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A STUDY OF ELECTROMETER CIRCUITS FOR THE MEASUREMENT OF SMALL CURRENTS AND VOLTAGES IN HIGH RESISTANCE CIRCUITS

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by

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INTRODUCTION

The purpose of this thesis is to outline the fundamental principles that are involved in the operation of d.c. amplifiers that are used for the measurement of small currents and small voltages in high resistance circuits. An attempt will be made to state and explain these principles in such a manner that a person with a knowledge of elementary physics can understand them. After perusing the literature on this subject, the author of this thesis feels that a contribution would be made in this field if a logical development of its principles be presented for the benefit of a person who is not an expert in electronics. A biologist interested in measuring the difference in potential between two parts of an animal need not be thoroughly acquainted with all phases of electronics to know the fundamental reason why an ordinary millivoltmeter will not measure a difference of potential of one millivolt between two parts of an animal. He can construct a d.c. amplifier for measuring small voltages in a high resistance circuit if he has a few principles of electrometer circuits in mind. A person interested in measuring ionization currents through an ionization chamber, or in measuring photoelectric currents in photocells, can, without a thorough background in electronics, set up an amplifying circuit and understand its principles of operation.

In this thesis, the simple things will be presented first and the more complex things will be built upon them. An attempt will be made to have the unknown to follow the known. Such questions as these will be discussed in this thesis; why is it that a quadrant electrometer or an electrometer circuit is necessary for the measurement of small voltages and small potential in high resistance circuits, and why is an ordinary voltmeter or ammeter unable to measure such small currents and voltages; why is it that electrometer tube circuits are superior to an electrometer; why is it that ordinary radio tubes must be supplanted by special tubes of high input resistance in electrometer circuits; exactly how are the small currents and voltages applied to the grid circuit of the electrometer tube and what is the difference between the drift method and steady deflection method; what role does the grid current of the electrometer tube in small current and voltage measurements play; of what currents is the grid current made; what is the general theory of the amplification of small currents and voltages; why is it of paramount importance to eliminate the drift in the output due to changes in filament voltages, in plate voltages, in auxiliary voltages, in filament emission; what methods have been suggested for the elimination of the drift due to these various changes; what are some circuits that have experimentally proven themselves to be the best; what are the relative merits of the General Electric FP-54, the Western Electric D-96475, and Victoreen VW-41 tubes used in the Barth circuit.

CHAPTER I

In order to understand more clearly the principles and operation of a vacuum tube electrometer circuit, a short description of the quadrant electrometer will be given. An electrometer is an instrument that operates on the principle of electrostatic attraction in the measurement of currents and voltages. It usually consists of three parts, a suspended rotating needle and two fixed plates (called quadrants). The needle is charged to a potential (usually 100 volts) with respect to one quadrant and the potential to be measured is applied across the quadrants, and magnitude of the rotation of the needle is an indication of the voltage to be measured.

The electrometer is used to measure currents between 10^{-8} and 10^{-16} ampere. The smallest current an ordinary wall galvanometer will measure is about 10^{-10} ampere. The range of voltage that an electrometer can measure is from 10^{-5} to 10 volts. However, a special Kelvin electrometer can measure many thousand volts.

In figure 1 is a side view and top view of a Dolezalek electrometer. A needle in the shape of a figure 8 is suspended by means of a gold or phosphor bronze filament. A small mirror is attached to the suspension. By means of a telescope focussed on the mirror, the amount of rotation of the needle is detected. The quadrants of an electrometer consist of the four parts that result from cutting a circular brass pill-box shaped chamber, as shown in the figure. The opposite quadrants are connected by a conductor. If quadrants 1 and 3 are positive, and

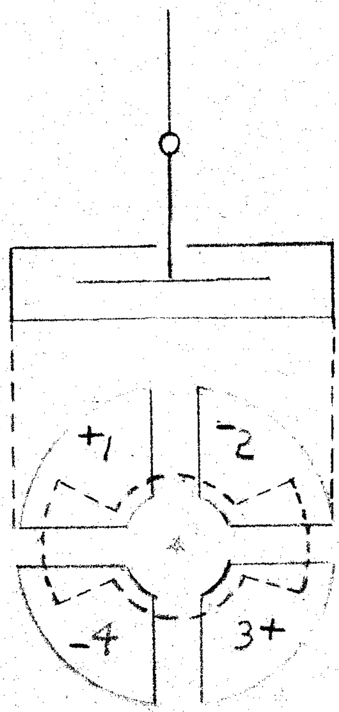

Fig. 1

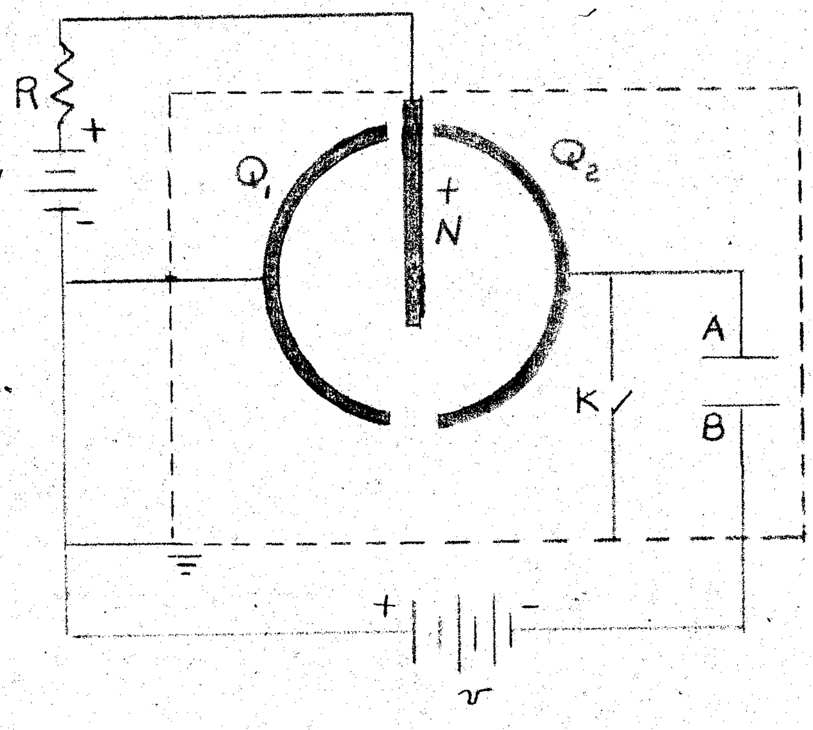

Fig. 2

2 and 4 negative, and if the needle is charged positive, the needle will rotate counter-clockwise. The amount of rotation will be an indication of the voltage across the quadrants. The above electrometer is shielded by a metal box to prevent disturbance caused by air currents and electrostatic effects.

As will be seen later, there are two methods of measuring currents in vacuum tube circuits, the so called rate of deflection method (also called drift method) and the constant deflection method. These two methods are also used in measuring currents with electrometer tube circuits.

Figure 2 shows the electrometer circuit for measuring small ionization currents by the rate of deflection method. The dotted line shows the shield about the electrometer; it is grounded. Q_1 and Q_2 are the quadrants; N is the needle; R is the protective resistance so that no damage is done if the needle touches Q_1; V is the voltage across the needle and Q_1; v is the voltage that accelerates the charges between the plates; the gas in the region between A and B is ionized by means of X-rays, ultraviolet rays, radioactive substance, etc.; K is the grounding key. When the accelerating voltage v is applied, the key K should be closed so that the induced charge on plate A does not reach the quadrant Q_2. The key is only opened when readings are taken. With the key opened, the charges of electricity flowing through the region between A and B will charge the quadrant Q_2, raising its potential. The needle N will be attracted to Q_2 and the time rate of its movement will be an indication of the magnitude of the ionization current.

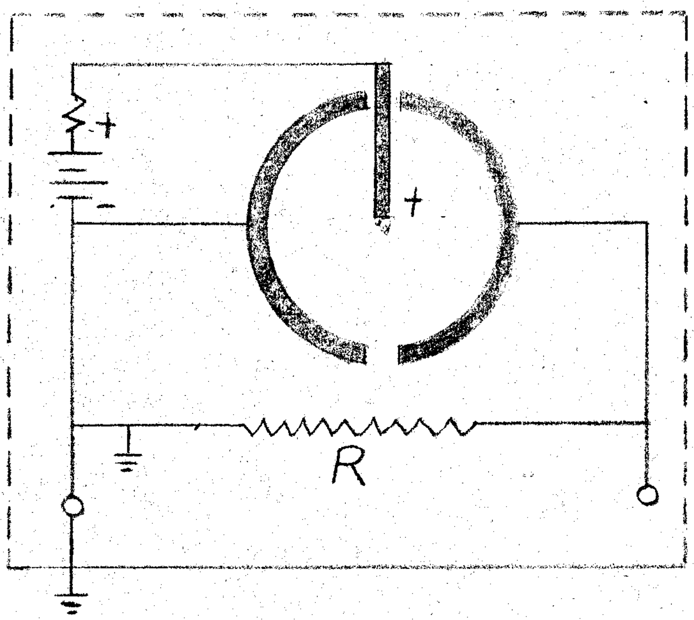
+
-
+
R

Fig. 3.

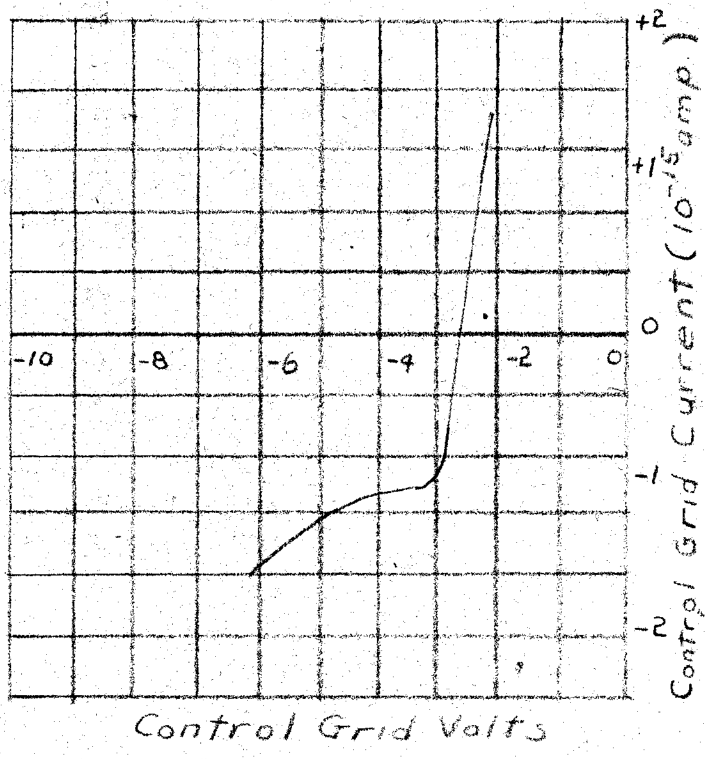
+2
+1
0
-1
-2
-10
-8
-6
-4
-2
0
Control Grid Current (10⁻¹⁵ amp.)
Control Grid Volts

Fig. 4.

This method of measuring currents is known as the rate of deflection method.

Figure 3 shows how the constant deflection method is applied. R is the large resistance through which the current to be measured is made to flow. The current through R produces an "ir" drop across the two quadrants. This "ir" drop causes the needle to be deflected a certain amount. Knowing the "ir" drop from the deflection of the needle and knowing the resistance R (which is between 10^6 to 10^{10} ohms), the current i can be computed from Ohm's law.

The constant deflection method is more convenient to use but it is not as sensitive as the rate of deflection method. The constant deflection method is satisfactory down to 10^{-14} ampere.

CHAPTER II

Although the vacuum tube electrometer has supplanted to a great extent the quadrant electrometer, the purpose of stating the principle underlying the operation of the electrometer is to point out that the same principle of electrostatic action is made use of in the vacuum tube. In a electrometer tube the grid current is about 10^{-15} ampere and therefore the control the grid has over the plate current is almost purely electrostatic. Because of the electrostatic action, the electrometer is a voltage measuring instrument, even though, as was shown above, it can measure currents. Likewise, because of the electrostatic action that the control grid exercises over the plate current, the electrometer tube is essentially a voltage measuring instrument even though it is also used to measure currents. To sum up what is now being emphasized: the less current there is in the grid circuit, the more electrostatic is the control the grid exercises over the plate current, and because of a small grid current, the plate current can be controlled without practically any expenditure of energy.

Because so much depends upon the grid current, a discussion of it will be given. Excellent discussions are given by W. B. Nottingham (1), G. F. Metcalf and B. J. Thompson (2), and P. A. MacDonald (3).

The tubes are used in circuits such that the grid voltage is

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(1) W. P. Nottingham, Journal of the Franklin Institute, 209, 291 (1930).
(2) G. F. Metcalf and B. J. Thompson, Phys. Rev. 36, 1489 (1930).
(3) P. A. MacDonald, Physics, 7, 270 (1936).

always negative with respect to the filament, and never positive. If it were made positive, there would be too much energy consumed in the grid circuit due to the large grid current. The best way to approach an analysis of the grid current is to study its constituents. Using the conventual manner of designating the direction of current, the positive y axis of Fig. 4 indicates the direction of the current when it goes from the grid through the space between the grid and filament, to the filament. The minus y axis indicates the opposite direction. The grid current of Fig. 4 is the resultant current of all of its constituents. This is a very important point to keep in mind. The heated filament emits electrons. Due to the negative electrostatic field of the grid, a cloud of these electrons forms near the filament and constitutes what is called a space charge. Even though the grid is negative with respect to the filament, some of these electrons have such high velocities that they land on the grid and produce an electronic current in the grid circuit. In Fig. 4, the direction of this current would be indicated by the positive y axis. According to the figure, very few of these electrons would go to the grid if the grid voltage is greater than -3 volts. But the grid current is practically made up of all these electrons when the grid voltage is more positive than -3 volts, because the contribution made by the other constituents of the grid current would be negligible to the above mentioned electrons.

The second constituent of the grid current are the positive ions that are given off from the filament. L. P. Smith (4) and

Wahlen (5) have shown that hot filaments emit positive ions in large numbers. It has been shown that a hot filament emits 10^8 times as many electrons as positive ions. If this positive ion current were plotted alone, the curve would fall below the positive axis of Fig. 4.

The grid is heated by radiation that comes from the filament and it, as a consequence, emits electrons and photoelectrons. Light coming from the outside and from the filament inside of the tube, causes photoelectrons to be emitted from the grid. As a matter of fact, a very sensitive electrometer circuit will react to this outside light immediately. This was very much in evidence with the Barth circuit set up by the author. The electrons and photoelectrons produce a current which is virtually the same as far as direction of current is concerned as if the filament were emitting positive ions.

The soft X-rays produced at the plate by the electrons striking the plate, cause X-ray photoelectrons to be emitted from the grid. Again a current is produced which is as if the filament were emitting positive ions.

There is also a positive ion current due to the presence of positive ions in the residual gas in the tube. Metcalf and Thompson (2) found that if the potential across a tube was greater than the ionization potential, there was a positive ion current of 10^{-13} ampere even though the tube was thoroughly evacuated.

Leakage current over the glass or insulation of the tube may also

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(4) L. P. Smith, Phys. Rev., 35, 381 (1930).
(5) Wahlen, Phys. Rev., 34, 164 (1929).

contribute a current whose direction would be below the x axis (negative on the diagram).

The above constituents form the grid current. As to their elimination, the following precautions are taken.

The grid is operated at a voltage such that the high velocity electrons are prevented from landing on the grid and the filament is operated at a temperature such that the velocity of the electrons is not too great. A space charge grid is placed between the filament and grid, so that its positive potential repels the positive ions that are emitted from the filament. This grid, of course, increases the mutual conductance of the tube.

The filament is operated at a low temperature so that its radiation will not be intense enough to cause electrons or photoelectrons to be emitted by the grid. The grid may be made of a metal like molybdenum whose threshold work function is large. Its structure may be large and open.

A low potential like 8 or 10 volts will diminish the soft X-rays.

The positive ion current due to ionization is diminished by keeping the potentials of the tube below the ionization potentials of the gas in the tube. The leakage current over the insulation is relatively small compared to the other currents. It is greatly reduced by having the grid come out at the top of tube.

With the above precautions, special electrometer tubes have been made whose grid currents are of the order of 10^{-15} ampere. As stated above, the ordinary radio tubes have grid currents of not more than

10^{-8} ampere but considerably more than 10^{-15}.

