AMPLIFICATION OF
SMALL ELECTRICAL CURRENTS

by

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INTRODUCTION

The problems this thesis attempted to solve were those arising from the construction of apparatus suitable for amplifying small electrical currents. The first task was to study the different methods which have been devised for this purpose and then to select the method which would best fit the experimental conditions under which the amplifiers were to be used in the laboratory. The problem was approached in two ways. The first was the construction of a relatively simple but extremely effective amplifier which was used to measure photoelectric cell currents. The second was a construction of a much more elaborate nature, embodying the use of the so-called electrometer tube.

The general theory of both of these amplifiers is much the same. It is the theory of any d-c amplifier varied, however, to allow for the extremely small currents which are involved. As is well known, when a certain potential is applied to the grid of a vacuum tube the plate current will have a fixed value, and when a different potential is applied to the control grid the plate current will have still another fixed value. The potential on the grid may be maintained by a current through a high resistor in parallel with the control grid. So if a small direct current is flowing through this high resistor, the potential of the grid is fixed at a certain value. A different current in the high resistor will cause a corresponding change in the potential of the control grid. Thus the original small direct current is amplified since the current flowing in the grid circuit is much smaller than that flowing in the plate circuit.

There are two methods by which high current amplification may be obtained. The first is by use of a vacuum tube of high mutual conductance. High mutual conductance means that a small change in grid potential produces an extremely large change in plate current. This method is used in most d-c amplification and is widely used commercially. The second method is by use of a tube which has a high grid to filament resistance, for when this is true a very large bias resistor can be used across the grid of the tube. Thus small currents through the bias resistor result in comparatively large potentials on the grid. The gain in overall amplification is then extremely large. The latter method is the type of amplification which was employed in this problem.

Ordinary radio tubes have a grid input resistance of around 10^8 ohms. One tube, the 954, has an input resistance of about 10^9 ohms. But even this input resistance is much too low to measure the currents which were desired in this investigation. Gabus and Pool (1) have experimented with this tube by changing its operating voltages and the use of the grids. They have managed to raise the value of its input resistance to a much higher value. In the first part of the investigation reported here a 954 tube was used in the manner in which Gabus and Pool suggest.

In the amplification of extremely small currents, however, it is necessary to use a tube which has a much higher input resistance than is found in even this 954 radio tube. Consequently, it was found necessary to employ one of the so-called electrometer tubes. Either the General Electric, FP-54, or the Western Electric, No. D-96475 tubes fall in this class. These tubes have input resistances in the neighborhood of 10^{16} ohms. With one of these tubes it is possible to use very large input resistors and still have remarkably stable amplification. The limit of sensitivity which is possible with one of these tubes depends upon the stability of the tube and the battery supply.

Since many experimenters have investigated the problem of improving the stability of such circuits, it was decided first to study various circuits proposed by them and decide which one would be the best for this amplifier. D. B. Penick (2) has compared a large number of these balanced, single tube, direct-current amplifier circuits. He has also given the balance equations and other general information for the Earth circuit, which he regarded as the most generally adaptable. Besides the single tube circuits, others have been developed using two tubes which were balanced against each other. These two tube circuits, however, have two drawbacks. In the first place they require the use of two rather than one expensive tube. In the second place the characteristics of the tubes have to be carefully matched. Since it is difficult to find two tubes with characteristics as closely matched as is necessary, and since it is possible to get as good results with a balanced single tube circuit, it was decided to use a single tube circuit in this amplifier.

With regard to stability of the amplifier circuit some of the best results have been obtained by Hafstad (5). He used the simplest possible circuit and several batteries for power supply. He found that random fluctuations were effectively eliminated when new lead cells were used. But even then it was necessary to operate them in a constant temperature room. In the filament circuit he used a counter cell to compensate for declining battery voltage and for slowly changing tube characteristics. While Hafstad's method was extremely effective, it was unnecessarily expensive. Other types of circuits have been devised which give nearly as good results. In these latter circuits all the voltages for the tube are supplied by one battery. The circuits are stabilized by adjusting the resistance net work through which the voltages are supplied to fit the characteristics of the tube. These adjustments are made in such a way that the net effect of small variations in battery voltage on the output galvanometer current is very small.

For purposes of comparison, several of these circuits are shown in simplified form in Plate I Fig. 1. In the first, Fig. 1, a, from Compton and Haring (4), the resistances, R_2 and R_3, were adjusted for desired values of space-charge grid and plate voltages, respectively. R_p and R_4 were set at convenient values, such that the galvanometer current was approximately zero when the desired plate current was flowing. The value of R_1 was set so that small changes in filament circuit current produced minimum changes in galvanometer current, and the biasing battery E_x was always adjusted to such a potential in relation to R_1 that the control grid was at its desired voltage.

In the Soller (5) circuit, Fig. 1, b, the biasing battery was inserted in the galvanometer circuit instead of in the grid circuit. Here the circuit was balanced by setting

R_1 to give the desired value of the control grid bias, and setting R_3 and E_k together for the proper plate voltage. R_p and R_4 were then adjusted for zero galvanometer current and good circuit stability. Turner and Sieglin (6) have published a modification of the Soller Circuit, which has slightly different characteristics.

In all three of these balanced circuits, one undesirable feature was the necessity of using a separate biasing battery, since no compensation was made for voltage fluctuations of this biasing battery. It was possible to reduce such fluctuations as were due to temperature by taking the proper precautions. But the use of this battery was at best a complicating factor in the operation of the amplifiers.

DuBridge and Brown (7) designed the circuit, Fig. 1, c, which dispensed with the biasing battery. It gave good results in several laboratories. This circuit was balanced by adjusting the value of R_{23}, the values of R_p and R_n being always set for zero galvanometer current and the proper plate voltage. R_d made possible the operation of the space-charge grid at a lower voltage than the plate when this was desired.

