a definite 'spiky' nature and are most probably current variations rather than the effects of field changes. A record obtained immediately after this measurement, under natural conditions, that is with the plate removed, showed the same 'spiky' fluctuations. D shows how steady the record should be when the field is constant and conditions are calm.

A glowing fuse was placed on the ground about 4 feet away from the collector, on the windward side. Smoke was carried over the collector at a height of no less than 6 inches above the ground. The fluctuations due to the field changes caused by the passage of ions from the fuse over the collector had an amplitude of the order of 6×10^{-16} amp.-cms.$^{-2}$. The test demonstrated the effect of the passage of groups of ions over the collector. Unfortunately, no calculations could be made.

7.3 COMPENSATION FOR FIELD CHANGES.

An attempt was made to compensate for field changes using the method described by Scrase (1933), except that no wire net was used. A signal from the agrimeter was fed to the input of the amplifier via a variable capacitance as shown in Figure I. The capacitance consisted of a parallel-plate mica condenser in parallel with a variable air-condenser. The capacitance of the system could be varied between 600 - 800 $\mu\mu F$. Cover plates were placed over the agrimeter and the collector at the same height above each one, so that the same field could be applied simultaneously to each system. Both plates were connected to an H.T. battery situated in the laboratory. Field changes were then applied simultaneously to the agrimeter and the collector and the variable capacitance was adjusted until no effect was observed at the output of the amplifier. It was soon found that such a condition could not be realized, for the reactions of the two field changes on the amplifier were not simultaneous. The best setting of the condenser was such that the two changes produced equal changes at the output, one after the other. It seemed that the effect was due to the different response times of the agrimeter and the conduction current apparatus.

When the field changes were applied separately to the amplifier it was found that the collector was more sensitive than the agrimeter. Further tests were then made with a modified input circuit for the collector. High grade mica condensers and high resistances were used to increase the time constant of this circuit. This time only the variable air-condenser was necessary, but again time synchronization of the two signals could not be obtained. During these tests it was observed that the agrimeter injected spurious signals into the amplifier, due to some mechanical defect in the agrimeter and this increased difficulties considerably. In fact, the presence of these spurious signals of period about 1 second led to the abandonment of attempts at compensation.

The cable connecting the agrimeter to the air-earth current apparatus has a capacitance of the order of about 500 $\mu\mu F$. which increases the time-constant of the system unnecessarily. To reduce this capacitance a cathode-follower was introduced at the agrimeter with a short length of screened cable in the grid circuit, and the output from the cathode-follower was then taken to the air-earth current apparatus via the cable of capacitance 500 $\mu\mu F$. Furthermore, by connecting the braided sheath of the cable in the grid circuit to the cathode as shown in Figure 30. it was possible to reduce the capacitance of the agrimeter system to a minimum.

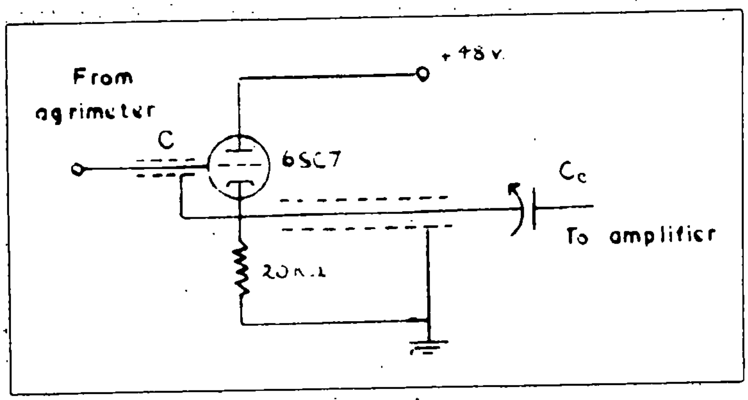


FIGURE 30.

The effective input capacitance of the cathode-follower can be shown to be given by the relation:-

$$C_{in} = C(1 - A) \tag{7.1}$$

where A is the stage gain. The more closely A approaches unity the smaller C_{in} becomes. One section of a 6 SC 7 twin triode was used as a cathode-follower, because it was the only valve available which had a grid current no greater than 10^{-10} amperes, when operated at a low anode potential. No valve-holder was used, and connections were made directly to the valve pins, so that the grid to cathode insulation would be adequate.
The cathode-follower worked satisfactorily, but unfortunately it enhanced the spurious signals from the agrimeter and no fair compensation tests could be performed. This method would probably be adequate if certain mechanical difficulties in the agrimeter were overcome.