The potential of the grid in Fig. 4 where the grid current is zero, is called the floating grid potential or the contact potential. It is that potential that will exist between the filament and grid, after the grid has reached equilibrium with the grid circuit open. With the grid circuit open, charges that we have been speaking about will go to their respective electrodes, charging them and thus producing a difference of potential between the electrodes. If that magnitude of difference of potential is actually applied to the grid circuit, there will then be zero current in the grid. This floating grid potential is measured in the following manner. With the grid circuit open, the plate current is recorded after equilibrium has been attained, the tube operating at normal voltages. Then a voltage is placed in the grid and it is adjusted until the plate current noticed previously is reached. That grid voltage is the floating grid potential.

The floating grid potential is very critical because it is that potential at which high velocity electrons begin to land on the grid, and as can be seen from Fig. 4, the curve is very steep at this point. At floating grid potential, all the different charges of electricity mentioned above are in motion but they nullify each other to produce a net current of zero. Tubes are operated at a potential slightly more negative than the floating grid potential.

The reason the quadrant electrometer was first described and then the low grid current of special electrometer vacuum tube, was to show that the smaller the grid current in an electrometer vacuum tube, the more the electrometer vacuum tube is similar in operation to the quadrant electrometer. Now it will be shown why it is necessary to use an instrument that draws no current or a negligible amount of current, in order to measure currents and voltages in high resistance circuits.

An ordinary milliammeter has a resistance of 50 ohms and a current of 1 ma will cause full scale deflection. The power consumed by this milliammeter when the needle has deflected full scale is 5×10^{-5} watts. Now if this milliammeter is placed across two parts of an animal whose difference of potential is, for example, 50 mv, there is not enough power to cause any appreciable deflection much less full scale deflection. Thus on open circuit there is an emf of 50 mv but there is not enough power available to cause a milliammeter to deflect. The 50 mv between the two parts of the animal could be measured by an instrument easily, if the instrument drew no current or in other words, if it consumed no power.

Small currents through glass electrodes, high-vacuum photocells or ionization gauges are too small to be measured by galvanometers, whose limit of sensitivity is of the order of 10^{-10} ampere per mm. If the currents from these high resistant sources fell within the range of galvanometers, they could then be measured by galvanometers. Putting the same idea in other words, the power output of these sources is far below the power necessary to operate a galvanometer. The power consumed in very sensitive d.c. amplifiers is so small that 30 electrons per sec. which is equal to 5×10^{-18} ampere can be measured. If tubes could be constructed with grid currents as low as 10^{-17} ampere, then 3 electrons per sec. could be measured (2).

It has been stated above that the electrometer tube approaches the quadrant electrometer in operation because of its low grid current. If the grid current is low, then the input resistance of the tube is high. All the precautions taken to reduce the grid current, automatically increase the input resistance or impedance. If the grid current is plotted against the grid potential, a curve similar to that of Fig. 4 is obtained. The reciprocal of the slope of this curve is the input impedance or resistance of the grid circuit. The resistance changes with the grid current. It should be noticed that the resistance is negative at certain points and also the resistance decreases rapidly when the grid potential becomes more positive than the floating grid potential.

It has been shown that currents and voltages from high resistance sources do not have sufficient power to operate the ordinary meters. But they can be measured by instruments that draw very little current, or in other words, whose input resistance is high. By means of an example, another view of the requirement of high input resistance can be obtained. The plate current of a vacuum tube is controlled principally by the grid voltage. A small current from high vacuum photocells can be measured by sending the current through a high resister that is in the grid circuit as shown in Fig. 5. The grid voltage will be changed to the extent of the "ir" drop across the resister and the plate current is changed accordingly. The larger the resistance R is,

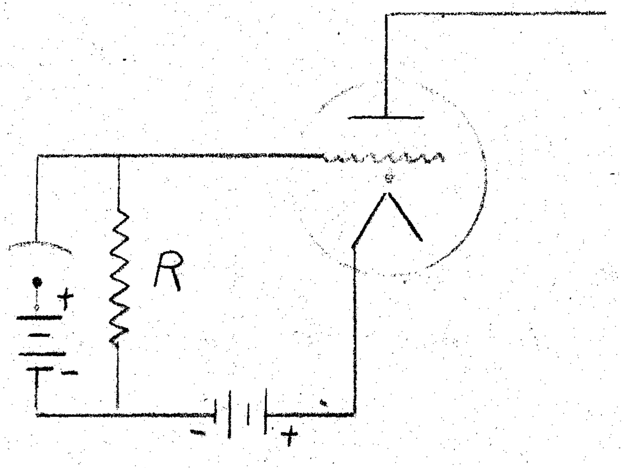

Fig. 5

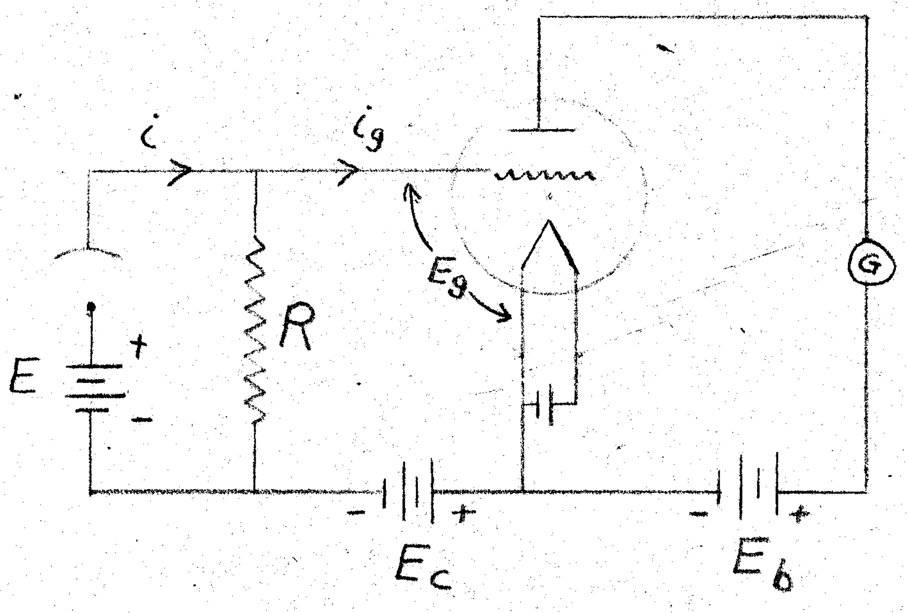

Fig. 6

the greater is the "ir" drop, and the greater is the change in the plate current and the smaller is the current that can be detected. The point is this, the grid resister R is shunted by the grid resistance of the tube itself. Therefore, the value of the resistance of this parallel combination is smaller than R if the grid resistance of the tube itself is smaller than R. Thus if small currents are measured in this fashion it is absolutely necessary for the grid resistance of the tube itself to be greater than R. The grid resistance of the tube itself is commonly called the input resistance or input impedance of the tube. For the General Electric FP-54, the Western Electric D-96475 and the Victoreen VW-41 Electrometer tubes, the input impedance is 10^{16} ohms (approx.).

If the voltage of a source whose internal resistance was 10^{10} ohms and if it was placed in series with the bias of a tube whose grid current was 10^{-10} ampere, there would be a drop across the source of one volt; whereas on open circuit the source would have an emf of probably 10 mv. If no current were in the grid circuit, or if the grid impedance was infinite, in this particular case, the grid voltage would be increased by 10mv.

Tube manufacturers are interested in obtaining as large an output as possible, consistent with freedom from distortion and life of a tube in radio apparatus. The output of a tube is approximately proportional to the square of the applied voltages.(6) But these are

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(6) G. H. Gabus and M. L. Pool, 8, 196 (1936).

greater than the ionization potentials of the gas in the tubes, thus producing ions in the gas, and thus decreasing the input resistance of the tubes. The input resistance of a modern radio tube ranges from 10^8 to 10^9 ohms. In order to get a great response from a phototube amplifier, the input resistance of the tube must be as big or greater than the output impedance of the phototube. The high vacuum phototube when slightly illuminated has an output resistance of 10^{12} ohms.

CHAPTER III

A consideration of the measurement of a photoelectric current by means of a triode tube will show some basic concepts of an amplifying circuit. Some basic definitions must first be given.

The grid voltage of a tube will exercise greater control over the plate current than the plate voltage. For example, for a change of 1 ma in the plate current it may require a change of 2 volts in the plate potential (with the grid voltage constant), whereas the same change in plate current can be produced by a change of .2 volt in the grid potential (with the plate voltage constant). This is stated mathematically by the equation

$$(1) \qquad \frac{\partial i_p}{\partial E_g} = \mu \frac{\partial i_p}{\partial E_p}$$

The partial derivatives are used because in the case of the derivative on the left, the plate voltage is held constant; in the case of the derivative on the right, the grid voltage is held constant. The derivative $\frac{\partial i_p}{\partial E_g}$ is the slope of the plate current - grid voltage characteristic curve with the plate voltage held constant. The derivative $\frac{\partial i_p}{\partial E_p}$ is the slope of the plate current - plate voltage characteristic curve with the grid voltage held constant.

With the grid voltage constant an increase in the plate voltage will produce an increase in the plate current; with the plate voltage constant, at the value before it was changed, a decrease in the grid voltage is necessary to produce the same increase in plate current.

To produce an increase in the plate current, a positive change in the plate voltage is necessary or a negative change in the grid voltage is necessary. This is expressed mathematically as

$$(2) \quad \mu = -\left(\frac{\partial e_p}{\partial e_g}\right)$$

μ is called the amplification factor. It is approximately constant over a wide range of changes of plate and grid voltages. In other words μ indicates how much more effective the grid voltage is than the plate voltage in controlling the plate current.

The plate impedance or plate resistance is the reciprocal of the slope of the plate current - plate voltage characteristic curve. Unlike ohmic resistance which is a constant, the plate impedance varies along the curve. It is accordingly defined as

$$(3) \quad Z_p = \frac{\partial e_p}{\partial i_p}$$

It is a partial derivative because the grid voltage is held constant.

If a family of characteristic curves of the plate current versus the grid voltage is plotted, different plate voltages held constant for each curve, the slope of the curves is called mutual conductance.

$$(4) \quad g_m = \frac{\partial i_p}{\partial e_g}$$

The partial derivative is used because the plate voltage is held constant.

The relation between μ, Z_p and g_m is given by μ. ?

(5) $\mu = \frac{\partial e_p}{\partial e_g} = \frac{\partial i_p}{\partial e_g}\frac{\partial e_p}{\partial i_p} = g_m K_p$

The mutual conductance defined by equation (4) is that of the tube itself. If the associated circuit is taken into consideration, the characteristic curve will be different and the mutual conductance will be different. This new mutual conductance is defined as the effective mutual conductance designated by the symbol g_m'

An expression for the effective mutual conductance will now be derived for the circuit of Fig. 6, but in this case a resistance r_p is placed in the plate circuit.

The plate voltage is given by

(6) $E_p = E_b - i_p r_p + \mu E_g + E_o$

E_o is the contact voltage.

E_b is the plate battery.

μE_g is equivalent to putting a battery in the plate circuit.

(7) $i_p = \frac{E_p}{Z_p} = \frac{(E_b - i_p r_p + \mu E_g + E_o)}{Z_p}$

or $\quad i_p\left(1 + \frac{r_p}{Z_p}\right) = \frac{E_b + \mu E_g + E_o}{Z_p}$

Differentiating with respect to E_g

$$\frac{\partial i_p}{\partial E_g} = \frac{\mu}{Z_p\left(1 + \frac{r_p}{Z_p}\right)} = \frac{g_m}{1 + \frac{r_p}{Z_p}}$$

(8) $g_m' = \frac{\partial i_p}{\partial E_g} = \frac{g_m}{1 + \frac{r_p}{Z_p}}$

An equation showing how E_g varies with i, the current that is being measured can be derived. The voltage across the grid and negative terminal of the filament is given by

$$(9)\quad E_g = E_c - i_g R + i R$$

Differentiating with respect to i,

$$\frac{\partial E_g}{\partial i} = R - R\frac{\partial i_g}{\partial i} = R - R\frac{\partial i_g}{\partial i}\frac{\partial E_g}{\partial E_g}$$

$$\frac{dE_g}{di} = R\left(1 - \frac{\partial E_g}{di} K_g\right)$$

K_g is the slope of the grid current versus grid voltage curve.

Solving for $\frac{dE_g}{di}$

$$(10)\quad \frac{dE_g}{di} = \frac{R}{1 + R K_g} = \frac{1}{K + K_g}$$

K is the reciprocal of R, or the conductance of the input resistance R. To get an equation that shows how the plate current i_p varies with the photoelectric current i, multiply both sides of equation (10) by $\frac{di_p}{dE_g}$. This gives

$$(11)\quad \frac{di_p}{di} = \frac{1}{(K + K_g)}\frac{di_p}{dE_g} = \frac{1}{(K + K_g)}\frac{g_m}{\left(1 + \frac{R_p}{Z_p}\right)}$$

This equation gives the overall amplification of the amplifier expressed in terms of the parameters of a three element tube.

When amplifiers are used to measure small currents, and not to operate relays or counters, the interest lies not so much in the change of plate current, but how much will an indicating meter in the plate current deflect for a particular value of input current i.

If n denotes the number of divisions a meter (galvanometer) will deflect, then the voltage sensitivety can be expressed as S_v.

$$(12) \quad S_v = \frac{dn}{dE_g} = \frac{dn}{di_p}\frac{di_p}{dE_g} = S_g\, g'_m$$

S_g is the sensitivity of the indicating instrument expressed in the number of divisions of deflection per unit current.

The current sensitivity can be expressed as S_i

$$S_i = \frac{dn}{di} = \frac{dn}{dE_g}\frac{E_g}{di} = S_g\, g'_m\, \frac{1}{R+R_g}$$

or

$$(13) \quad S_i = S_g \frac{1}{(R+R_g)} \frac{g'_m}{\left(1+\frac{r_p}{R_m}\right)}$$

Time Constant

If a photoelectric current is sent through a large grid resistor R, as shown in Fig. 6, the indicating meter in the plate circuit will not immediately assume a definite deflection. It will gradually deflect and then assume a definite position. For current measurements it is always more convenient to have the indicating instrument to assume its final position as quickly as possible. This is accomplished, as will be explained, by making the capacity of the whole grid circuit a minimum and by not making the grid resistor too large. In the explanation that is to follow, it will be assumed that the grid current is considerably smaller than the input current, that is, the photoelectric current.

Let C be the capacity of the grid system which in this case includes the grid to filament capacity, the capacity of the photoelectric cell and the capacity of all the associated leads.

$$Q = CE_g$$

(14) $$i = \frac{dQ}{dT} = C\frac{dE_g}{dT}$$

i is photoelectric current. As soon as the current i flows, it begins to charge the grid system, causing a rise in potential E. Due to this rise in potential a current is sent through the resistor in the opposite direction to i, equal to $\frac{E_g}{R}$. The above differential equation becomes

(15) $$\frac{dE_g}{dT} = \frac{1}{C}\left(i - \frac{E_g}{R}\right)$$

This is a linear differential equation and has the solution

(16) $$E_T = iR\left(1 - e^{-T/RC}\right)$$

After a lapse of infinite time, $E_T = E_0$

$$E_T = E_0\left(1 - e^{-T/RC}\right)$$

where E_T is the potential between grid and filament after the lapse of time T.

In order to have a standard method of comparing different circuits, a time constant is defined to be equal to the product of the resistance and capacitance, that is RC. Substituting RC for T, the following equation is obtained.

(17) $$E_T = E_0\left(1 - \frac{1}{e}\right) = 0.632E_0$$

In words, this equation means this: after a time interval equal to RC, the potential between grid and filament will be 0.632 times the potential it would have after a lapse of an infinite time interval.

If the time interval is allowed to be ten times the time constant, for all practical purposes the potential E_T will be equal to the equilibrium potential, E_0.

Since the time constant is equal to RC, it becomes obvious why there is a limit to the magnitude of the grid resistor R and why it is important to make the capacity of the grid system a minimum. The FP-54 tube has a capacity of 3 x 10^{-12} farad. The capacity of the photoelectric cell ~~al~~together with the associated leads would roughly amount to 7 x 10^{-12} farad. If the resistor R is 10^{+11} ohm, the time constant would be one second. After ten seconds the potential between the grid and filament would be approximately the equilibrium potential. That means after ten seconds the deflection of the galvanometer will be an indication of the "ir" drop across the resistor R. Thus it is seen why it is not convenient to use a grid resistor greater than 10^{12} ohms and why it is important to make the capacitance of the grid system a minimum.