As Harnwell and Van Voorhis (8) pointed out, this circuit was not sufficiently flexible to be adaptable to widely differing tube characteristics. It was therefore limited in its usefulness. They used two methods for extending its flexibility. The first method resulted in a circuit very similar in the control grid branch to Fig. 1, a. The other method shunted a resistance from the plate to filament of the tube as shown in Fig. 1, d. They increased the control of the balance condition but their method reduced the sensitivity of the tube to some extent.

A circuit which has the main advantages of all of these circuits without their salient disadvantages was developed by Barth (8). Its essential elements are shown in Fig. 1, e. In this circuit the balance was effected by varying the resistances R_2 and R_3, R_n and R_p being set for zero galvanometer current and the proper plate voltage. It was noted that when R_2 equals R_3 this circuit degenerated into the DuBridge and Brown circuit. Similarly it takes on the form of Fig. 1, f, when R_2 is less than R_3. Its equations for balance, therefore, are equally applicable to Fig. 1, e, and 1, f. This is the circuit which was chosen in the present investigation to be used in conjunction with an FP-54 tube.

AMPLIFIER WITH 954 TUBE

As mentioned in the introduction, Gabus and Pool (1) tested a number of radio tubes at greatly reduced operating voltages. They discovered that as the voltages were decreased the input resistance of all tubes increased. Generally, however, the grid transconductance decreased so rapidly that when the input resistance was increased to 10^9 ohms by reduction of all voltages, the plate current became too small to operate a portable galvanometer satisfactorily. It was discovered that none of the radio tubes tested had an input resistance higher than 2×10^8 ohms when operated at normal voltages. The 954 tube ranked highest in regard to input resistance and sensitivity. The grid leads in this tube were widely separated from each other and from all other leads. Each lead was brought out through a "pinch" in the glass wall of the tube and no base was used. This insured a very high insulation resistance.

The circuit used in the construction of the 954 amplifier is shown in Plate II Fig. 1, a. Particular care was taken to keep the grid circuit capacity to ground a minimum by making all connections as short and direct as possible. The voltages on the tube were reduced to the following values: plate, 8 volts; screen grid, 13½ volts; heater, 4½ volts. The grid no. 2 was used in its normal capacity as a screen grid, but the connections to grids no. 1 and no. 3 were interchanged resulting in the following action; the cathode emitted electrons; grid no. 1 tied to the cathode reduced the space charge; grid no. 2 accelerated the electrons but repelled any ions that were formed between it and the cathode; grid no. 3 normally used as a suppressor, functioned as the control grid. The number of ions reaching grid no. 3 from the vicinity of the cathode was greatly reduced because they were repelled by the positive voltages applied to grid no. 2 and the plate.

As a direct result of the high insulation resistance, the reduced voltages, and the special use made of grids no. 1 and no. 3, the input resistance rose from about 10^8 to 10^{13} ohms. Further reduction of the heater voltage would no doubt result in an even higher input resistance.

Since there was considerable variation in the characteristics of individual vacuum tubes, Gabus and Pool (1) tested five 954 tubes to determine their behavior under the above operating conditions. In every case the heater, grid, and plate voltages used were the same. They did, however, adjust the screen grid voltages in $1\frac{1}{2}$ volt steps to partially compensate for differences in individual tubes. Out of all the tubes examined one was rejected as unsuitable.

In the circuit as shown by Gabus and Pool (1), the bias for the control grid is obtained by connecting the cathode to the positive terminal of the "A" battery, while the control grid lead through the high coupling resistor is tapped off the negative terminal of the "A" battery. In using this circuit it was discovered that this method of biasing did not give a sufficient bias to the grid and in order to accomplish this, it was necessary to use a small "C" battery in series with the "A" battery. This arrangement is shown in Plate II Fig. 1, a. The necessity for using a "C" battery in conjunction with this circuit was probably due to the fact that a rather large "dark" current was flowing through the phototube, thus causing too large a potential drop across the high coupling resistor. By the proper biasing the tube was operated at a point where the amplification curve was nearly linear, and good results were obtained.

In this circuit a null method was used for balancing out the residual plate current and only the current due to change in the input current was measured. This was effected by applying a reverse potential through a variable resistance across the microammeter in the plate circuit. This null method proved to be very effective, as the circuit could be set for use under any conditions which might arise.

Apparatus

R. C. A. 954 tube

Special socket for 954 tube

R. C. A. Phototube 917

Resistor 10^{10} ohms

Resistor 200,000 ohms, variable, with off and on switch

Toggle off-on switch

Microammeter 0-200 microamperes

3 - No. 6 dry cells

1 - #762 B battery

1 - #772 B battery

1 - 6 volt C battery

Six-foot, flexible, 6-lead, shielded cable

Brass cylinder 2" in diameter, 8" long. Ends fitted with screw caps

Metal box, 6 x 7 x 13 inches, constructed from 18 gauge sheet iron and painted with crystallizing lacquer, to house batteries, meter and the various controls

Brass and mica for mounting tubes inside brass cylinder.

Construction Details

A metal box, 6 x 7 x 13 inches was constructed of 18 gauge sheet iron and painted with crystallizing lacquer. It was used to house the batteries. The front of the box was used to mount the meter and the controls. Three No. 6 dry cells supplied the heater voltage, and the other potentials were supplied by the smallest available "B" batteries. These batteries were designed for use in portable receivers. The current drain was so small that the life of the batteries was almost equal to their shelf life.

The phototube and 954 amplifier tube were mounted within the brass cylinder two inches in diameter and eight inches long. The method of mounting these tubes is shown in Plate II Fig. 1, b. For this purpose the regular 954 tube socket, which is mounted on brass, with all the leads insulated with mica, was used. It was found to be necessary to cut away the socket at the grid no. 3 lead, in order that the effective grid input insulation resistance would be raised. It was also necessary to cut off the corners of this socket so that it would fit into the brass cylinder. A wafer socket to hold the phototube was mounted on a brass ring, being carefully insulated with sheet mica. These two sockets were then mounted on a brass post two inches long, which was drilled in the middle and tapped, so that it could be fastened to the side of the brass cylinder. A bakelite post was fastened opposite the brass post. It was used to mount the two clips which were used to hold the high input resistor. This method of mounting proved to be very effective, and was compact and easily removed from the cylinder whenever it was necessary to change input resistors or make any adjustment in the apparatus.