7.4 THE AIR-EARTH CURRENT.

Both 1 hour and 24 hour records have been obtained. Typical records are shown in Plates 2 and 3. Unfortunately, only a few records of simultaneous current and field measurements were obtained and it is unwise to draw any conclusions from them. It is not easy to estimate the value of the current from the 24 hour records because of the presence of the fluctuations. The most satisfactory procedure is to draw in the line about which the fluctuations are symmetrical, but sometimes this is difficult to judge, as in trace C of Plate 3. This method gives an estimate of the mean current. The mean value of the current is easier to assess in the 1 hour records, but here again the field change fluctuations introduce an error of uncertain magnitude.

It was thought that a steadier record would be obtained by increasing the time-constant of the input circuit and so smoothing out the fluctuations. The most effective way of doing this is to increase R_q (Figure 14.) to 10^{11} ohms. This scheme was not adopted because in conditions of rain the potential of the collector would vary from 1 - 20 volts below and above 'earth'. Also at times the system indicated abnormally high air-earth currents due to excessive charging-up. It was found that the normal circuit giving the closely packed fluctuations shown in Plate 2 was the most satisfactory, from the point of view of operation and analysis. The presence of a resistance of the order of 10^{11} ohms in series with the collector makes it difficult to discover when the insulation of the collector is faulty. Normally this is easily observed, for the screened collector indicates a large current if the insulation is low.

It is safe to state that the air-earth current at Durham varies between 0 - 2 x 10^{-16} amp.-cms.$^{-2}$ on cloudless days and at other times it can be greater than 2 x 10^{-16} amp-cms.$^{-2}$. The normal fine-weather field has a value of about 200 volts-metres.$^{-1}$

7.5 THE CONDUCTIVITY OF THE AIR.

By placing a metal plate or wire net above the collector and applying a potential to the plate or net it was possible to estimate the conductivity of the air. Traces C and D of Plate I show the results of two attempts. A reliable result is obtained if the field between the plate and the collector is adjusted to the fine weather value. The results obtained with the wire net are:-

Electric field strength - 2.4 volts-cms^{-1}

Conduction current - 0.8×10^{-16} amp.-cms.$^{-2}$

$$\lambda = \frac{i}{F} = \frac{0.8 \times 10^{-16}}{2.4} \text{ ohm.}^{-1}\text{-cms.}^{-1}$$

$$= 3.3 \times 10^{-17} \text{ ohm.}^{-1}\text{-cms.}^{-1}$$

7.6 RAIN.

Records covering periods of rainfall show the following characteristic. In showery weather the current frequently changes polarity within short time intervals, of the order of a few minutes. This has been observed in light showers with currents of the order of 10^{-15} amp.-cms.$^{-2}$ and in heavy thunder showers when currents of 10^{-13} amp. cms.$^{-2}$ were recorded. As a result the 24 hour record was found to be very unsatisfactory for the measurement of rain currents, for the peaks are packed closely and no analysis is possible. The beginning and end of the shower shown in trace B of Plate 4 indicates the rapid fluctuations to be expected.

The 1 hour record is ideal for rain measurements. Traces A of Plates 3 and 4 are typical records of continuous rain and a thunderstorm shower respectively.

Few rain records of each type are available, so that an analysis of the records would have little meaning.

7.7 INSULATION FAILURES.

The only serious failure of the insulation during these tests was that mentioned on page 38 . No trouble was experienced during periods of heavy rainfall. Occasionally an undetected strand of a spider's web caused a temporary breakdown.