CHAPTER IV

In ordinary amplifiers that are not used to measure extremely small currents and voltages, the changes that take place in the electrode voltages do not effect the stability of the amplifier. Fig. 7 shows a very elementary amplifying circuit. In the plate circuit, provision is made so that when there is no input current in the grid circuit, there is no current through the galvanometer. The adjustment of R brings about the zero current in the galvanometer. The point is this, the galvanometer will drift from its zero position. This is due to changes in batteries E_c, E_f, E_b and E_g. Even though all these batteries are of the large capacity automobile type, they are still subjected to minute changes in voltage which cause the instability. It might be remarked here that even though some manuals in electronics suggest a simple circuit as drawn in Fig. 7 for measuring small currents and voltages, the circuit will prove to be very unsatisfactory because there is no provision made to stabilize the changes in the battery voltages. The reason why there is so much literature on this subject, is because it was always recognized that the instability of the amplifier, due to changes in battery voltages, had to be eliminated by some sort of compensation. Although some of the elementary circuits that will be described are not actually used for fine measurements, nevertheless, they will be described so that fundamental principles involved in the more complex circuits will be better understood.

Fig. 8 shows a very simple circuit which compensates for

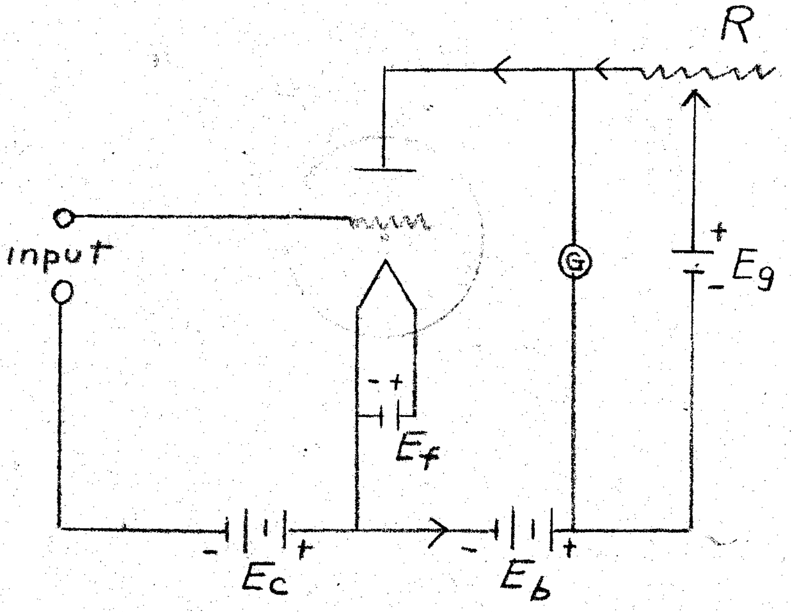

Fig. 7

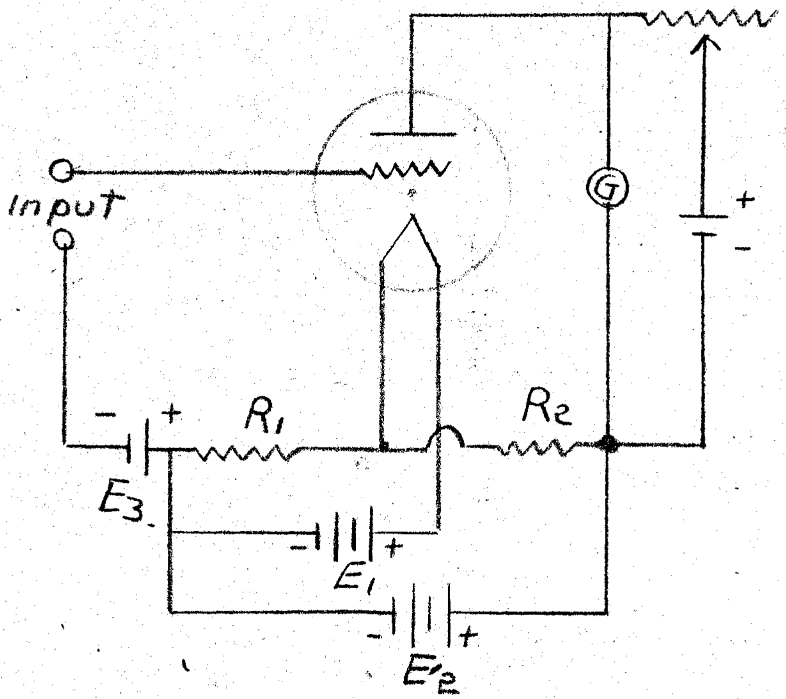

Fig. 8

changes in the plate battery and filament battery. Consider the filament circuit that includes the filament, R_1 and E_1. If the voltage of E_1 increases, then the filament will emit more electrons and as a consequence the plate current will increase. But with the increase of voltage of E_1, there is an increase in the "ir" drop across R_1, thereby making the grid more negative and finally causing a decrease in the plate current. It is possible to choose a value for R_1 such that there is no change in the plate current even though there is a change in the battery E_1. If there is a change of Δi_f in the filament current, there is a corresponding change in the plate current equal to .

$$(18) \quad \Delta i_p = \frac{\partial i_p}{\partial i_f} \Delta i_f - R_1 \frac{\partial i_p}{\partial e_g} \Delta i_f$$

$$= \frac{\partial i_p}{\partial i_f} \Delta i_f - R_1 g_m \Delta i_f$$

If there is no change in plate current due to a change of Δi_f in the filament, then the above equation is zero and solving for R_1 the following equation is obtained.

$$(19) \quad R_1 = \frac{\partial i_p}{\partial i_f} \frac{1}{g_m}$$

If R_g is so chosen as to satisfy the above equation then changes due to filament current (or voltage) will not cause a change in the plate current. The reason for adding a battery E_3 in the grid circuit is due to the fact that usually the drop across R_1 is not sufficient to produce enough negative bias for the grid circuit. This method was first suggested by Dearle and Matheson (7).

There is a simple way of neutralizing the effects of the changes of the battery E_2 on the plate current. If the voltage of E_2 increases, then the increase in voltage drop across R_2 will cause an increase in the plate current but there is a simultaneous increase of grid potential due to the increase of the voltage drop across R_1 which decreases the plate current. These two effects can offset each other with the proper choice of resistances R_1 and R_2. By definition:

$$\mu = -\left(\frac{\Delta E_p}{\Delta E_g}\right)$$

If the current through battery E_2 changes to the extent of ΔI then the voltage drops across R_1 and R_2 will change to the extent of $\Delta I\, R_1$ and $\Delta I\, R_2$ respectively. Therefore if

$$\mu = -\frac{\Delta I\, R_2}{\Delta I\, R_1} = -\frac{R_2}{R_1}$$

then there will be no change in the plate current. For complete neutralization R_1 must be chosen to satisfy the equation

$$R_1 = \frac{\partial i_p}{\partial i_f}\,\frac{1}{g_m}$$

and then R_2 must be chosen to satisfy $R_2 = \mu R_1$.

Practically all the circuits that give the best stability are bridge circuits in one form or other. Fig. 9 shows an ordinary Wheatstone bridge circuit. Despite changes in the battery, no current will flow through the galvanometer if $R_1 R_4 = R_2 R_3$. Now if the resistance R_1 is substituted by a tube whose plate impedance is Z_p,

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(7) R. C. Dearle and L. A. Matheson, Rev. Sci. Inst. I, 215 (1930)

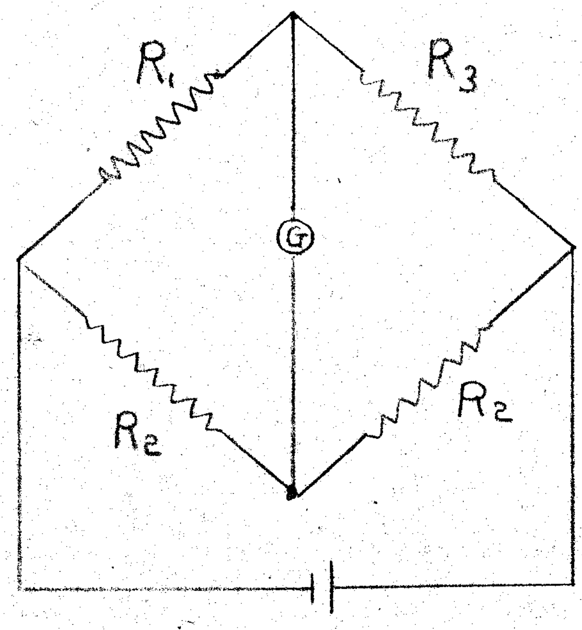

Fig. 9

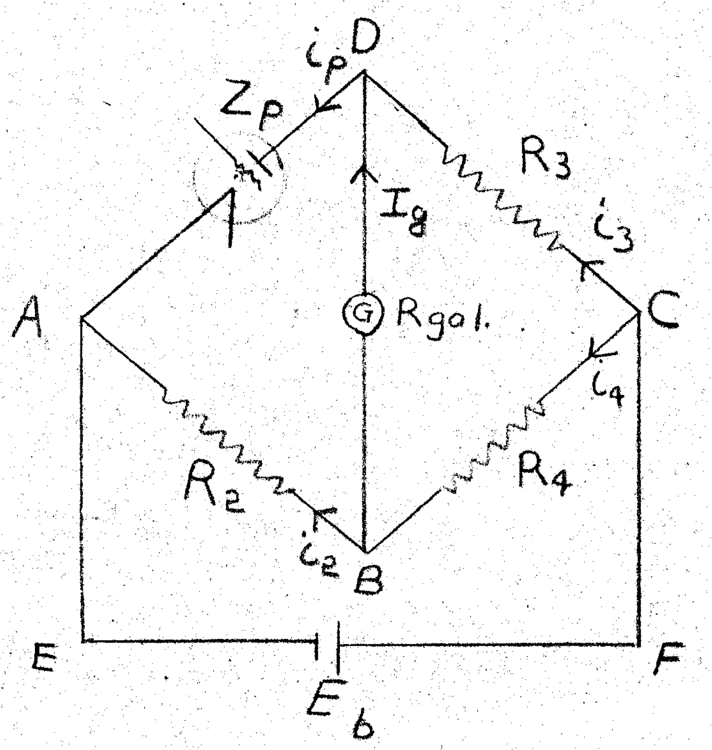

Fig. 10

then the circuit in Fig. 10 is obtained. If the impedance Z_p acts as an ohmic resistance, then no current will flow through the galvanometer despite changes in the battery as long as $R_4 Z_p = R_3 R_2$. But Z_p varies unlike R in Ohm's law, as can be readily seen from Fig.11. Over the interval ΔS the Wheatstone bridge with a tube in one arm, would be balanced for small changes in the battery potential. A mathematical expression can be derived for the variation of the current through the galvanometer with respect to the grid voltage E_g of the tube. It is derived in the following manner. The plate current is given by the expression

$$(20) \quad i_p = \frac{1}{Z_p}\left(E_p + \mu E_g + E_o\right)$$

E_o is the contact potential. Applying Kirchhoff's laws around the loops BCDB, ABDA, AEFCBA, and at the junctions D and B, five equations are obtained. Solving the five simultaneous equations for I_g, the following equation is obtained.

$$(21) \quad I_g = \frac{(R_3 R_2 + R_3 R_4)(E_o + \mu E_g) - (R_4 Z_p - R_3 R_2) E_b}{R_3 Z_p R_2 + R_4 Z_p R_2 + R_3 R_4 Z_p + R_3 R_2 R_4 + R_{gal}(Z_p + R_3)(R_2 + R_4)}$$

If μ, Z_p and E_o are assumed to be independent of E_b, the derivative of the above equation with respect to E_b gives

$$\frac{\partial I_g}{\partial E_b} = \frac{(R_4 Z_p - R_3 R_2)}{K}$$

K being the sum of the terms in the denominator. From this equation, it is seen that for the galvanometer current to be independent of E_b, the numerator must be equal to zero.

$$R_4 Z_p = R_3 R_2$$

If R_3 is equal to R_4 and R_2 is equal to R_p to Z_p then the above equation becomes

(22) $$\frac{\partial I_g}{\partial E_b} = \frac{g_m}{2 + r_{gal}\left(\frac{1}{Z_p} + \frac{1}{R_3}\right.}$$

Now if a resistance R_d is shunted across the galvanometer to damp the instrument critically, the above equation becomes

(23) $$\frac{\partial I_g}{\partial E_b} = \frac{g_m}{2\left(1 + \frac{R_{gal}}{R_{cd}}\right)}$$

This equation is derived in the following manner. The I_g of equation (22) is that which in Fig. 12 flows through the parallel combination of R_d and R_{gal}.

(24) $$i_g = I_G\left(\frac{R_d}{R_d + R_{gal}}\right)$$

(25) $$I_g = \frac{i_g\,(R_d + R_{gal})}{R_d}$$

The parallel resistance of galvanometer and shunt is obviously

(26) $$R = \frac{R_d\,R_{gal}}{R_d + R_{gal}}$$

Substituting I_g in equation (22) and also R for r_{gal}, the following equation is obtained.

(27) $$\frac{\partial i_g}{\partial E_g} = \frac{g_m}{2\left[1 + R_{gal}\left(\frac{1}{2Z_p} + \frac{1}{2R_3} + \frac{1}{R_d}\right)\right.}$$

Since $Z_p = R_2$ and $R_3 = R_4$, it is readily seen that the galvanometer is critically damped when

(28) $$\frac{1}{R_{cd}} = \frac{1}{2Z_p} + \frac{1}{2R_3} + \frac{1}{R_d}$$

Therefore

$$(29) \qquad \frac{\partial i_g}{\partial E_g} = \frac{g_m}{2\left[1 + \frac{R_{gal}}{R_{cd}}\right]}$$

For the basic circuit the equation, as was seen, was

$$\frac{\partial i_g}{\partial E_g} = \frac{g_m}{1 + \frac{R_p}{Z_p}}$$

Since $\frac{R_g}{R_{cd}}$ and $\frac{R_p}{Z_p}$ are comparatively small, the bridge circuit is one half as sensitive as the basic circuit with the galvanometer in the plate circuit. This decrease in sensitivity is due to the fact that in the bridge circuit there are two alternative current paths about the galvanometer. The resistance shunted across the galvanometer could be chosen by placing a variable resistance across the galvanometer, and by varying it until the galvanometer was critically damped.

If in Fig. 11 the point B was used for the operating point, then the circuit would behave as an ordinary Wheatstone bridge over the interval ΔA since the tangent to that part of the curve goes through origin and therefore the tube would act as an ohmic resistance. However, if A is chosen, then the arm containing the tube is equivalent to an ohmic resistance with a resistance Z_p and an emf equal to $E_b - i_p Z_p$. By Introducing such a source of voltage, however, would not make the plate current of the tube independent of E_b since the battery introduced would also fluctuate.

Wold(8) devised a circuit which was later improved by Wynn-Williams(9)

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(8) P. I. Wold, U.S.Patent, 1232, 879 (1917).
(9) C. E. Wynn-Williams, Proc. Camb. Phil. Soc. 23, 810, (1927).