An opening to admit light to the phototube was cut in the brass cylinder over the plate of the phototube. A glass plate was waxed into this opening. Since the cylinder was fitted with screw caps the whole thing was air tight. It was dried, using as a drying agent either anhydrous calcium chloride or phosphorous pentoxide. A sleeve was fitted over the window of the cylinder which had a number of different size openings cut in it. Thus the portion of the sensitive plate of the phototube which was exposed to the light could be regulated.

The tubes mounted in the brass cylinder were connected with the rest of the circuit through a six-foot, six-lead, shielded, flexible cable. Both tubes were shielded from extraneous light. With this arrangement the phototube could be used to take measurements in a totally dark room, while the readings were made in a well lighted room. The whole apparatus was electrostatically shielded. Extreme care was used throughout to make good connections and to keep the insulation of all parts extremely good.

For use as a high input resistance with this circuit an S. S. White, 33,000 megohm resistor was purchased, but for some reason this resistor eventually became infinite. So some resistors were made following the method suggested by Andrewes, Davies, and Horton (9). These resistors were made by fusing together in an oxidizing flame ground soda glass and cuprous oxide. By varying the concentrations it was possible to get some very good resistances of from 10^8 to 10^{10} ohms. To give these resistors strength, they were sealed in glass tubes equipped with side tubes for drying purposes. These resistors turned out to be very effective and were used throughout the experiments with this amplifier.

The amplifier when completed was used in a densitometer and tests proved it to be much more sensitive than any other similar apparatus in the laboratory. For this special purpose the brass cylinder was mounted in a light tight box. The lid of this box was fitted with an adjustable slit. Plate II Fig. 2 shows the completed amplifier.

Discussion

The sensitivity attained by this amplifier was determined by the value of the input resistance R_o. The greater this resistance the greater the sensitivity of the circuit; however, it was found that it was impractical to use a grid resistance higher than 10^{11} ohms, for the time constant of the grid circuit, assuming a total capacity of 10^{11} farads, reached the rather large value of one second. A further increase in sensitivity, no matter what tube is used causes a corresponding increase in the time constant.

The 0-200 microammeter in the plate circuit had a low sensitivity. This was necessary since the drift and fluctuations of the circuit were such as to throw a more sensitive galvanometer completely off the scale. With this microammeter, however, the variations were imperceptible.

It was necessary to make a compromise in the stability, sensitivity, and the time constant of the circuit. As the coupling resistor was made larger to increase the sensitivity, the resultant resistance of the input circuit approached the unshunted input resistance of the tube as a limit. In the case of the 954 this was 10^{13} ohms corresponding to a maximum sensitivity of 1.4×10^{-13} amperes input per microampere output and a time constant of 100 seconds. In comparing a number of different light intensities where speed is essential such large time constants cannot be tolerated. For this reason a high coupling resistor not exceeding 10^{11} ohms and a low sensitivity galvanometer are preferred.

In case it is desirable to use a more sensitive type of current reading meter such as a sensitive galvanometer, then a balanced circuit of the type discussed in the introduction would have to be used. Where it is necessary to measure a current of a few electrons per second the balanced circuit with an FP-54, or similar electrometer type tube is indispensable.

THE FP-54 AMPLIFIER

For this amplifier the Barth circuit was chosen and as explained by Penick (2), it was first necessary to set up the equations for balancing the circuit. These equations made possible the determination of the values of the five circuit resistances, R_1, R_2, R_3, R_p, and R_n, in Plate I Fig. 1, e, in terms of the corresponding tube characteristics. The equations are valid under the conditions that (1) the voltages on the elements of the tube have their desired values, (2) the galvanometer current be approximately zero, and (3) the galvanometer current be constant for small variations in filament current. The latter are produced by varying R_4 or the battery voltage. The equations defining these values were derived by a method given by Harnwell and Van Voorhis (8). Considering, as they did, that R_d is included in the characteristics of the tube, the equations are as follows:

$$I_f R_1 = -E_g \quad \text{(A)}$$

$$I_f R_2 + E_f = E_n + I_n R_n = E_{nt} \quad \text{(B)}$$

$$I_f R_3 + E_f - E_p + I_p R_p = E_{pt} \quad \text{(C)}$$

$$\frac{1 + R_p\left(\dfrac{\partial I_p}{\partial E_p} - \dfrac{\partial I_p}{\partial E_n}\right)}{1 + R_n\left(\dfrac{\partial I_n}{\partial E_n} - \dfrac{\partial I_n}{\partial E_p}\right)} = \frac{\dfrac{\partial E_f}{\partial I_f} + R_3 - R_p\dfrac{\partial I_p}{\partial I_f} + R_1 R_p\dfrac{\partial I_p}{\partial E_g}}{\dfrac{\partial E_f}{\partial I_f} + R_2 - R_n\dfrac{\partial I_n}{\partial I_f} + R_1 R_p\dfrac{\partial I_n}{\partial E_g}} \quad \text{(D)}$$

In these equations I_f is the filament current, I_p is the plate current, I_n is the space charge grid current, E_f is the filament voltage, E_n and E_p are respectively the space charge grid and plate voltages, E_g is the potential of the control grid and the other symbols represent the usual terms given in this type of equation. The terms and symbols used in these and the following equations are taken up in more detail on page 22.