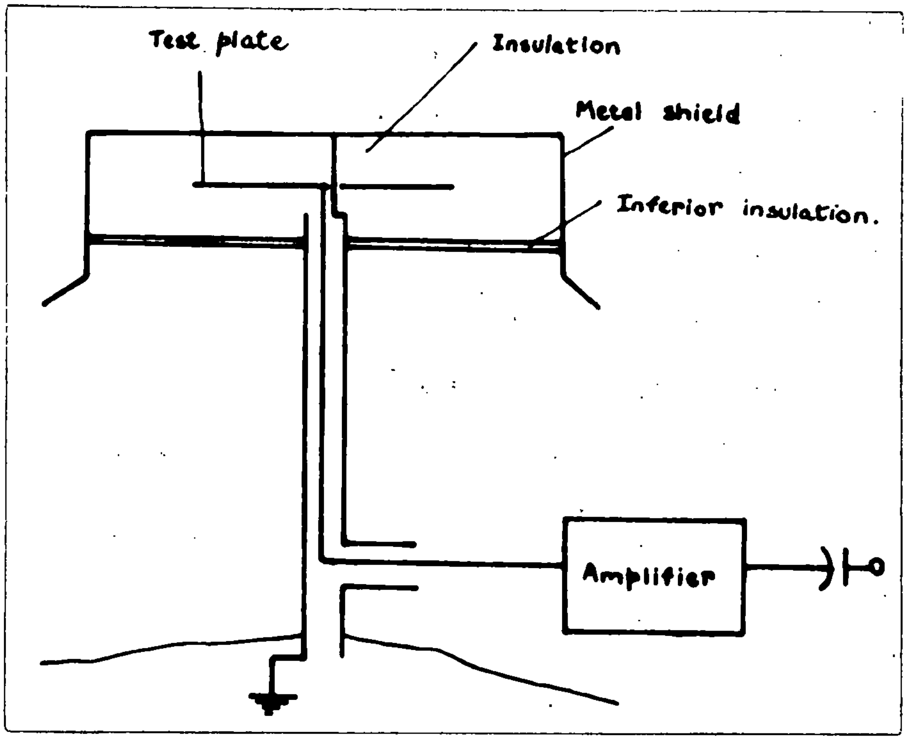

Test plate
Insulation
Metal shield
Inferior insulation.
Amplifier

FIGURE 31.

CHAPTER VIII.

CONCLUSIONS.

The tests have shown that the electronic method of studying the electrical effects at the surface of the earth is entirely successful. The equipment needs little supervision and maintenance, and the stability is adequate for continuous operation.

Measurement of the air-earth current, however, is not satisfactory because of the failure to obtain compensation for field changes. If a reliable method can be developed, then the air-earth current measurements will be more significant than those obtained by Scrase (1933), for he really observed the conductivity of the air rather than the air-earth current.

Rain current measurements are reliable for periods when the field changes are small. A good resolution is necessary on the recording paper, in order to display clearly the frequent changes in the polarity of the rain currents, which usually occur.

Towards the end of the work when it became apparent that the agrimeter would not give the desired response an alternative method was devised, but could not be tackled because of lack of time. The method is shown schematically in Figure 31. The inverted test plate will respond to field changes while the collection of charge from the conduction current is prevented by the insulation mould around it. The 'earthed' metal shield prevents the collection of static charges on the insulation, while the outer coating of inferior insulating material will disperse these charges on the exposed surface rapidly.

SUMMARY.

Electrical effects, which are related to changes in the electrical structure of the atmosphere above can be constantly observed at the earth's surface. These effects can be classified as follows:-

(1) Changes in the vertical electric field.

These cause variations in the 'bound' charge on the surface of the earth, and can be observed as transient currents.

(2) Transference of charge from the air to the earth.

There are two main processes:

(a) An ionic conduction current.

(b) Charge carried by precipitation elements.

(3) Discharge from points.

The present research is more concerned with the transference of charge from the air to the earth. In the past most observers have found it more convenient to measure the precipitation currents and ionic conduction current independently. Few have been able to make systematic observations during all hours of the day for long periods. The recording technique has usually been a photographic one; a method which suffers from the

disadvantage that the results are studied long after the events have occurred.

An investigation has been made to examine the possibilities of using an electronic method to measure the atmospheric electric currents continuously, with a view to the eventual establishment of a system in which all the electrical elements (field, currents, point-discharge, etc.) are recorded on a multi-channel electro-magnetic pen-recorder, so that the electrical nature of various weather situations can be observed immediately.

An apparatus has been developed which will record the electrical effects which occur at the surface of the earth under natural conditions. It had been hoped to avoid the effects of field changes by obtaining a compensating signal from an electric field measuring instrument, but this part of the work has not yet been successful because of mechanical difficulties in this instrument.