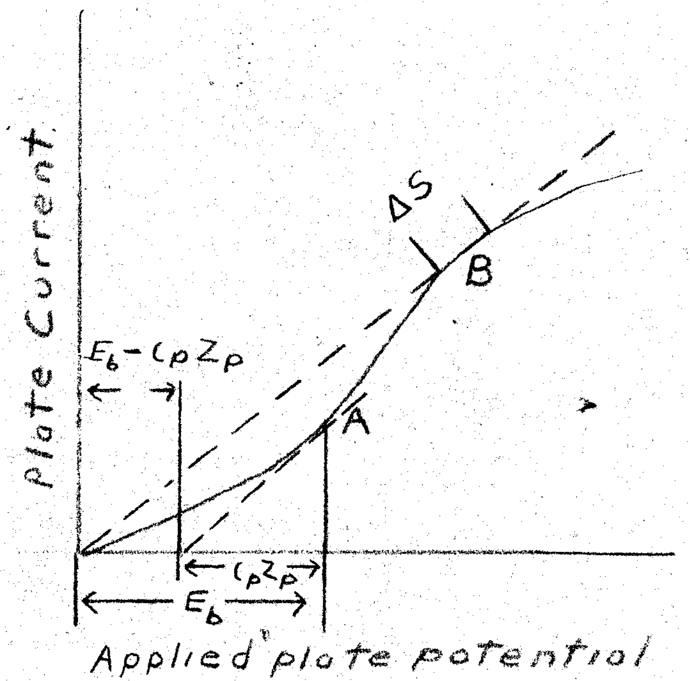
Plate Current
ΔS
B
$E_b - i_p Z_p$
A
$i_p Z_p$
E_b
Applied plate potential

Fig. 11

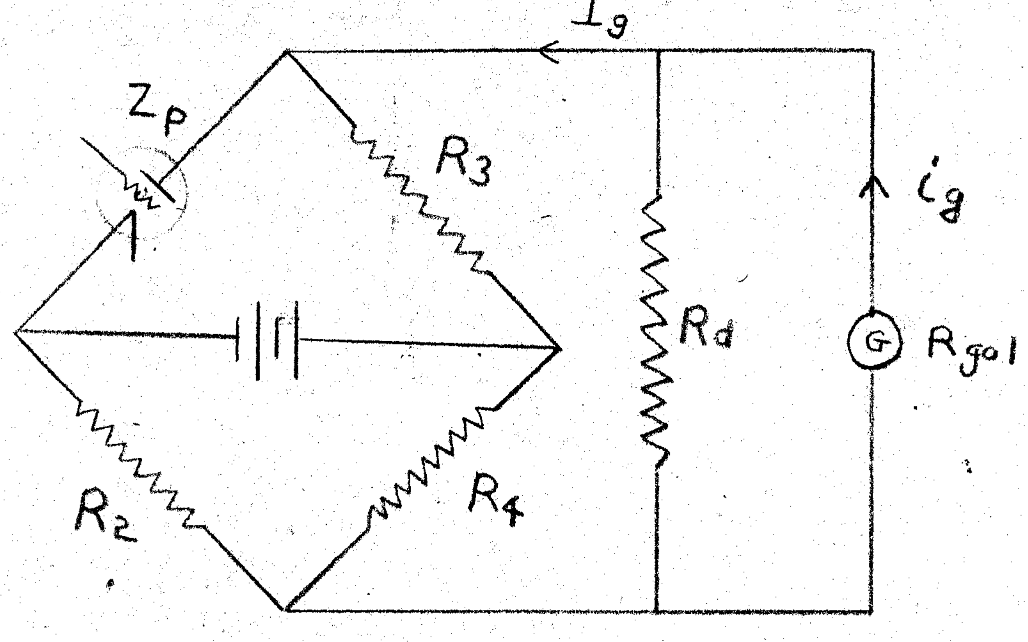
I_g
Z_p
R_3
i_g
R_d
G
R_{gal}
R_2
R_4

Fig. 12

using two tubes of the same type in a Wheatstone bridge. Fig. 13 gives the Wynn-Williams circuit. Tube 1 is the active tube in whose grid circuit is placed the input. Tube 2 is the so-called dummy tube. The potentiometer R_1 is varied so that over a certain range of filament current (or what amounts to the same thing, over a range of filament voltage) there is no change in the galvanometer current. Thus the galvanometer current is made independent of the filament voltage over a certain range. Then, the resistance R_2 in one arm of the bridge circuit is varied until there is no change in the galvanometer current for a limited range of resistance of R_4. Although the Wynn-Williams circuit has been superceded by the more improved circuits which will be discussed later, its operation shows clearly the Wheatstone principle.

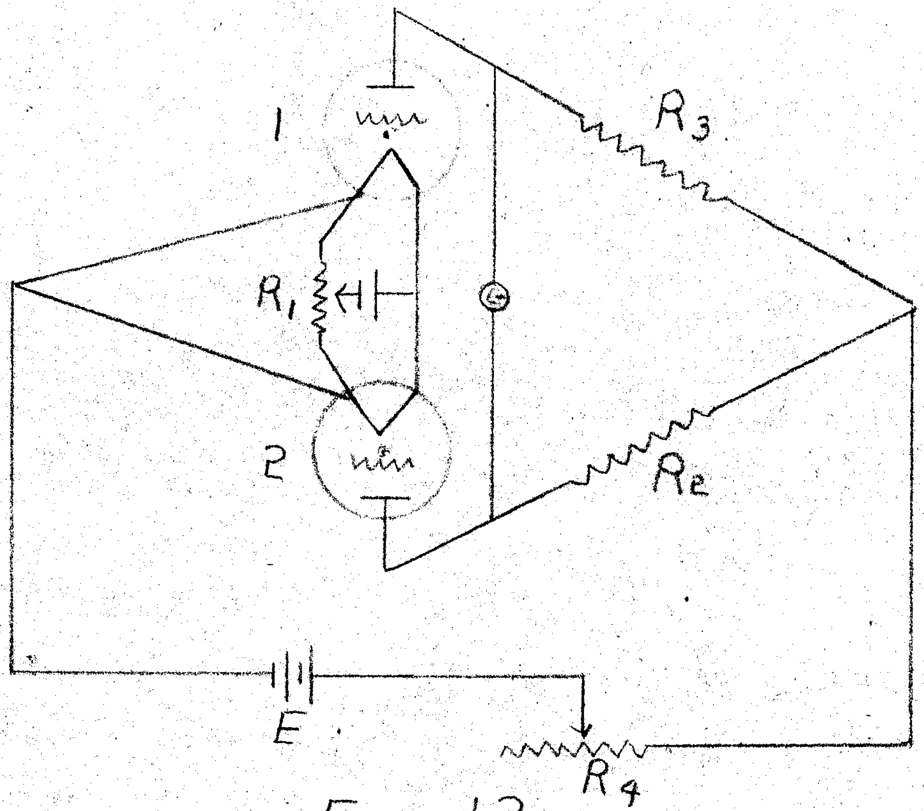

Fig. 13

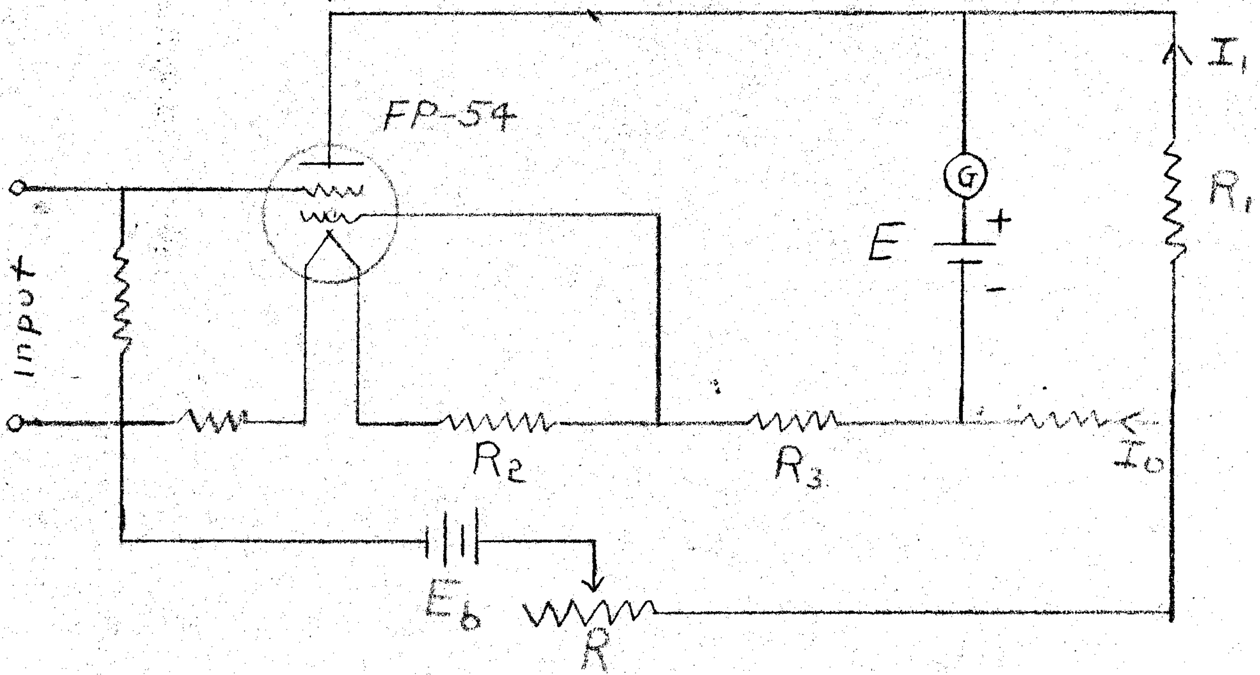

Fig. 14

Soller's Circuit

Any discussion of d.c. amplifiers would be incomplete without mentioning Soller's(10) balanced , compensating circuit. This circuit was the first, stable, one tube, compensating circuit devised. It is recognized as being very ingenious by men who have specialized in d.c. amplifiers.

It has already been shown that the tube does not behave as an ohmic resistance and that it is equivalent to a resistance and an emf in series. If a resistance and an emf is placed in one arm of a Wheatstone bridge, there must be a compensating potential somewhere in the bridge. Soller has placed this compensating potential in series with the galvanometer. The arms of the Wheatstone bridge can easily be seen from Fig. 14 to be R_1, R_o, $R_3 + R_2 + R_{fila}$, cathode-anode resistance. It might be noted here that the anode-screen grid does not form one arm of the Wheatstone bridge; this arrangement was used by DuBridge and Brown, and Barth whose circuit will be described later. This observation is very important to note.

Soller wanted to find out what is the relation that must exist between I_o and I_1 such that for all values of I_o, there will be no current through the galvanometer for properly chosen resistances R_o and R_1 and how these two resistances must be chosen. His line of reasoning is as follows.

For no current through the galvanometer the following condition

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(10) W. Soller, R.S.I. 3, 417, (1932).

$$R_0 I_0 - E = I_1 R_1$$

must be satisfied.

or

(30) $$R_1 = \frac{(R_0 I_0 - E)}{I_1}$$

If I_0 changes to the extent of ΔI_0, the following condition must hold for no current through the galvanometer.

(31) $$R_0 (I_0 + \Delta I_0) - E = R_1 (I_1 + \Delta I_1)$$

Substituting R_1 in (31) and rearranging the terms, the following equation is obtained.

$$R_0 (I_1 \Delta I_0 - I_0 \Delta I_1) = -E \Delta I_1$$

or

(32) $$R_0 = \frac{E}{I_0 - I_1 \dfrac{\Delta I_0}{\Delta I_1}}$$

Assuming that E is constant, then the denominator must be constant. In the limit the denominator becomes the differential equation.

$$I_0 - I_1 \frac{d I_0}{d I_1} = K_1$$

This is a separable differential equation whose solution is

(33) $$I_0 = K_2 I_1 + K_1$$

This equation gives a straight line. Now if at the operating point the relation between I_0 and I_1 gives a straight line, then the circuit is balanced and will remain balanced.

Fig. 15 gives actual curves which Soller obtained for three different FP-54 tubes. Since I_0 is the filament current and since 110 ma is the operating filament current for the FP-54, the three tubes give

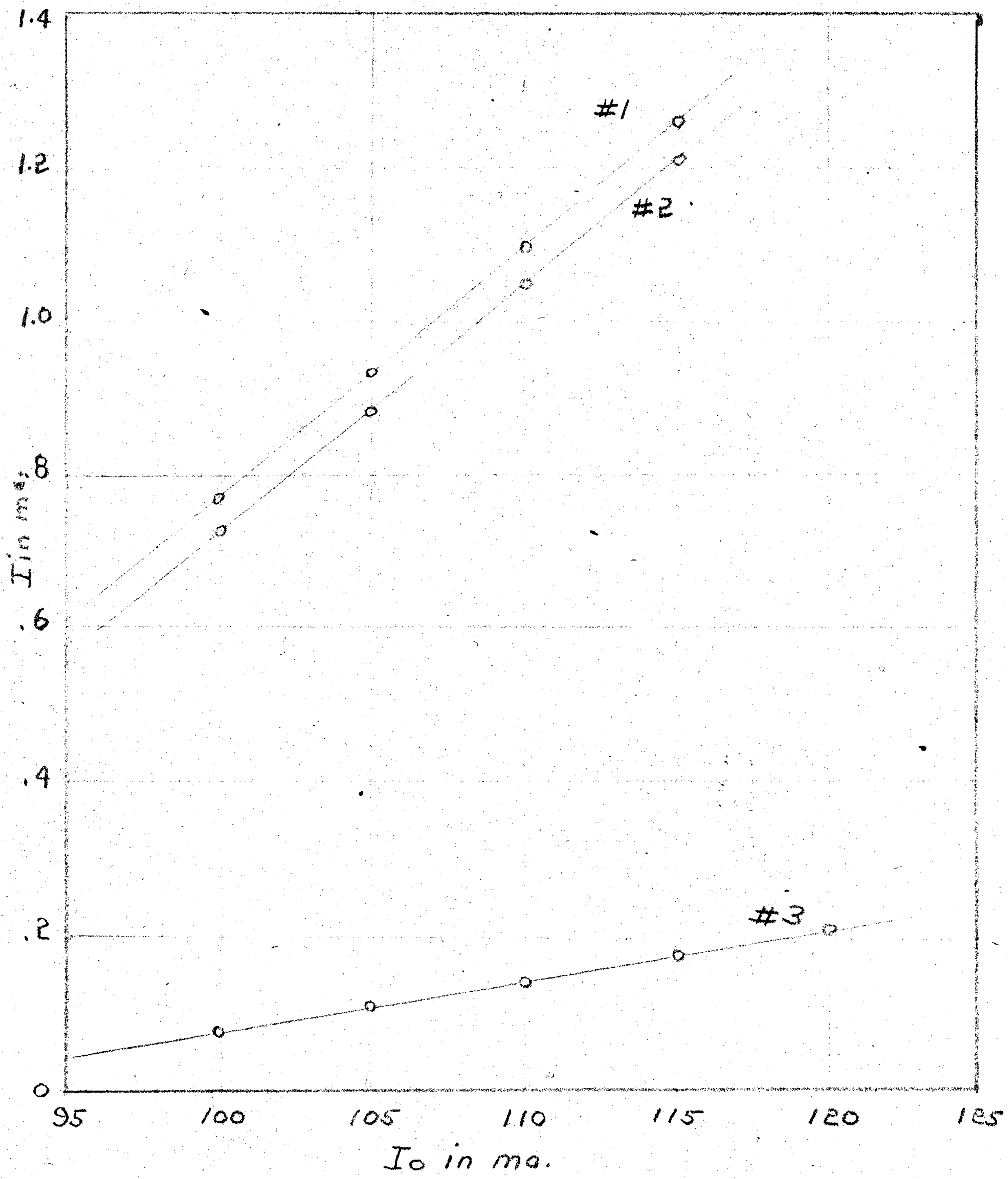

Fig. 15

very straight lines at the operating point. Soller found that his circuit was easily balanced with any of the three tubes.

From the curves the value of $\frac{\Delta I_o}{\Delta I_1}$, I_0 and I_1 were obtained, and when substituted in (32) they gave the value of R_0. R_1 was then determined from (30).

It might be stated here that even though Soller's circuit marked a definite advance in the stability of one tube circuits, nevertheless, since it has an emf (dry cell) in series with the galvanometer, there is no provision made for changes in potential that take place in it. In other words, all the electrode voltages do not come from one common source.

Turner & Siegelin

Turner and Siegelin (11) modified Soller's circuit and although their circuit does not add anything essentially different to Soller's circuit, it will be discussed here because it shows clearly the purpose of the battery that is in series with the galvanometer. Using the circuit in Fig. 16, Turner and Siegelin obtained values of the plate current and of E. These were plotted, as shown in Fig. 17. All voltages applied to the tube have their recommended values. From Fig. 17 it is seen that if the tube had been replaced by a battery whose voltage would be the intercept of the line ACB on the V axis and also by a resistance in series whose resistance is equal to the reciprocal of the line ACB, then the line ACB would have been obtained. As a matter of fact, insofar as it is possible to balance any one tube bridge circuit, it is because the tube acts as a resistance in series with an emf. The stability depends upon how well the curve can be replaced by a tangent to the curve. The actual value of the emf to be placed in series with a resistance is seen from Fig. 17 to be equal to 8.80 volts; and the resistance is equal to 3.38×10^4 ohms.

Now if this tube is placed in a circuit equivalent to Fig. 18, then a balance can be obtained under certain conditions. Applying Kirchhoff's laws to the circuit, the five following equations are obtained.

$$I_1 = I_4 + I_g$$

$$I_g + I_2 = I_5$$

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(11) Turner & Siegelin, R.S.I. 4, 429 (1933).