Since there were five unknowns and only four equations, one of the unknowns has to be set arbitrarily. This arbitrary element gives the circuit a degree of flexibility which was entirely lacking in the DuBridge and Brown circuit. Thus, if it is desired to fix the voltage of the supply battery at a convenient value, R_2 may be set at such a value that the required voltage drop is produced by the normal filament current across the series combination of R_2, R_1, and the filament of the tube. The value of R_n is defined immediately by Equation (B). Equations (D) and (C) are used to determine the values of the two remaining unknowns R_3 and R_p. Solving for these quantities yields:

$$R_p = \frac{R_n\left\{\left(\frac{\partial I_n}{\partial E_n} + \frac{\partial I_n}{\partial E_p}\right)\left(E_p + I_f\frac{\partial E_f}{\partial I_f} - E_f\right) - \left(I_n - I_f\frac{\partial I_n}{\partial I_f} + I_f R_1\frac{\partial I_n}{\partial E_g}\right)\right\}}{\left(\frac{\partial I_p}{\partial E_p} + \frac{\partial I_p}{\partial E_n}\right)\left\{\left(E_p + I_f\frac{\partial E_f}{\partial I_f} - E_f\right) + R_n\left(I_n - I_f\frac{\partial I_n}{\partial I_f} + I_f R_1\frac{\partial I_n}{\partial E_g}\right)\right\} - \left\{1 + R_n\left(\frac{\partial I_n}{\partial E_n} + \frac{I_p}{E_p}\right)\right\}\left(I_p - I_f\frac{\partial I_p}{\partial I_f} + I_f R_1\frac{\partial I_p}{\partial E_g}\right)} \quad \text{....(E)}$$

$$R_3 = (1/I_f)(E_p + I_p R_p) \quad \text{.................................(F)}$$

Measurement of Tube Characteristics

The tube characteristics involved in these equations included many which were not usually important in commercial circuits and for which data are not available. It was, therefore, necessary to evaluate these characteristics experimentally. A method suggested by Harnwell and Van Voorhis (3) was adopted for this purpose. The circuit used is given in Plate III Fig. 1. R_1 was made from six Leeds and Northrup plug type resistance boxes, so arranged that only 50,000 ohms were used. By varying the position of the plugs the potential of E_g could be varied in steps of .00012 volt. R_2 was a 760 ohm slide wire resistance operated as a potential divider and was used to vary the voltage applied to the plate and space charge grid. R_3, a 46 ohm slide wire rheostat, and R_4 a 180 ohm slide wire rheostat, were used to vary the filament current. R_f was a heavy duty 5.8 ohm resistance used with a potentiometer to measure the filament current. R_p, a ten thousand ohm resistance box, was used with a potentiometer to measure the plate current. R_n, a one thousand ohm resistance box was used with a potentiometer to measure the space charge grid current. R_d was a variable resistance used to reduce the space charge grid voltage to the required value. E_g, E_f, E_p and E_n were measured with a potentiometer connected as indicated by the arrows shown in Plate III Fig. 1. Now, in order that the various tube characteristics be found, it was necessary to find the effect caused by varying in turn each of the independent variables and noting the effect upon the dependent variables involved. For instance, it was necessary to find the effect of change in grid potential upon both the plate current and the space charge grid current, so I_f, E_n, and E_p were held constant and the potential of E_g was varied in small steps from the normal potential of -4 volts, and the different values of the plate current and space charge grid current were found. These values were plotted on a graph and a tangent was drawn to the resulting curve at the point of normal operation and from this tangent the I_p/E_g and I_n/E_g were found. The graphs from which these various tube characteristics were found are given in Plate IV Fig. 1 and Fig. 2. The various tube characteristics which were found in this manner are given below. Plate III Fig. 2 is a photograph showing the apparatus used for measuring the tube characteristics.

Filament current, I_f..............90 milliamperes

Plate voltage, E_p................ 6 volts

Space-charge grid voltage, E_n..... 6 volts

Control-grid voltage, E_g..........-4 volts

I_p/I_f..........................3000 x 10^{-6} amps/amp.

I_n/I_f..........................23000 x 10^{-6} amps/amp.

E_f/I_f..........................50 ohms

I_p/E_g..........................3.7 x 10^{-6} amp./volt

I_n/E_g..........................18 x 10^{-6} amp./volt

I_p/E_p..........................10 x 10^{-6} amp./volt

I_n/E_p..........................10.5 x 10^{-6} amp./volt

I_p/E_n..........................5.9 x 10^{-6} amp./volt

I_n/E_n..........................10.8 x 10^{-6} amp./volt

Filament voltage, E_f..............2.5805 volts

Plate current, I_p.................24.5 x 10^{-6} amp.

Space-charge grid current, I_n....130.0 x 10^{-6} amp.

Conditions for Balance

After having measured the various tube characteristics, the conditions under which the circuit was to be operated were determined. It was decided first of all that the amplifier should be operated by two 6 volt storage batteries. As a convenient operating value, E_{nt} was set equal to 7.3

which gave the following relationship:

$R_n =$

$$= \frac{R_p\left\{\left(\frac{\partial I_p}{\partial E_p} + \frac{\partial I_p}{\partial E_n}\right)\left(E_n + I_f\frac{\partial E_f}{\partial I_f} - E_f\right) - \left(I_p - I_f\frac{\partial I_p}{\partial I_f} + I_fR_1\frac{\partial I_p}{\partial E_g}\right)\right\}}{\left(\frac{\partial I_p}{\partial E_p} - \frac{\partial I_n}{\partial E_n}\right)\left\{\left(E_p + I_f\frac{\partial E_f}{\partial I_f} - E_f\right) + R_p\left(I_p - I_f\frac{\partial I_p}{\partial I_f} + I_fR_1\frac{\partial I_p}{\partial E_g}\right)\right\}}$$

$$- \left\{1 + R_p\left(\frac{\partial I_p}{\partial E_p} + \frac{\partial I_p}{\partial E_n}\right)\right\}\left(I_n - I_f\frac{\partial I_n}{\partial I_f} + I_fR_1\frac{\partial I_n}{\partial E_g}\right) \quad \ldots \text{(G)}$$

$$R_2 = (1/I_f)(E_n - I_nR_n - E_f) \ldots\ldots\ldots\ldots\ldots\ldots \text{(H)}$$

On setting E_{pt} equal to 7.194 volts and solving the equations, as before, the following values of the unknown resistances were found:

R_1 = 44.44 ohms

R_3 = 51.15 ohms

R_p = 48,734 ohms

R_n = 4,740 ohms

R_2 = 44.84 ohms

R_d = 15,360 ohms

E_{nt} = 6.616 volts

These calculations agreed fairly well with the experimentally measured balance values. The experimental value of E_{nt} was equal to 6.495 volts when the circuit was balanced. This compared closely with the calculated value of 6.616 volts given above. More is said about the experimental results later.