The apparatus consists of a collecting bowl which is mounted in a pit with its exposed surface flush with the surrounding ground. Compensation for splashing has been obtained by using the guard-ring principle, and the effects of contact potential differences have been removed by coating the outer surface of the collector and the inner surface of the pit-lining with aluminium 'metallic' paint. Insulation difficulties have been overcome by using polystyrene and keeping it warm by electrical heating. The current reaching the exposed surface of the collector is carried in concentric screened cable with solid polyethylene insulation to a D.C. negative feedback amplifier.

The amplifier has an electrometer input stage and the ionic current develops a voltage across a 10^{11} ohms resistor connected in the grid circuit of this valve. A low impedance output is obtained by using a cathode-follower. This is connected to a heavily damped mirror-galvanometer which records the currents on photographic paper in a drum camera. To control zero-drift a method of degenerative feedback for long term voltage changes has been developed, using a compensating valve in the input stage. The amplifier can handle currents in the range 2×10^{-13} amperes - 2×10^{-10} amperes without saturating. Long-term drift is equivalent to a current change of 1×10^{-14} ampere per hour referred to the input while the short term fluctuations are less than 4×10^{-14} ampere. Either 1 hour or 24 hour records of the atmospheric currents can be obtained. An electrically controlled relay circuit is used to 'zero the amplifier' every half an hour or, alternatively, every hour.

A shunt selecting unit has been developed which automatically alters the sensitivity of the galvanometer and is controlled from the output of the amplifier. The circuit uses electronic trigger circuits to operate relays. The sensitivity is indicated on the edge of the photographic paper by using an additional galvanometer lamp. This unit is still in the prototype stage.

Power supplies are obtained from three highly stabilized mains operated power units. All amplifying valves have their heaters connected in series and are heated from one of these power units.

During 6 months of operation the apparatus has given a reliable performance, but measurement of the air-earth ionic current has been made difficult because of the presence of field change transient currents. The use of a second exposed plate, mounted in insulating material and used in the inverted position, has been suggested as a method of obtaining the field changes without the conduction current, for amplification. The amplified field changes would then be passed in the correct phase via a suitably adjusted capacitance to the current amplifier input to balance out the field changes.

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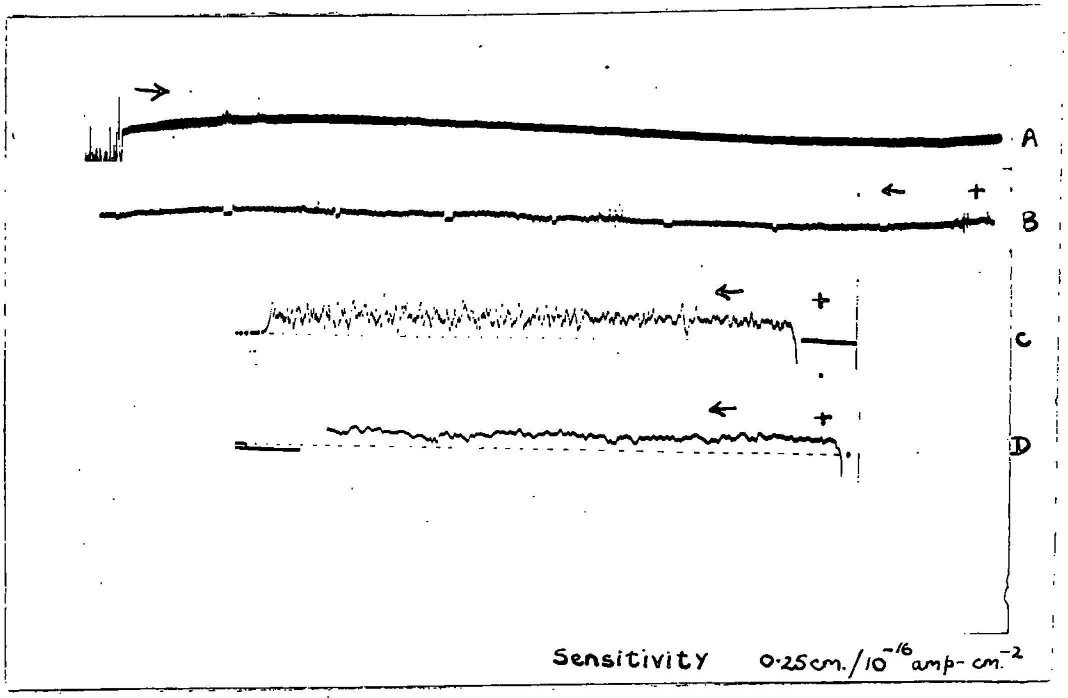


PLATE I.