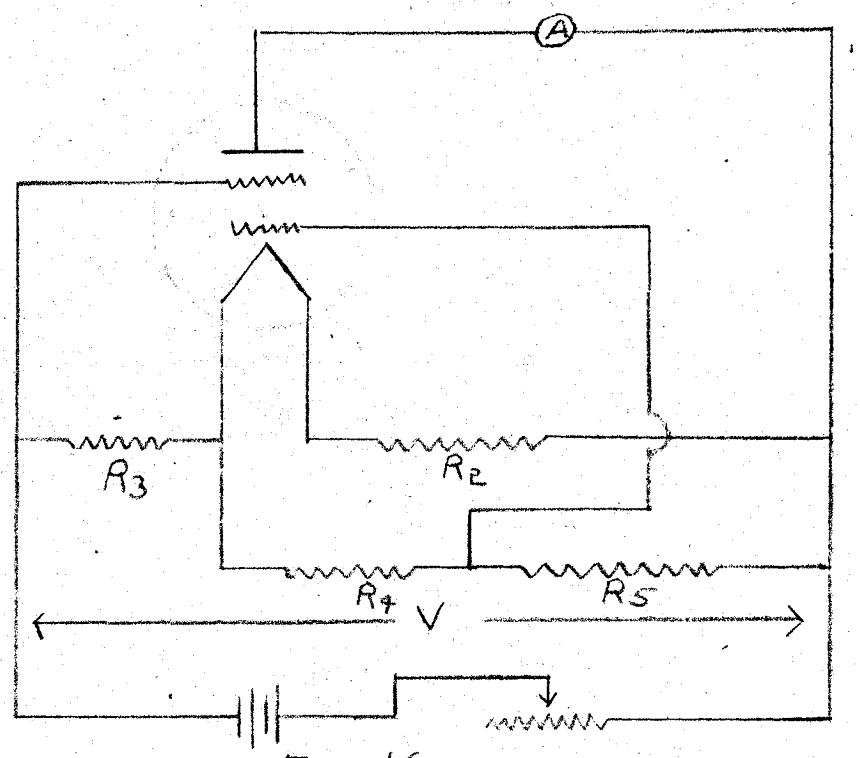
A
R3
R2
R4
R5
V

Fig. 16

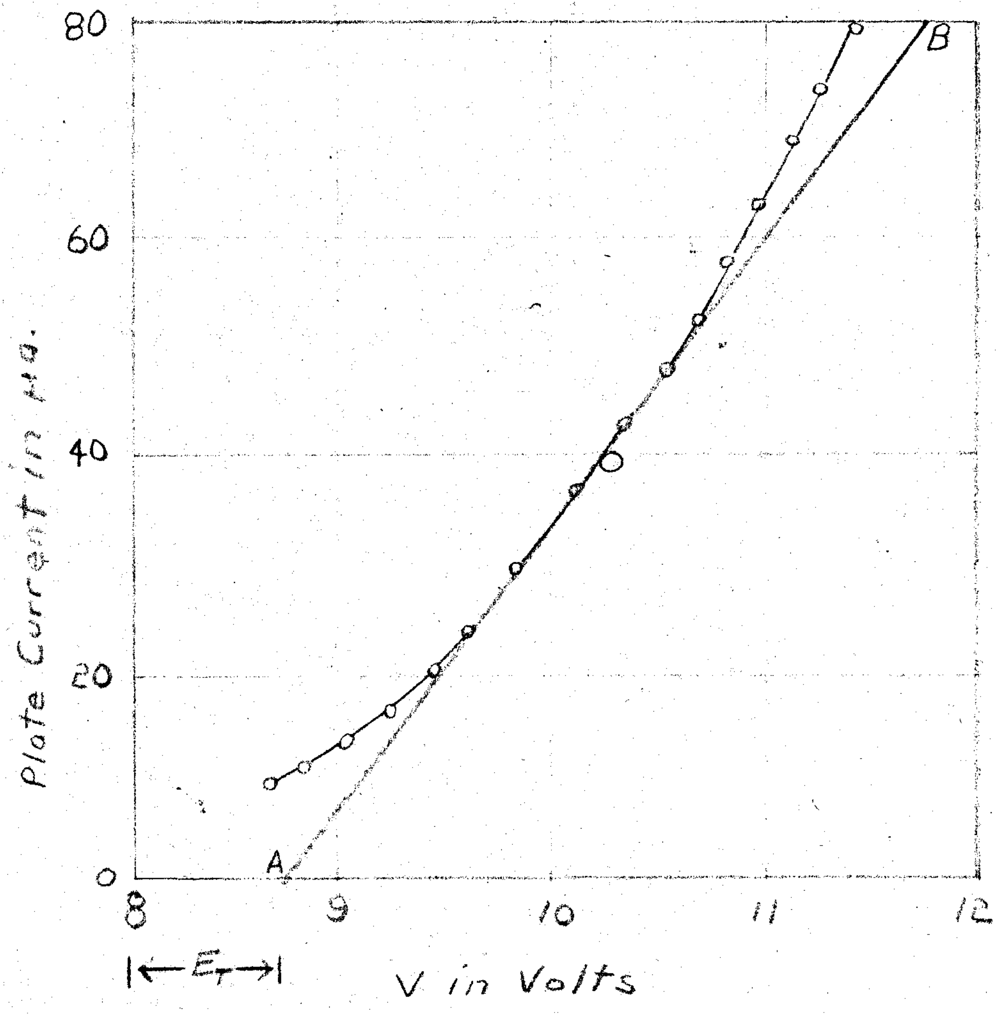
80
60
40
20
0
8
9
10
11
12
Plate Current in μa.
V in Volts
A
B
E_T

Fig. 17

$$I_1 R_8 + E_b - I_2 R_6 = 0$$

$$I_4 R_t + E_t - I_5 R_7 - E_b = 0$$

$$I_2 R_6 + I_5 R_7 - E = 0$$

If these five simultaneous equations are solved for I_g, the following equation is obtained:

$$I_g = \frac{(R_7 R_8 - R_6 R_T)E + (R_6 + R_7)(E_T R_8 - E_B R_7 - E_B R_8)}{R_6 (R_7 R_8 - R_6 R_7) + (R_6 + R_7)(R_T R_g + R_6 R_7)}$$

When I_g is zero, that is, when there is no current flowing through the galvanometer, then the numerator must be zero. The numerator is zero when

$$R_7 R_8 = R_6 R_t$$

and

(34)
$$E_t R_8 = E_b \times R_t + E_b R_8$$

In order that I_g be independent of E, then the derivative of I_g with respect to E must be zero; that is,

(35) $$\frac{dI_g}{dE} = \frac{(R_7 R_8 - R_6 R_T)}{R_6 (R_7 R_8 - R_6 R_7) + (R_6 + R_7)(R_T R_g + R_6 R_7)} = 0$$

Equation (35) is zero when

$$R_7 R_8 = R_6 R_t$$

Equation (34) can be solved for R_8 giving,

$$R_8 = R_T \left(\frac{E_B}{E_T - E_B} \right)$$

With E_t and R_t known from Fig. 17, R_8 can be calculated and the resistances R_7 and R_6 can be adjusted so that their ratio, that is,

$$\frac{R_7}{R_6} \text{ is equal to } \frac{R_t}{R_8}$$

Turner and Siegelin devised a circuit shown in Fig. 19, making use of the data derived above. The resistances R_1, R_3, R_2, R_4 and R_5 were so determined as to give the proper filament current and electrode voltages.

As noted above, although this circuit is essentially the same as Soller's, nevertheless, its discussion was included in this paper to show the purpose of the compensating voltage E_b.

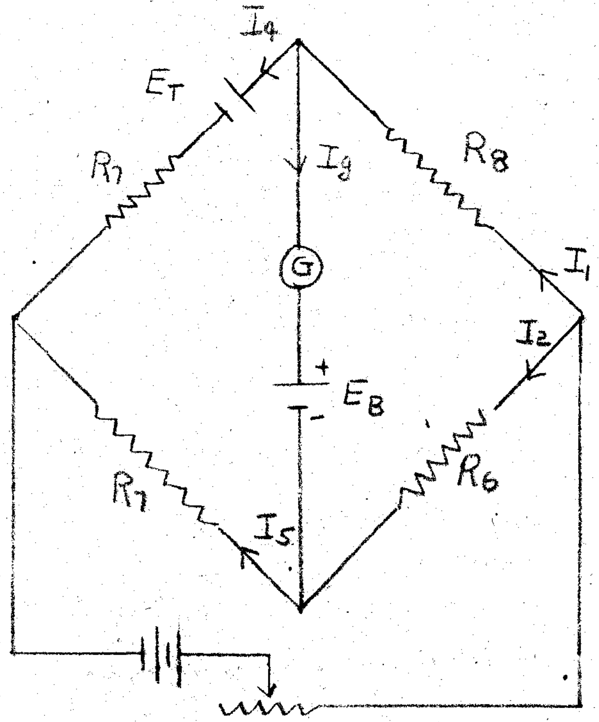
I4
E_T
R7
Ig
R8
G
I1
I2
+
E_B
-
R6
R7
I5

Fig. 18

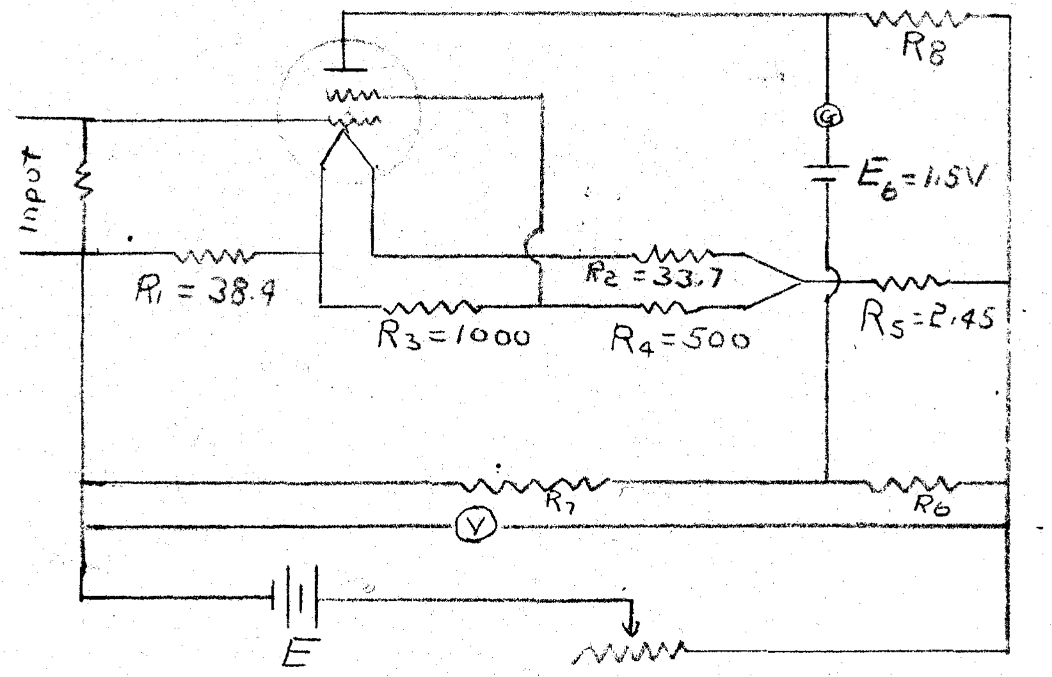
Input
R8
G
E6=1.5V
R1 = 38.4
R2 = 33.7
R3=1000
R4=500
R5=2.45
R7
R6
V
E

Fig. 19

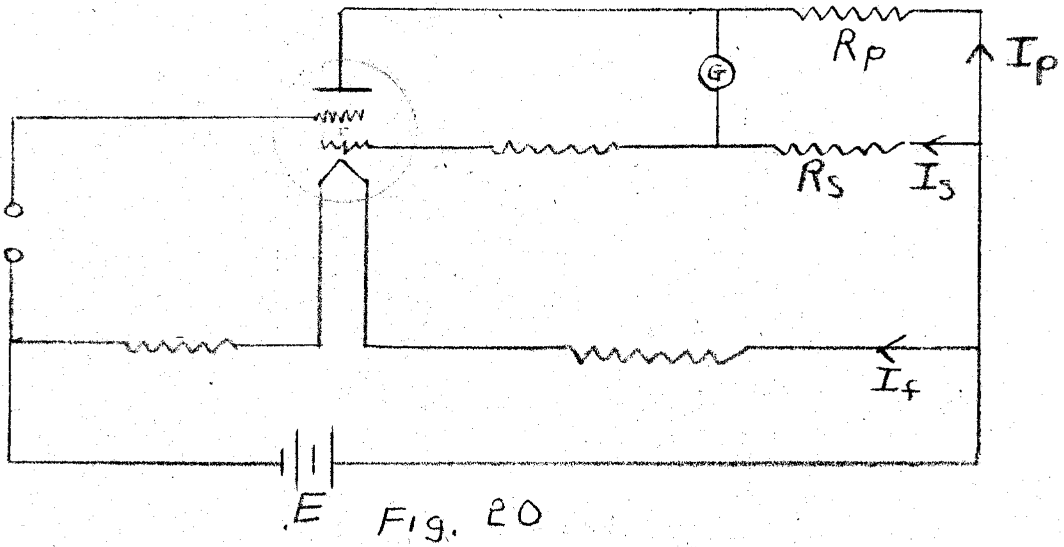

Fig. 20

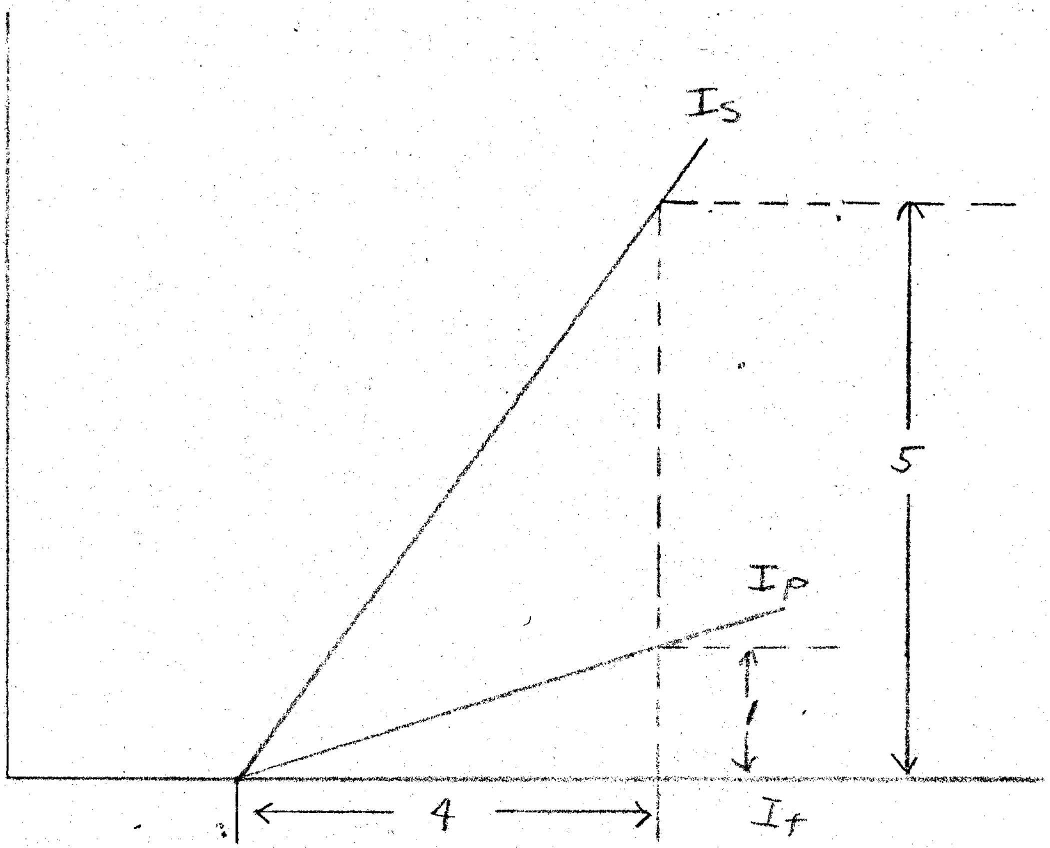

Fig. 21

DuBridge and Brown

Soller placed a compensating potential in series with the galvanometer and he did not use the cathode-space charge grid as one arm of the Wheatstone bridge. DuBridge and Brown (12) eliminated the emf in series with the galvanometer and made the cathode-space charge grid as one arm of the Wheatstone bridge and made use of one source of potential.

Fig. 20

Their circuit is a great improvement over previous circuits because only the changes of one source of voltage have to be compensated for.

When no current flows through the galvanometer

$$R_p I_p = R_s I_s \tag{36}$$

However, if e be the difference in potential across the galvanometer, then

$$e = R_p I_p - R_s I_s \tag{37}$$

In order for e to be independent of the changes of voltage of E or of I_f, then

$$\frac{d\,e}{d\,I_f} = 0 \tag{38}$$

Performing the differentiation and making use of the conditions stated in equations (36) and (37), the following differential equation is obtained

$$\frac{d\,I_p}{d\,I_f} = \left(\frac{R_s}{R_p}\right) \frac{d\,I_s}{d\,I_f} \tag{39}$$

---

(12) L. A. DuBridge and H. Brown, Rev. Sci. Inst. 4, 532 (1933).