Apparatus

Having found the unknown values of the resistances suitable for balance, the final design of the circuit details was made. The circuit was made as adaptable to varying conditions as was possible. It was decided to put the tube and high input resistor in an evacuated cylinder and connect it to the rest of the circuit through shielded cables. This improved the adaptability of the amplifier as the input leads were made very short. This is necessary when such small electrical currents are to be amplified. The final design of the circuit is shown in Plate V Fig. 1, and the plan for the instrument box and control panel is shown in Plate VI Fig. 1, a, and 2, d.

The list of parts necessary for the construction of this amplifier is as follows:

R_o -- Westinghouse vacuum tube sputtered resistor 10^{10} and 10^{11} ohms

R_1 -- I. R. C. Type A. B. A. (Adjustable) -- 50 ohms

R_2 & R_3 -- General Radio Co. Type 333-A Rheostat-Potentiometer 0-30 ohms I. R. C. Type A.B.A.

(Adjustable) -- 0-150 ohms

R_4 -- General Radio Co. Type 333-A Rheostat-Potentiometer 0-30 ohms

R_d -- I. R. C. Type WW-4 14,500 ohms, Type A.B.A. 1,500 ohms

R_n -- Leeds and Northrup Co. Type 4775 Inclosed Switch Resistance box 0-9,999 ohms

R_p -- General Radio Co. Type 471-A Rheostat-Potentiometer 0-10,000 ohms

10 - I. R. C. WW-4 10,000 ohm resistances

Yaxley Switch--single circuit--11 stops

1 -- General Electric Co. FP-54 tube

1 -- Toggle off-on switch

1 -- Weston Electric Co. Type 301 Milliammeter 0-100 ma.

1 -- Weston Electric Co. Type 301 Microammeter 0-500 μa

1 -- Isolantite socket, sub-panel type, four prong

1 -- Isolantite socket, surface type, four prong

1 -- 30 ft. spool of no. 28 manganin wire

50 ft. of shielded single-lead cable

Hook-up wire, and other miscellaneous materials for assembling the amplifier

Brass cylinder 5" diameter and 12" long. Brass plate stock for making the other fittings of the cylinder as shown in Plate VII Fig. 1

Wood for making the instrument box and panel. Sheet tin to shield electrostatically the instrument box

High-grade bakelite, artificial amber, to make the input insulator

Ceresin wax for coating the insulator

Stopcock, gaskets, etc., for making the cylinder vacuum tight.

Construction Details

In the construction of this amplifier two things were kept in mind. The first, that the instrument was to be made as rugged as possible since it was to be portable. The second, that since it was to be used for the measurement of such minute currents, every possible means must be used to provide good insulation and protection from stray current and other effects which might occur in the laboratory.

The instruments were mounted on a panel as this could be easily opened and any adjustments or changes could be made on the circuit. The instrument box was made following the plans given in Plate VI Fig. 1. The top and sides were made from 1" oak and bottom from white pine. The back was made of plywood. The panel was constructed from a very good grade of press-wood. The finish was golden oak. The inside of the box was electrostatically shielded with a light-weight roofing tin. The seams were soldered together and a spring contact was maintained with the shielding of the panel. The instrument box was connected to the brass cylinder by three ten-foot shielded cables. The whole apparatus was grounded at the usual point, the negative of the battery. The shielding of the cables formed the return lead to the battery. The panel was mounted at an angle of 60° to facilitate making readings and adjustments on the instrument board.

The construction of the brass cylinder and method for mounting the tubes are shown in detail in Plate VII Fig. 1. Since it was necessary to measure very minute currents with this amplifier, the input resistance, R_o, had to be very large and the over-all insulation resistance had to be correspondingly larger. In order that the effects of ions in the gas caused by cosmic rays and other sources and the effect of moisture would be decreased, it was decided to evacuate this cylinder. The brass cylinder was built vacuum tight and the FP-54 tube and the Westinghouse resistor were mounted in it following a method suggested by S. W. Barnes (10).

In making the brass cylinder a strip was cut off one end about ½" wide; then a section was cut from this strip so that it would just fit into the large cylinder. This strip was bolted into the cylinder 3" from the bottom and formed a ledge for the brass plate to fit on. A hole large enough to allow the FP-54 tube to slip in was cut in the bottom plate. The small removable plate to which the tube was mounted by soldering with woods metal was bolted to the bottom of the large plate. Studs also were set to allow the fastening to the inside of the cylinder of the surface socket which held R_o. Next a ring was cut from 1/8" brass plate and soldered to the top of the cylinder and a top plate was cut so that it just fitted over this ring and was fastened on with stud bolts. Next a 1" brass tube to hold the lead-in insulator was fitted into the side of the brass cylinder and soldered on. Another tube was fitted in toward the bottom of the chamber to hold the stopcock. This tube was fitted with a shoulder to prevent the stopcock from slipping into the evaporated chamber. A 1/16" brass plate was made the same size as the top and bolted on the bottom of the cylinder with studs.

One of the big construction problems was the insulation of the grid input. But according to Strong (11), artificial amber or high-grade bakelite is as good an insulator as the natural amber. For this reason it was decided to use bakelite coated with ceresin wax for this insulator. The bakelite plug was turned down as shown in Plate VII Fig. 1 and was fitted with a brass rod to use as the lead, and waxed in position. The plug was first dipped in the melted ceresin wax to prevent surface contamination of the insulator. This wax has so little adsorption that its surface resistance is better than 10^{18} ohms even when the humidity of the air surrounding it is as high as 90%.