A. Zero-trace for period of I6 hours. Amplifier disconnected from collector after first hour of the trace.

B. Zero-trace for period of I6 hours. Collector was screened and remained connected to the amplifier, except for 5 minutes every 2 hours.

C. Conductivity current, ($\frac{1}{2}$hour). Plate mounted above the collector and a potential was applied to it. 'Spiky' fluctuations due to wind.

D. Conductivity current, ($\frac{1}{2}$hour). Wire net of I inch mesh was used instead of the plate.

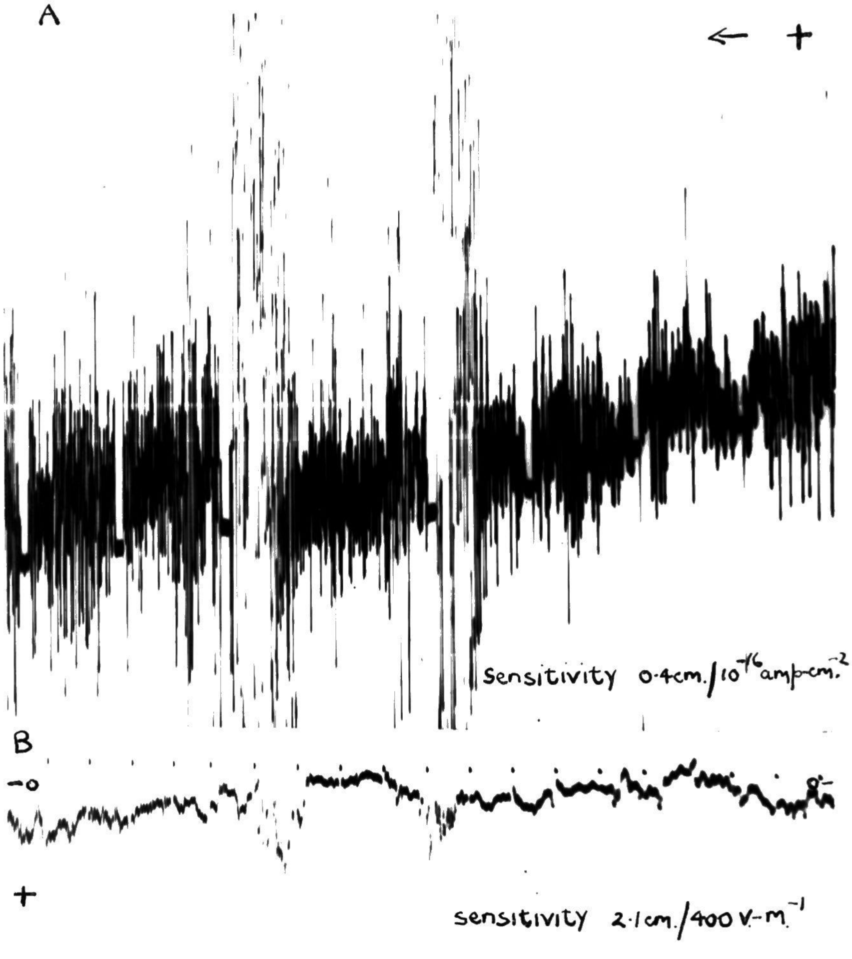


PLATE 2.