From equations (36) and (39), it is seen that the curves I_p vrs. I_f and I_s vrs. I_f must be straight lines and must intersect the I_f axis at the same point. Fig. 21 shows the geometry of the solution of equations (36) and (39). The values in the figure were arbitrarily chosen. The slope of the I_s vrs. I_f curve is given by

$$\frac{dI_s}{dI_f} = \frac{5}{4}$$

that of the I_p vrs. I_f curve is

$$\frac{dI_p}{dI_f} = \frac{1}{4}$$

Using equation (39) and (36), the value for $\frac{dI_p}{dI_f}$ is the same as in the figure for

$$\frac{dI_p}{dI_f} = \frac{R_s}{R_p}\,\frac{dI_s}{dI_f} = \frac{I_p}{I_s}\,\frac{dI_s}{dI_f} = \frac{1}{5} \times \frac{5}{4} = \frac{1}{4}$$

Thus it is seen that if the values of I_s, I_p and I_f of a tube were plotted and if they produced curves, not necessarily straight lines, but linear over a portion of the curves so that tangents to the linear part of the curves would intersect at the I_f axis, then variations in the common supply voltage could be compensated for. The compensation would take place over that portion of the curves whose tangents intersect.on the I_f axis. The ratio of $\frac{R_s}{R_p}$ can always be adjusted to the current ratio, $\frac{I_p}{I_s}$.

Fig. 22 shows curves of FP-54 tube in DuBridge and Brown circuit shown in Fig. 20 and taken from their article in "Review of Scientific Instruments". At .087 ampere filament current, the circuit was stable

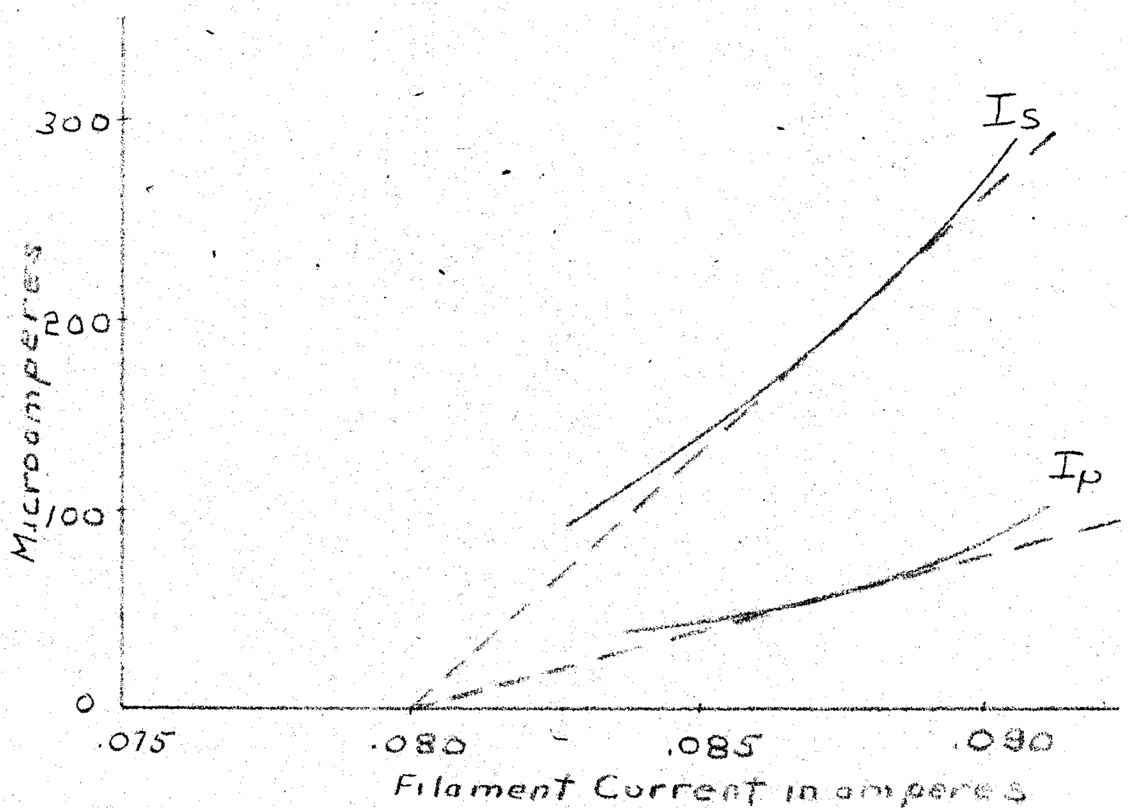
Microamperes
300
200
100
0
.075
.080
.085
.090
Filament Current in amperes
I_s
I_p

Fig. 22

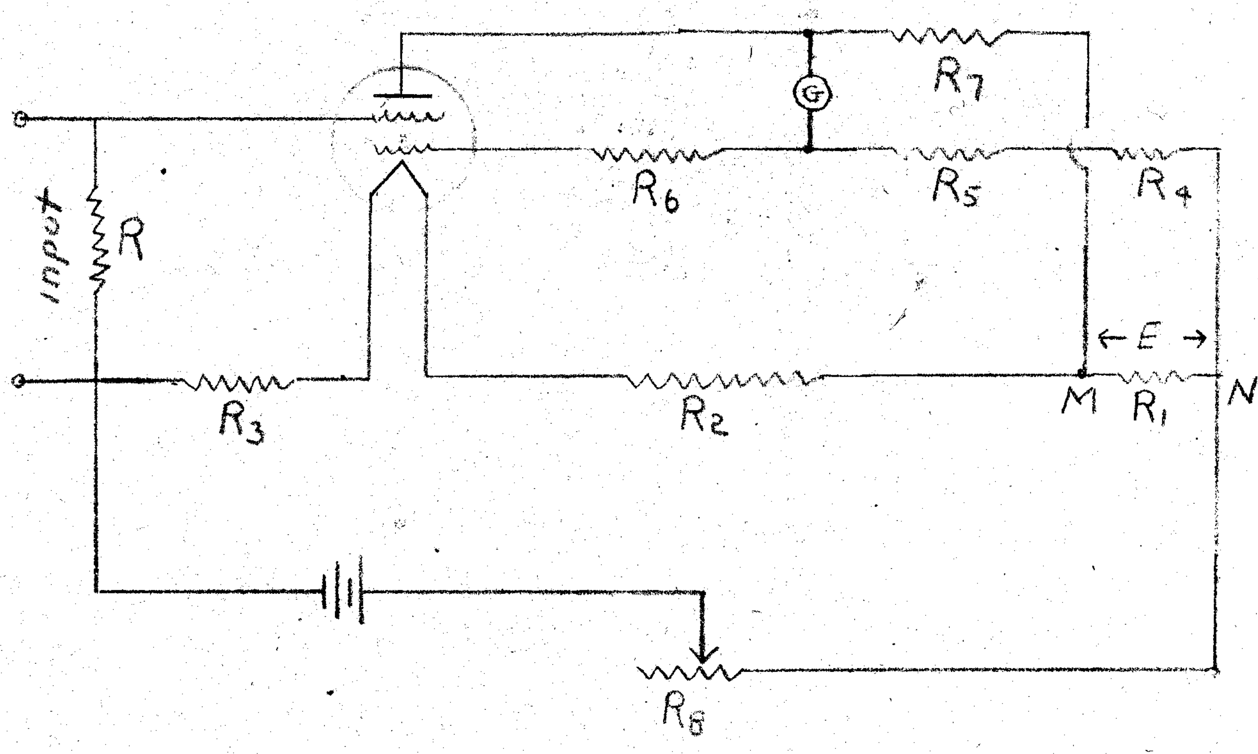
G
R_7
R_6
R_5
R_4
R
Input
← E →
R_3
R_2
M
R_1
N
R_8

Fig. 23

due to the compensation obtained from the portions of the curves whose tangent intersected at the I_f axis.

It might be remarked here that in all compensating bridge circuits two conditions must be satisfied. First, there must be zero current in the galvanometer; in Fig. 20, the condition for this is

$$R_p I_p = R_s I_s$$

Second, there must be zero current in galvanometer for a variation in voltage of the common battery; in this circuit the condition for this requirement is

$$\frac{d I_p}{d I_f} = \frac{R_s}{R_p} \frac{d I_s}{d I_f}$$

Barth Circuit

Before the appearance of Soller's circuit, two tube bridge circuits were in general use for measuring small currents and potentials. The ingenious way~~,~~ Soller compensated for changes in the storage battery by placing a small potential in series with the galvanometer, made it possible to construct a stable amplifier. But a more stable circuit could be constructed if it were possible to eliminate the battery in series with the galvanometer and to procure a compensating potential from one common source. In Soller's circuit there is no way of compensating for the potential of the battery in series with the galvanometer. Barth (13) devised a circuit in which the compensating potential varied linearly with the changes in the potential of the common battery and in which the cathode-screen grid resistance was used as one arm of the Wheatstone bridge. As has been noted in discussing Soller's circuit, the cathode-screen grid resistance was not used as one arm in the Wheatstone bridge.

Fig. 23 shows the Barth circuit as described in his article and Fig. 24 shows the same circuit in a simplified Wheatstone bridge form. The compensating potential is the "ir" drop across the resistor R_1 which together with R_7 constitute the one arm of the Wheatstone bridge. For no current in the galvanometer the following equation must be satisfied.

$$I_7 R_7 + E = I_4 (R_4 + R_5) \qquad (37)$$

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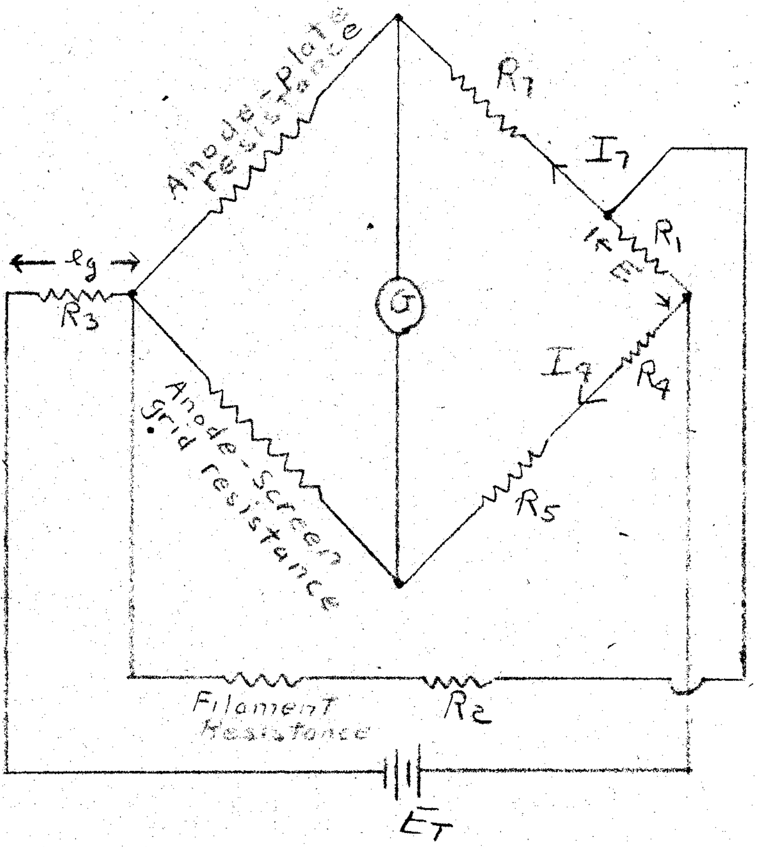
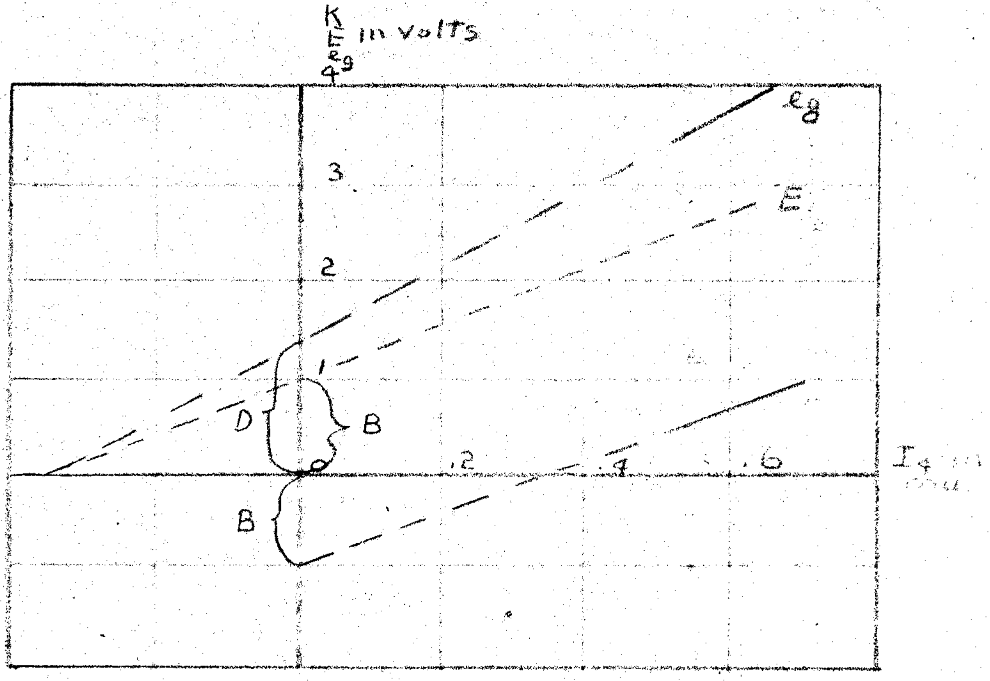
(13) G. Barth, Zeits. F. Physik 87, 399 (1934).



Anode-plate resistance
R7
I7
R1
I1
E
eg
R3
G
I4
R4
Anode-Screen grid resistance
R5
Filament Resistance
R2
ET

Fig. 24



K
E
eg/4 in volts
3
2
1
eg
E
D
B
0
B
.2
.4
.6
I4 in ma

Fig. 25

For no current in the galvanometer even though E_t changes slightly, the following equation must be satisfied.

(38) $R_7 \Delta I_7 + \Delta E = (R_5 + R_4)\Delta I_4$

Equation (38) states that in both arms the changes must be equal. From equations (37) and (38), the following equation is obtained after allowing the changes to approach zero.

(39) $$R_7 = \frac{I_4 \dfrac{dE}{dI_4} - E}{I_4 \dfrac{dI_7}{dI_4} - I_7}$$

Equation (39) is satisfied when

(40) $$I_4 \frac{dE}{dI_4} - E = -C_2$$

(41) $$I_4 \frac{dI_7}{dI_4} - I_7 = -C_1$$

(42) $$R_7 = -\frac{C_2}{C_1}$$

Solving (40) and (41), the two following linear equations are obtained

(43) $$I_7 = a I_4 + C_1$$

(44) $$E = b I_4 + C_2$$

Equations (43) and (44) state that in order that there be no current through the galvanometer even though there is a change of voltage in the common source, both the compensating potential E and the plate current I_7 must be linearly dependent upon the screen grid current I_4. Or in other words, the plate current and the screen grid current must be linearly dependent upon E which is linearly dependent upon the total voltage of the common source. The above equations tell us what is mathematically required for compensation. It so turns out that in the Barth circuit this linearity is actually obtained.

By changing equations (43) and (44), E, I_7 R_7 and eg, the potential drop across R_3 can be plotted against I_4, the screen grid current. The manner of changing equations (43) and (44) is that used by Barth in his paper.

(45) $K = I_7 R_7$ = the potential drop across the anode resistance

Substituting I_7 of (45) in (43), the following equation is obtained $\frac{K}{R_7} = a I_4 + c_1$

(46) $\frac{K}{\;} = A I_4 + B$

(47) $B = c_1 R_7$

$\searrow E = c_1 R_7$

eg is the potential drop across R_3.