R_1, the grid bias resistor was an I. R. C. Type A.S.A. 50-ohm adjustable resistor with a length of manganin wire which could be used to make the fine adjustments that were necessary. This resistor was mounted at the bottom of the cylinder and one end was fastened to the negative end of the filament and the other end was grounded on the brass cylinder. The negative end of R_c was grounded to the inside of the chamber. Thus, there was only one lead into the evacuated chamber. The other leads to the circuit were connected to the terminals of the sub-panel type of socket which was simply slipped on to the bottom of the FP-54 tube.

The details of R_2 and R_3 are shown in Plate V Fig. 1. These resistances were composed of a rheostat-potentiometer, 0-30 ohms, in series with a variable rheostat to control the value of E_{pt}. E_{pt} was controlled by adjusting the position of the tapping arm of the potentiometer. For the rheostat it was found that an I. R. C. Type A.N.A. adjustable resistor was unsatisfactory. Better results were obtained by winding manganin wire on a spool, thus making a fixed resistor. Better results could also be obtained by making R_1 a potentiometer, since it would be possible to adjust the potential of the control grid bias, without disrupting the whole circuit.

R_4 was a variable rheostat used to vary the current flowing through the net-work. The rheostat-potentiometer used in R_2 and R_3, and R_4 are mounted on the panel as shown in Plate VI Fig. 2.

R_d was made by using a fixed 14,500 ohm I. R. C. WW-4 resistor and two Type A.B.A. adjustable resistors, (1) a 1,500 ohm resistor and the other (2) a 150 ohm resistor. These were mounted on the back of the Leeds and Northrup Type 4775 inclosed switch resistance box, 0-9, 99 ohms. This resistance box was mounted in the panel by allowing the resistance elements to pass through the hole in the panel and then screwing the box back on by passing screws through the face of the box into the box behind. Thus, sandwiching the panel between the face and the box behind it, the dials were placed before the observer.

R_p was made up by using a 10,000 ohm rheostat in series, with a 100,000 ohm resistance variable in 10,000 ohm steps. This large variable resistance was made by using I. R. C. WW-4, 10,000 ohm resistors, soldering them to the leads of a Yaxley (11) stop switch and connecting them so that they were in series.

The two meters and the toggle switch were mounted as shown in the panel plan, Plate VI Fig. 2, and the way they were connected in the circuit is shown in Plate V Fig. 1.

For making connections in this circuit extreme care had to be taken so that no contact resistance or contact potential would be developed to the junctions. For this reason throughout the circuit the only soldering flux used was pure resin. It was possible to attain a vacuum of about 1 mm. in the cylinder which was good enough to prevent leakage by ionization, or by the moisture in the chamber. The galvanometer leads were shielded cables. The battery leads were made from an eight-foot shielded cable, and the shield also served as the connection to the negative terminal of the battery, thus grounding the circuit to the negative potential of the battery. Plate VIII Fig. 1 is a photograph of completed amplifier.

Method of Balancing

The following method of balancing the circuit was worked out following rather closely the method suggested by D. B. Penick (2). It consists of the following steps:

(1) Set up the circuit so that I_f equals 90 milliamperes. Then set E_g so that it has a value of -4 volts and set E_{pt} to any convenient value. In this experiment the value of E_{pt} was equal to 7.194 volts when the amplifier was operated from a 12 volt storage battery.

(2) Set E_{nt} to a value between 6 volts and E_{pt}. In this experiment a value of E_{nt} equal to 6.5 was used.

(3) With the galvanometer circuit open, set R_p to a value such that when the normal current is flowing through the plate circuit, E_p is equal to 6 volts. In order that there is the proper plate current flowing, R_n is adjusted until the voltage across the space charge grid is equal to 4 volts. Keeping the tube operating under these conditions, adjust R_d until E_n equals 6 volts. This is equivalent to a potential drop across R_d of 2 volts.

(4) Close the galvanometer circuit and make a final adjustment of R_n to bring the galvanometer current approximately to zero. Once R_p is set, it need not be changed

unless the value of E_{pt} is changed.

(5) Vary the filament current over a small range near the operating point by varying the resistance R_4, and determine whether E_{nt} is too high or too low.

(6) Change E_{nt} by a small amount in the proper direction (having returned I_f to its normal value), readjust R_n to bring the galvanometer current back to zero, vary the filament current as in (5), and repeat as many times as is necessary to obtain the desired precision of balance. When near the balance point, some time must be allowed after each variation in filament current for the filament to reach temperature equilibrium.

Stability

Stability curves of this amplifier are shown in Plate IV Fig. 2. For these curves the value of E_{pt} was held constant at 7.194 volts while E_{nt} was varied. These values of E_{nt} are given in terms of the dial reading of the potentiometer used in R_2 and R_3. As is clearly shown by these curves, the value of E_{nt} is extremely critical. These curves show characteristics, which had not been noted elsewhere in the literature on the subject. At values of E_{nt} below the critical potential the curve is a continuous straight line. At values above the critical value the curve breaks up into a compound curve. At the critical value this compound curve flattened out and traveled along the axis for a considerable change in I_f. The literature on this subject leads us to expect this curve to be of the parabolic type, and that the critical value of the potential should always be so adjusted that the portion of the curve with zero slope lies on the axis at the point of normal filament current. The curves as shown in this amplifier when adjusted to the critical potential of E_{nt} apparently give a greater range of stability from filament current variations than is ordinarily found. Apparently the tube characteristics of this particular tube give this type of balance curve.

It was desired to test the stability of this circuit under conditions which closely approximated the conditions which would be found in the experimental work for which this amplifier was to be used. This was done by applying a very small potential across the high resistance and plotting the galvanometer readings against elapsed time. The results of this experiment are shown in Plate IV Fig. 2. There was a gradual drift in the readings of the galvanometer, which probably was due to shifting tube characteristics. The circuit used made no attempt to balance out the effects of shifting tube characteristics. This shift in the position of the balance point was discovered by checking the position of balance against the filament current. The tube usedin this amplifier was an old one which had been in the department for several years, and it may have been damaged to some extent in that time. Probably a new tube would not show such a pronounced shifting of tube characteristics. The rate of shift was found to be constant, so that it would be possible to interpolate results with a fair degree of accuracy.