A. Record of air-earth current and field-change fluctuations.

B. Simultaneous record of the electric field. (Time scales differ slightly.)

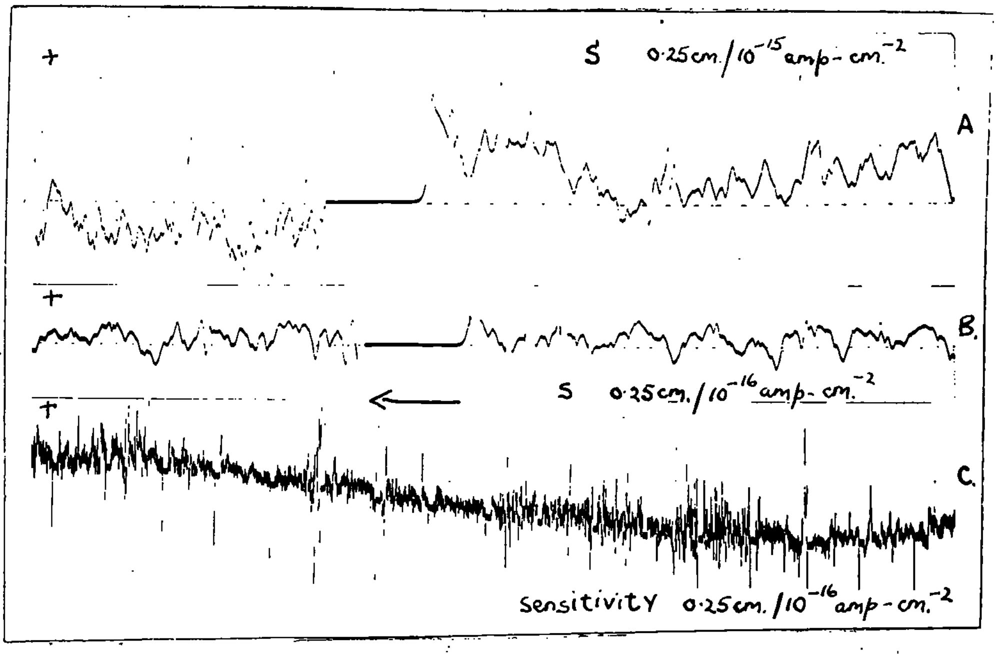
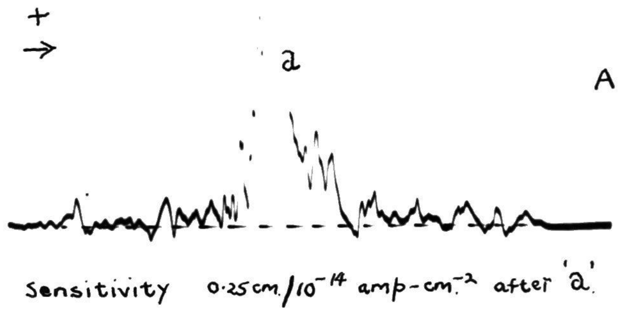


PLATE 3.

A. Record (I hour), taken during a period of continuous rain.

B. Record (I hour), of the air-earth current during calm and cloudless weather conditions.

C. Record (24 hours), of the air-earth current under similar conditions as 'B'.



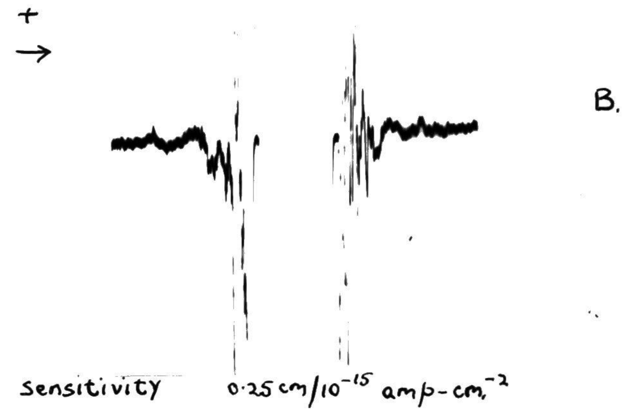


PLATE 4.

A. Record (I hour), of thunderstorm rain. Sensitivity was decreased at 'a' by a factor of IO.

B. Record (24 hours), of a long shower of rain. In the centre portion of the trace the amplitude was too large to be recorded.

ACKNOWLEDGMENTS.

The author is pleased to express his thanks to the members of the staff of the Science Laboratories, Durham, for the help and advice received during the course of the work. Especial thanks are due to Professor J.E.P. Wagstaff for the facilities enjoyed and the provision of equipment.

He is also indebted to Mr. E. Hugill for technical assistance and advice during the constructional part of the work.

Gratitude is also expressed to Dr. J.A. Chalmers, who suggested the problem and was unsparing in his advice and encouragement. His keen interest in the research was always a source of inspiration.

The following awards - Oliver Lodge Scholarship, 1947, & C.P. Sparks' Memorial Fund Grant, 1948 (I. E. E.), and a Maintenance Grant, 1948, 49 (D. S. I. R.) - made by the Institution of Electrical Engineers and the Department of Scientific and Industrial Research are gratefully acknowledged.