Substituting E of (47) in (44) the following equation is obtained

$$c_3 e_g = b I_4 + c_2$$

(48) $e_g = C I_4 + D$

(49) $D = \frac{c_2}{c_3} = \frac{c_2}{E} e_g$

(50) $R_a = -\frac{c_2}{c_1} = \frac{-D E R_7}{e_g B}$

$$(51) \qquad \frac{E}{e_g} = -\frac{B}{D}$$

From equation (51) the compensating potential E is zero when eg is zero. That should be the case because the two potentials are the "ir" drops across resistances in series. Fig. (25) shows eg and K plotted against I_4; these values were obtained with a German type of tube Osram - Rohre T 113 in a Barth circuit. Several values of I_4, eg and I_4 were plotted as shown by the solid lines. The dotted lines show the prolongation of the solid lines. The measuring of the constants B and D are apparent from the above equations. When I_4 is zero from equation (44) E is equal to C_2. From the following equations it can be readily seen that the intercept of the E line on the y axis is exactly equal to the intercept of the K line on the y axis but opposite in sign.

$$I_4 = 0 \quad \text{then} \quad E = C_2$$

$$\text{But} \quad K = B = C_1 R_7 \text{ and } R_7 = \frac{-C_2}{C_1}$$

$$\text{Therefore} \qquad B = -C_2$$

To draw the line E it is only necessary to draw a straight line through the intersection of eg on the x axis and through a point on the y axis which is B units above the x axis. It might be remarked that the operating conditions would not be such that I_4 be equal to zero, but from a theoretical viewpoint the values of B, - B and D are of interest. A line drawn parallel to the y axis will give the simultaneous values of E, K, I_4 and eg.

In Fig. 23 and Fig. 24, there is a resistance R_4 in one arm of the Wheatstone bridge. The introduction of the compensating potential E does not change the voltage on the screen grid if an equal "ir" drop is obtained across R_4 by the adjustment of R_4. Neither the balance of the bridge nor the proper electrode voltages are changed by the introduction of the compensating potential if R_4 is adjusted so that its "ir" drop is equal to the potential E.

It is not at all necessary to obtain data that is involved in Fig. 25 to balance the Barth circuit. It is even not necessary to plot the curves in Fig. 26, but these curves show how to obtain a balance. These curves are taken from Barth's paper. From the figure it is seen that for a change in the total voltage ranging from 0 to 4% there is no deflection of the galvanometer when the compensating voltage is 2.7 volts. Instead of recording data to get the proper value of E, one can observe for what particular value of E the galvanometer will reverse its direction and for what value of E gives no deflection of the galvanometer.

In Chapter V, the actual operation of the Barth circuit with three different electrometer tubes will be discussed.

Before discussing the operation of the Barth circuit, a few remarks will be made on the problem of shielding.

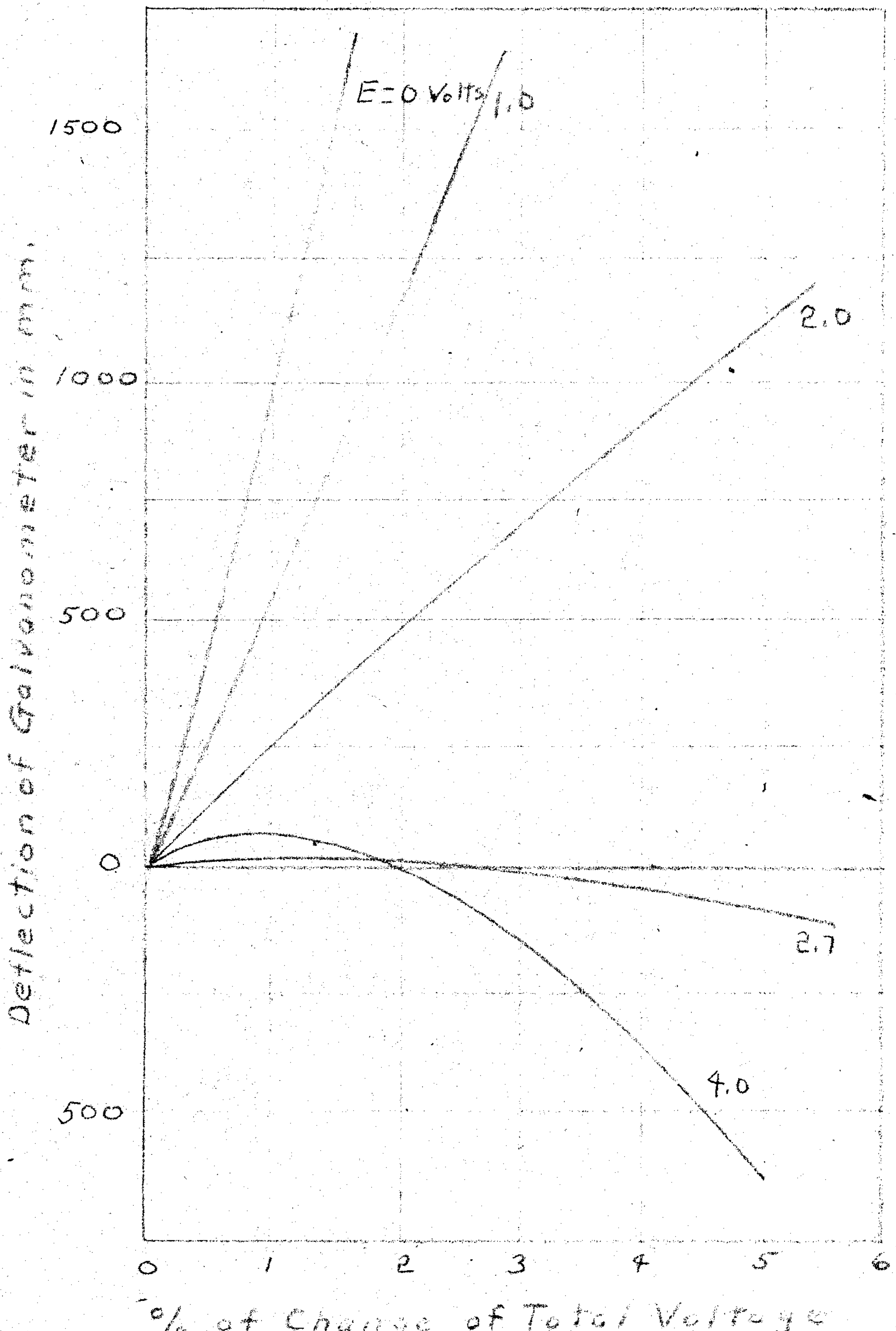

E=0 Volts
1.0
2.0
2.7
4.0
1500
1000
500
0
500
0
1
2
3
4
5
6
Deflection of Galvanometer in mm.
% of Change of Total Voltage

Fig. 26

Shielding

Anyone acquainted with the measurement of small currents and voltages, realizes that the most important requirement of amplifiers is zero stability. Instability of amplifiers is due to two general causes; first, drifts due to changes in the apparatus itself, and secondly, drifts due to external disturbances, principally electromagnetic. The chief feature of the compensated circuits described previously is the elimination of the drift due to the apparatus itself. With a good compensated circuit the plate current is balanced out with an accuracy of one part in 10^6. With an ordinary Wheatstone bridge, such accuracy is very easily obtained but that is due to ohmic resistances in the arms of the bridge; the relations between the currents and voltages of the various arms are strictly linear. However, it is different with the electrometer tube circuit. Linear relations are only obtained in as much as the characteristic curves are approximately straight at the operating point. With the Barth circuit in particular, excellent stability is possible. The author allowed the circuit to operate fourteen hours and the galvanometer only drifted .4 cm.

Once having chosen a good compensating circuit, one must exercise the greatest care in shielding the amplifier from external disturbances. The Faraday ice pail experiment shows that any closed conductor will reduce the zero frequency component of the electric field to zero. But for frequencies between zero and the frequency for which the skin effect becomes comparable with the shield thickness, the shield is ineffective. All frequencies greater than $\frac{c^2}{d^2\sigma\mu}$ are effectively shielded by a shield whose thickness is d and whose permeability and conductivity are μ and σ respectively. Copper makes a very good shield because of its high conductivity. But since there is no material of infinite conductivity and permeability, there can be no shield that will prevent disturbances that come from frequencies ranging from zero to infinity.

Since all the relations of an electrometer are linear, high frequencies will not disturb an electrometer to a great extent. Their effects cancel out. But high frequencies disturb an electrometer tube circuit because due to the non-linearity of the characteristic curves of the tubes, the effects do not cancel out. An electrometer tube thus becomes a detector of high frequencies and its d.c. component in the galvanometer in the plate circuit undergoes a change. In the X-ray laboratory at Stanford University an electrometer whose leads were unshielded with the exception of that of the insulated system, was undisturbed by the gas burst of an X-ray tube and by the discharge of large condensers. However, a carefully shielded electrometer tube circuit was greatly disturbed.

The author of this paper was not able to obtain stability in amplifying circuits until he placed everything in a large metal box; the tube and grid circuit shielded by their own metal container, the storage batteries, the galvanometer, the plate circuit, all were placed in a metal container. A drying agent was placed in the large box and also in the shield surrounding the tube and grid circuit. It is extremely important to insulate the grid side of the grid circuit. If that is not done then the high input impedance of the tube itself will be of little value, and there will be leakage across the poor insulation. An ordinary switch cannot be used in grid circuit because of leakage across the insulation. The author used a switch as shown in Fig. 33. This switch does not change the capacity of the grid circuit. A switch insulated by sulphur or quartz is often used. Careful thought should be given to the insulation of the high side of a grid circuit of an amplifier used for small current and voltage measurements.

Poor elecrrical contacts in an electrometer tube circuit will cause erractic fluctuations in the plate current. This is particularly true of the contacts to the storage batteries. It is good to cover the battery terminals with vaseline and to solder the leads to the terminals. All connections should be carefully soldered, first having tinned the two parts to be joined and then applying clean rosin core solder. Many authors recommend using a non-corrosive paste which is removed chemically before the two tinned surfaces are soldered; no paste is used for the final junction. It cannot be emphasized too much that the extra time spent in doing a good soldering job is amply rewarded by good results.

Ordinary radio potentiometers are not at all satisfactory for electrometer tube amplifying circuit. The author has had some sad experiences with them. The General Radio potentiometers are very good, especially the type labelled number 400. Before the potentiometers are used, their contacts should be gone over with sandpaper so that good contact is obtained. Those potentiometers that are used to balance the circuit should have dials, so that at a future time they can be readjusted with ease once knowing the proper settings.

It may be remarked for good stability, cleanliness is absolutely necessary. The tube and grid circuit must be free from all dirt and if it is necessary to handle the tube, clean cotton gloves must be used. Under no circumstance is a large grid resistor to be handled except by its terminal wires. It is only by sad experiences that one really appreciates these remarks.

CHAPTER V

The General Electric FP-54, the Western Electric D-96475 and the Victoreen VW-41 electrometer tubes were used in the Barth circuit. The following discussion concerns itself with the balancing of each electrometer circuit and with the measurement of ionization currents by both the drift and the steady deflection method.

1. The FP-54 Tube in the Barth Circuit

The characteristics of the FP-54 tube are as follows:

Filament voltage	2.5	volts
Filament current	0.09	ampere
Approximate direct interelectrode capacitance		
Control-grid-to-plate-to-space-charge-grid	6	micromicrofarads

TYPICAL OPERATING CONDITIONS

Normal operating voltages

Plate	6	volts
Control grid	-4	volts
Space-charge grid	4	volts

Average characteristics values at normal operating conditions

Plate current	60	microamperes
Control-grid current, approx.	10^{-15}	amperes
Input resistance, approx.	10^{16}	ohms
Amplification factor	0.9	
Plate resistance	45,000	ohms
Control-grid plate transconductance	20	micromhos

Fig. 27 shows the Barth circuit with the FP-54 tube. The FP-54 was of the newer type with a filament current of .090 ampere. The older type tube requires a filament current of .110 ampere. All the potentiometer rheostats were those made by General Radio. Their contacts were carefully sandpapered. For fine adjustment a 500 ohm rheostat was placed in series with the 20,000 ohm rheostate of R_8 and a 2 ohm rheostat was placed in series with the 50 ohm rheostat of R_3. The D'Arsonval galvanometer had a current sensitivity of 10^{-9} ampere per millemeter and required a damping resistance of 20 ohms (R_7). The initial values of the resistances were 45 ohms for R_1, 43 ohms for R_3, 2 ohms for R_4, 12,000 ohms for R_8, 3,000 ohms for R_5, 5,000 ohms for R_6.

While the circuit was being balanced, the grid of the tube was connected to the point A. The high resistor is placed in the grid circuit when a current is to be measured by the deflection method.

The resistor R_9 was adjusted until the filament current was .090 ampere, the rated value. The author learned that if the filament current was lower than .085 ampere or greater than .098 ampere, the circuit was hard to balance. By means of an electrometer voltmeter the different electrode voltages were measured. The variable resistances make it possible to obtain the proper voltages. With the proper voltages, the plate current was 63 microamperes. If the plate current falls short of 60 microamperes, the tube should be flashed by placing six to eight volts across the filament for one minute.

The sensitivity of the galvanometer was about 30% when the initial

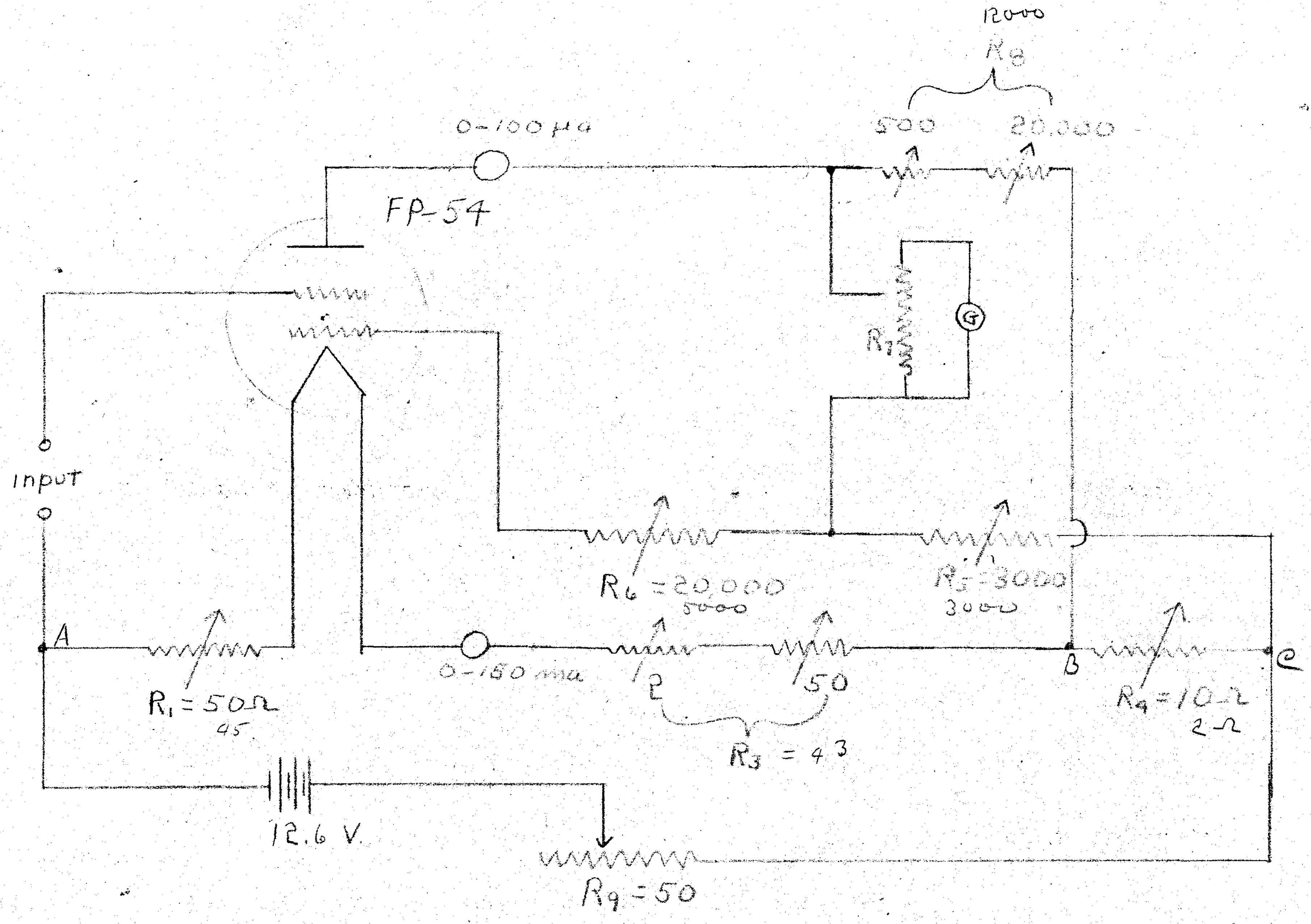

12000
R8
500
20,000
0-100 μa
FP-54
R7
G
Input
A
R1 = 50Ω
45
12.6 V.
R6 = 20,000
5000
R5 = 3000
3000
0-150 ma
2
50
R3 = 43
B
R4 = 10Ω
2Ω
C
R9 = 50

Fig. 27

adjustments were made. By the adjustment of R_8, the galvanometer deflection was made zero at full sensitivity. A steady drift of the galvanometer deflection was noticed which indicated that the circuit was not balanced. With the shunt of the galvanometer at about 30% sensitivity, and with a change of .1 ohm in R_4, the resistance R_9 was varied and the deflection of the galvanometer was observed. The balancing point is reached when the galvanometer reverses its direction with a constant increase or decrease of the filament current. The resistance R_4 was changed by steps of .1 ohm and the resistance R_9 was changed and a reversal of deflection of the galvanometer was looked for. When R_4 was 3.2 ohm the galvanometer reversed its direction. Often it is necessary to change the resistance R_3 by .2 ohms and then to vary R_4 as explained above to get the galvanometer to reverse its direction. If the galvanometer does not reverse its direction with different combinations of R_3 and R_4, the connections B and C should be reversed. The author never found it necessary to do this. After having found a combination of R_4 and R_3 that gave a reversal of galvanometer deflection then the shunt was placed at full sensitivity. The resistance R_8 was used throughout the balancing process to keep the galvanometer on the scale.