Sensitivity

The sensitivity of this amplifier was measured by applying various potentials across the high resistance, R_o, and reading the resulting galvanometer deflections in millimeters. These results were plotted on a graph and the slope of the resulting line gave the sensitivity of the amplifier in terms of millimeters deflection of the galvanometer per volt of applied potential to the grid. This graph is shown in Plate IV Fig. 2. A galvanometer having a current sensitivity of 4.2×10^{-10} amps. per mm. deflection was used. The amplifier had a voltage sensitivity of 26,000 mm/volt. Using an input resistor, R_o, of 10^{12} ohms, this gives a current sensitivity of 3.8×10^{-17} amperes per millimeter deflection.

Uses of the FP-54 Amplifier

This amplifier was built to be used in the study of photoelectric and thermionic effects of carefully out-gassed metals. It can, however, be used for any purpose, for which a sensitive electrometer is needed. It can be used in any form of densitometer work, or with a carefully calibrated photoelectric cell to measure the intensity of very faint light sources.

SUMMARY

The methods by which two direct current amplifiers have been built are described. In the first case an amplifier was built with ordinary radio parts. This amplifier proved to be very sensitive and, due to the type of construction, very stable. It is eventually to be used in densitometer work and the preliminary experiments with it proved it to be remarkably well adapted for this work. The second amplifier was built much more elaborately and embodied the use of the General Electric FP-54 tube. It is eventually to be used to measure very small currents, 10^{-15} amperes, and for this purpose had to be not only extremely sensitive, but also very stable. The theoretical background for this amplifier is discussed in detail, and the actual methods used in the construction were given in detail. An experimental procedure for balancing the amplifier was also given as well as an analysis of the stability of this amplifier. Suggestions for improving the design of the circuit were given, so as to improve the ease in making adjustments necessary when balancing the circuit, or in rebalancing the circuit in case a new tube is used. It is pointed out that the actual balance point of the amplifier was different from any previously shown in the literature on the subject and the reasons for this were discussed.

ACKNOWLEDGMENTS

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EXPLANATION OF PLATE I

Fig. 1, a. The Compton and Haring balanced circuit.

Fig. 1, b. The Soller circuit with biasing battery E_K.

Fig. 1, c. The DuBridge-Brown circuit.

Fig. 1, d. The Harnwell and Van Voorhis circuit with shunted plate.

Fig. 1, e. The Barth circuit.

Fig. 1, f. The modified Barth circuit.

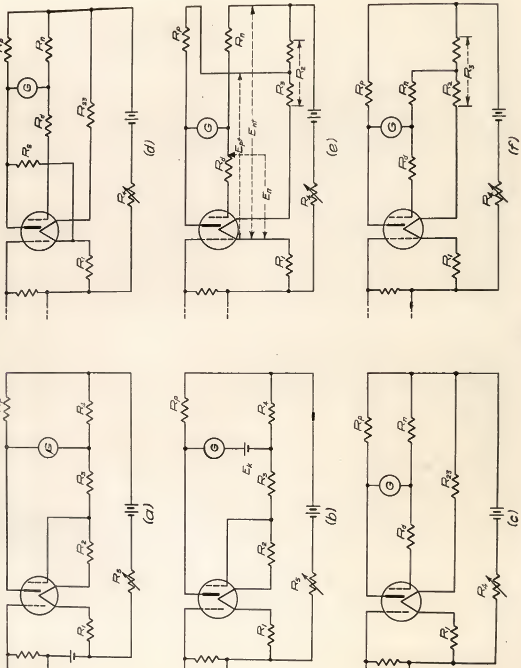


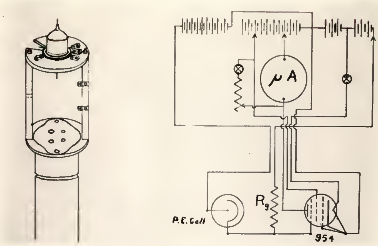
Fig. 1

EXPLANATION OF PLATE IX

Fig. 1, a. Electrical wiring diagram for 954 tube.

Fig. 1, b. Mounting for tube and resistor.

Fig. 2. Photograph of amplifier box and phototube chamber.



(b) Fig. 1 (a)

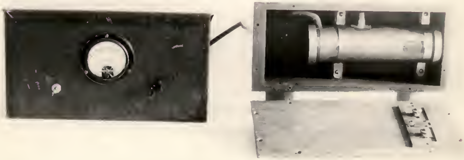


Fig. 2

EXPLANATION OF PLATE III

Fig. 1. Circuit used to measure tube characteristics of FP-54 tube.

Fig. 2. Photograph of apparatus used in measuring characteristics of the FP-54 tube.

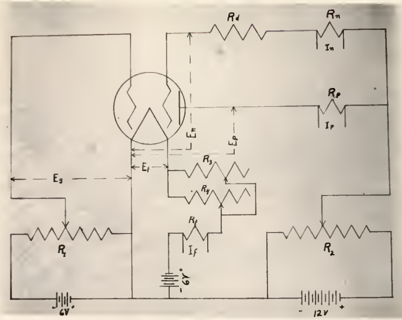


Fig. 1

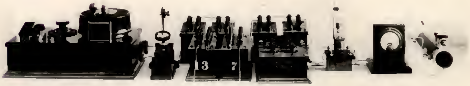


Fig. 2

EXPLANATION OF PLATE IV

Fig. 1. Curves used in determining characteristics of FP-54 tube.

Fig. 2. Curves of the FP-54 tube characteristics and graphs showing the stability and sensitivity of the amplifier

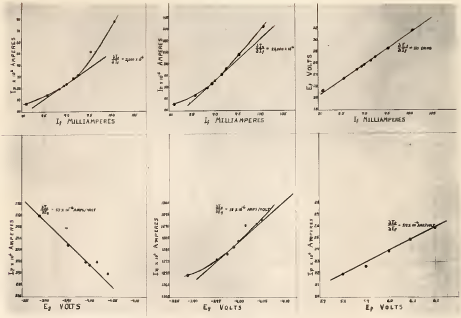

If MILLIAMPERES
If MILLIAMPERES
If MILLIAMPERES
Eg VOLTS
Eg VOLTS
Ep VOLTS

Fig. 1

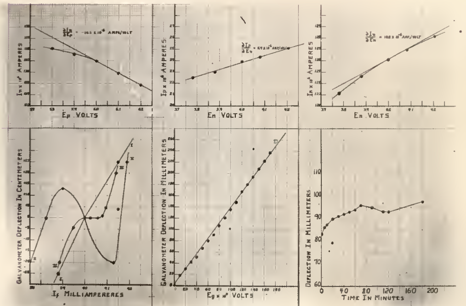
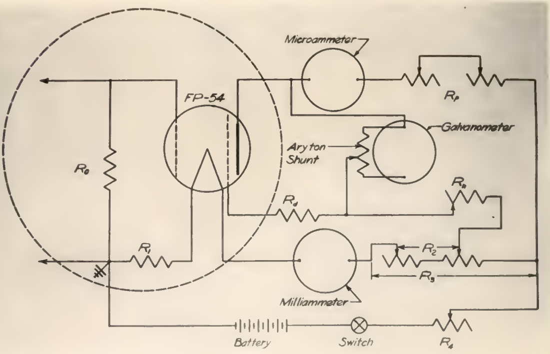

Ep VOLTS
En VOLTS
En VOLTS
GALVANOMETER DEFLECTION IN CENTIMETERS
If MILLIAMPERERES
GALVANOMETER DEFLECTION IN MILLIMETERS
DEFLECTION IN MILLIMETERS
TIME IN MINUTES

Fig. 2

EXPLANATION OF PLATE V

Fig. 1. Electrical wiring diagram for balanced circuit using FP-54 tube.



Microammeter
FP-54
R_p
Galvanometer
Aryton Shunt
R_g
R_s
R_d
R_1
R_2
R_3
Milliammeter
Battery
Switch
R_4

Fig. 1

EXPLANATION OF PLATE VI

Fig. 1. Diagram of instrument box.

Fig. 2. Diagram of control panel.

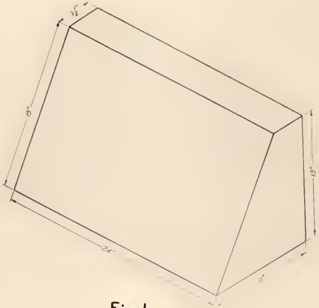

3½"
15"
13"
24"
11"

Fig. 1

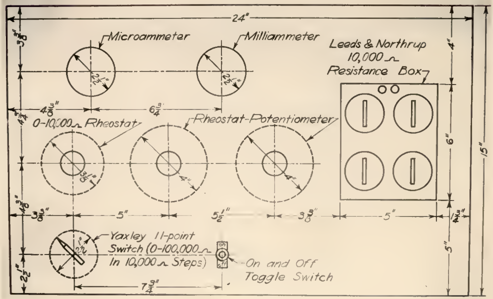

24"
Microammeter
Milliammeter
Leeds & Northrup
10,000 Ω
Resistance Box
0-10,000 Ω Rheostat
Rheostat-Potentiometer
Yaxley 11-point
Switch (0-100,000 Ω
In 10,000 Ω Steps)
On and Off
Toggle Switch
15"
6"
4"
5"
5½"
7¾"

Fig. 2

EXPLANATION OF PLATE VII

Fig. 1. Mounting for FP-54 tube with vacuum resistor and lead-in bakelite plug.

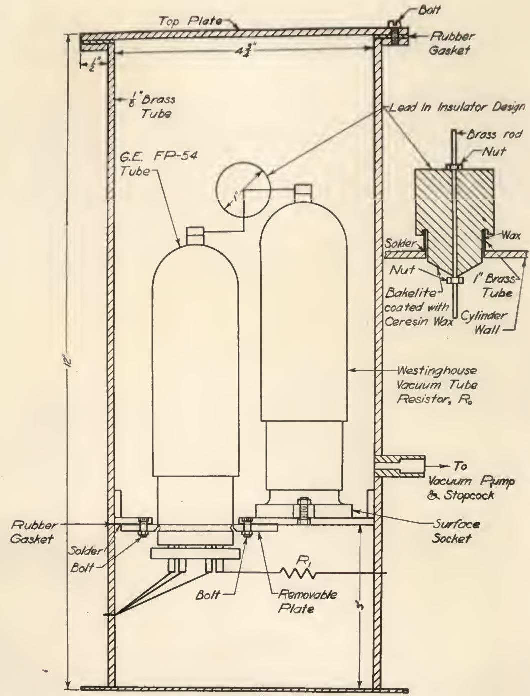


PLATE VII, FIGURE 1

EXPLANATION OF PLATE VIII

Fig. 1. Photograph of the completed FP-54 amplifier.

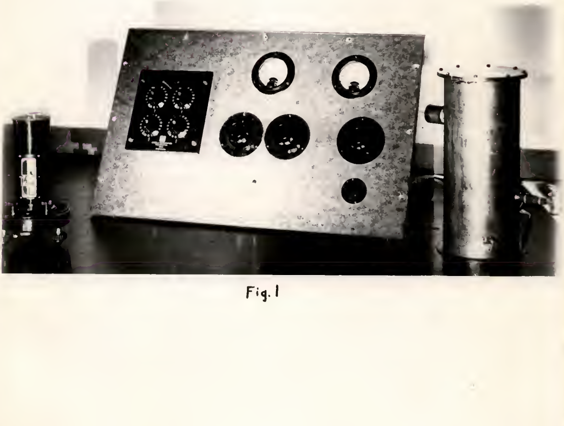


Fig. 1