The deflection of the galvanometer was then plotted against the filament current and curve 1 of Fig. 28 was obtained. The filament current was then set at the value which corresponded to the flat portion of the curve and then the deflection of the galvanometer was plotted against time. Fig. 29 shows the resulting curve.

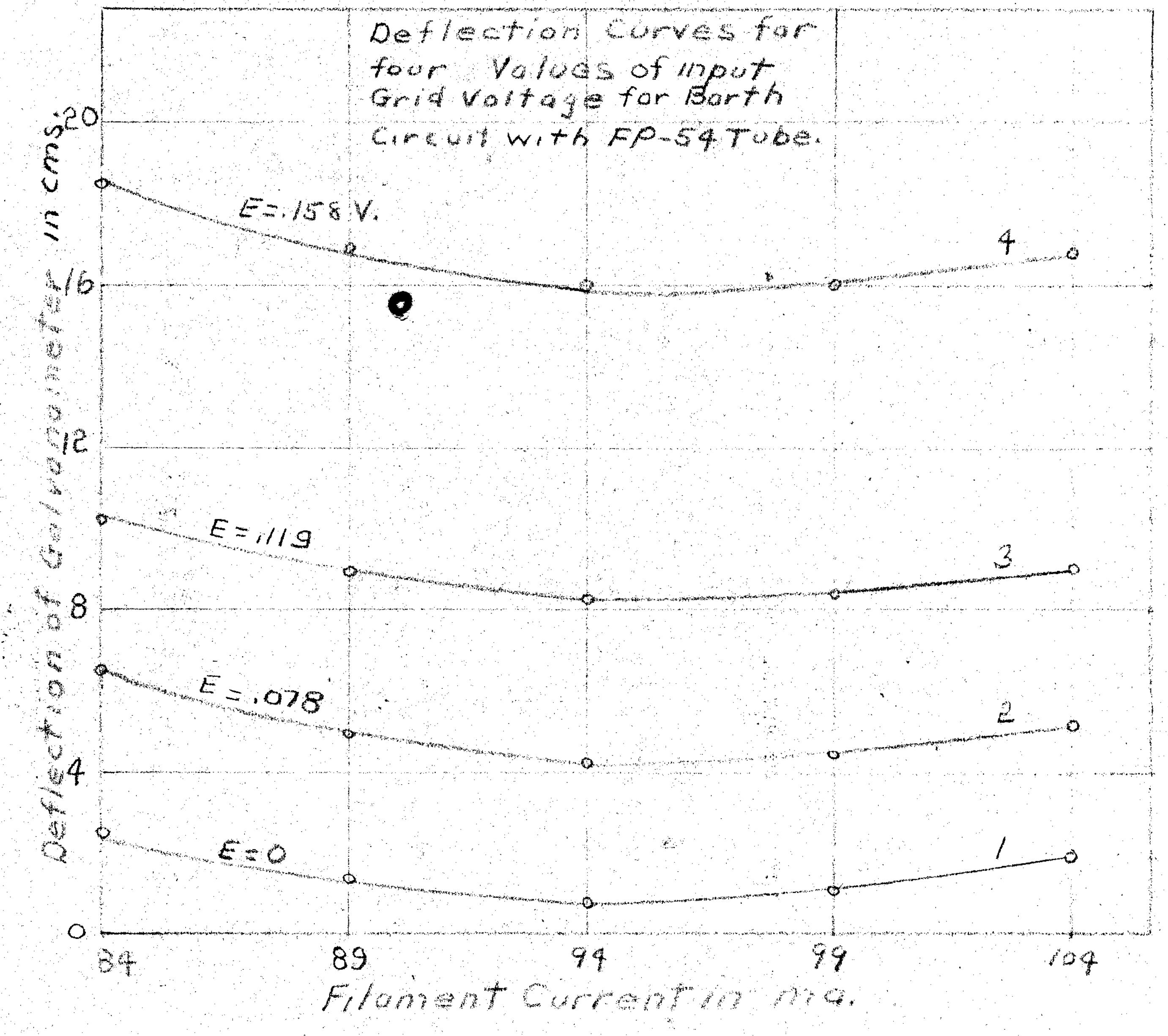

Deflection Curves for four Values of input Grid Voltage for Barth Circuit with FP-54 Tube.
Deflection of Galvanometer in cms.
Filament Current in ma.
0
4
8
12
16
20
84
89
94
99
104
E=.158 V.
E=.119
E=.078
E=0
1
2
3
4

Fig.28

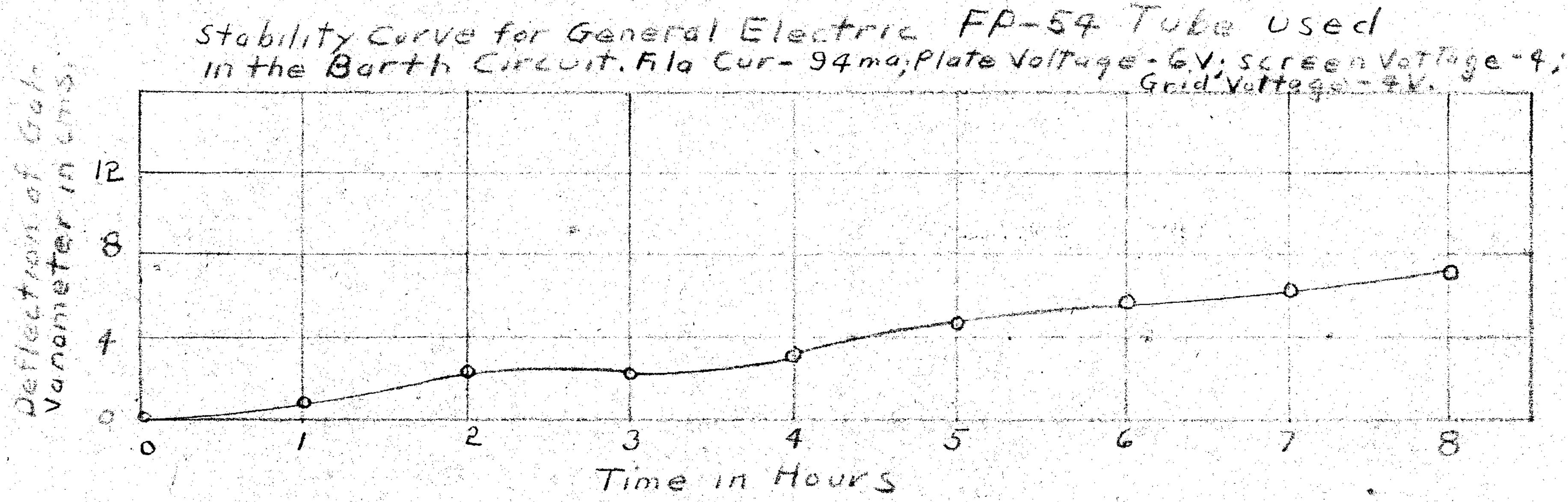

Stability Curve for General Electric FP-54 Tube used in the Barth Circuit. Fila Cur-94ma; Plate Voltage-6V; screen Voltage-4; Grid Voltage-4V.

Fig. 29

A potentiometer with a 10,000 ohm resistance and with a small dry cell was calibrated by means of a student L & N potentiometer. The markings on a dial were used for the calibration. Then the voltage from the potentiometer was placed in series with the grid circuit, that is between the grid and the point A of the circuit. The positive terminal being at the grid. Table 30 shows the deflection of the galvanometer corresponding to various input voltages. To make a wide range of voltage calibration possible, the shunt of the galvanometer was set at different sensitivities.

To see whether the flat portions of the curves would be above one another for different input voltages, various input voltages were used and the deflection of the galvanometer was plotted against the filament current. Fig. 28 shows the results. If the flat portions of the curves did not appear above each other, then for a particular filament current and for a particular input voltage, the operating point would not be on the flat part of the curve; this condition would not give stability because the important thing is to make the operating point on the flat part of the curve.

A word should be said about shielding. The tube, high input resistors, the ionization chamber with its batteries, the condenser and the air switch were all placed in a metal box that was one and a half feet wide, two feet high and two feet long. When the point A of the circuit is connected to the grid directly, no shield is really necessary. For one can approach the grid with one's hand and there is no change in the deflection of the galvanometer. But since the

Input Voltage in Volts	Deflection of Gal. in Cms.	Sensitivity of Gal.
.017	3.9	Full Sensitivity
.051	9.4	"
.084	19.3	"
.127	8.8	50%
.164	13	"
.214	16.9	"
.245	20.7	"
.292	24.4	"
.322	16.3	25%
.368	18.6	"
.404	21.2	"
.436	23.4	"
.46	9.5	12%
.495	10.7	"
.528	11.9	"
.559	12.65	"

VOLTAGE CALIBRATION FOR BARTH CIRCUIT WITH

FP-54 TUBE

Fig. 30

circuit is always used either with a high resistor or with a source of current in series with the grid circuit, it is absolutely necessary to have a good shield. The shield is necessary for the above mentioned parts of the grid circuit and the tube itself. It is good to have the storage batteries, the galvanometer and all the resistors of the circuit shielded, especially for very fine measurements. The author inclosed everything in a very large metal box and within this large box, he enclosed another metal box for the tube, etc. Within the smaller metal box was placed some drying agent $CaSO_4$. It might be remarked that phosphorous pentoxide is not very convenient for a drying agent because it gets sticky like molasses. Whereas $CaSO_4$ when pulverized is just as effective in keeping the container free from moisture as phospherous pentoxide.

The tube with its grid circuit must be shielded and treated exactly like an electroscope. Any charge induced on the grid will change the grid voltage which in turn will change the plate current. If the grid is shorted, that is, if there is no high resistance inserted in the grid circuit, then an induced charge on the grid will readily flow from the grid which together with the filament can be considered as plates of a condenser. But if a large resistor of 10^{10} ohms is placed in the grid circuit, or if the grid circuit is open, then a charge induced by one's hand or by any object, cannot flow away, and as a consequence, will change the potential between the grid and filament, with a consequent change in the plate current. This is the fundamental reason why it is necessary to shield the grid circuit. As explained before, the electrometer tube acts by reason of electrostatic action and it is absolutely necessary to shield the tube from external electrostatic disturbances.

There are two methods of measuring currents with an electrometer circuit; first, the direct deflection method, and second, the drift method. The author first used an ionization chamber that was completely enclosed, made of lead with the lead to the collecting plate insulated by sulphur. The voltage placed in series with the ionization chamber was 120 volts. The chamber contained some uranium nitrate. The ionization current measured by both the drift and the constant deflection method was 1.2×10^{-12} ampere. Although the tube itself has a capacity of 3×10^{-12} farad, the capacity of the tube and ionization chamber was 425×10^{-12} farad. As will be explained later, such a large capacity for the grid circuit limits the magnitude of small currents that can be measured. To reduce the capacity of the grid circuit and to reduce the ionization current, the author used the metal on the grid as one plate and one centimeter above it he placed a brass plate whose area was a square centimeter. A hole was drilled in a rod of wood and uranium nitrate was held fixed in the hole by parafin. This wood rod was held in place by a copper tubing that was fixed to the metal box. The ionization current could be increased by approaching the two plates that formed the ionization chamber with this rod that had uranium at its tip.

Fig. 31 shows the grid circuit for measuring the ionization current by means of the direct deflection method. The ionization chamber is drawn as shown in the figure, but as explained above, the

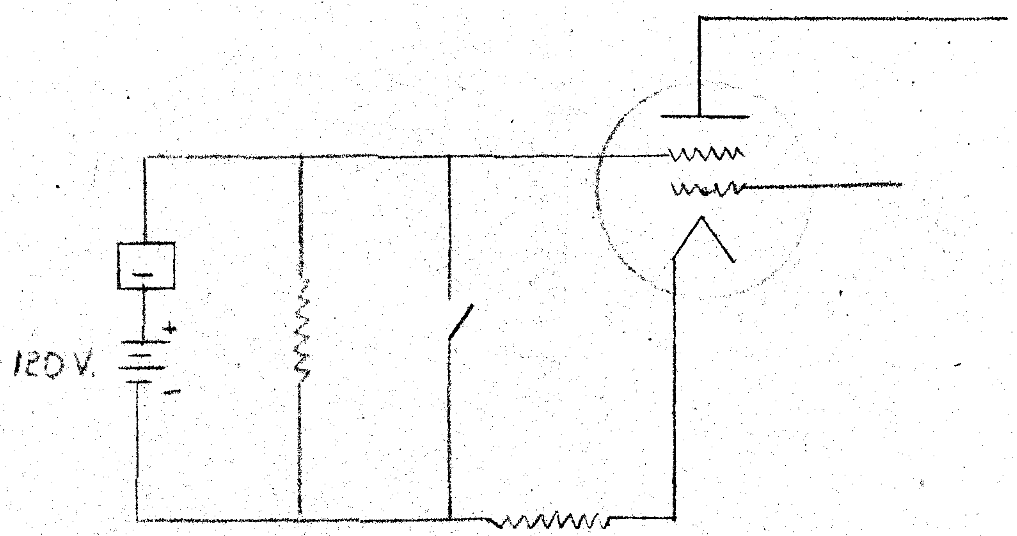


Fig. 31

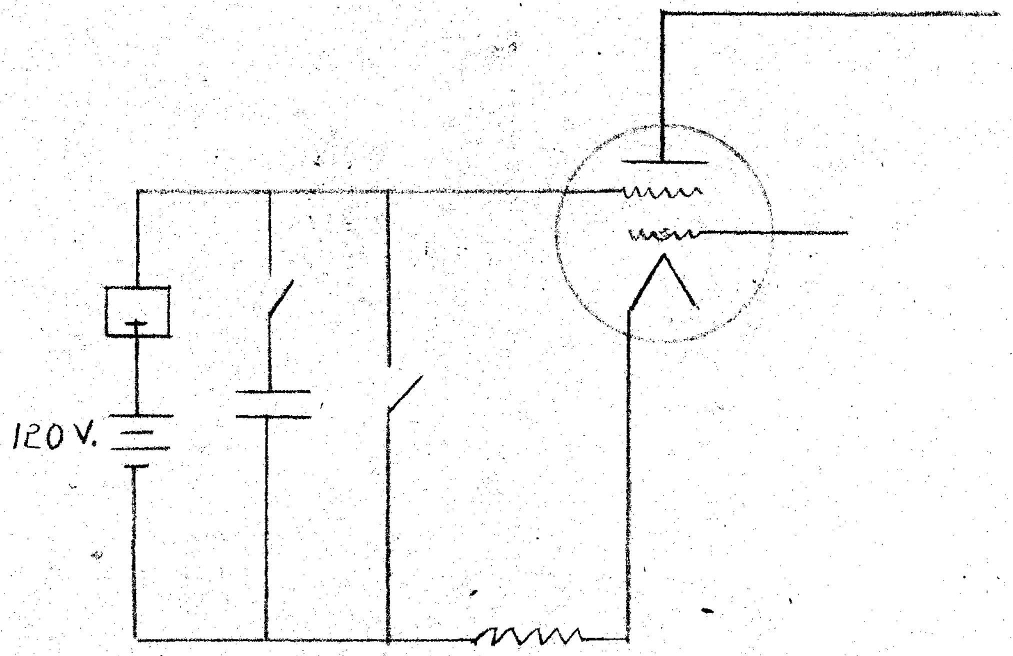


Fig. 32

the two plates consisted of the metal of the grid lead and the square centimeter of brass. It is important that the switch, used in the grid circuit, does not change the capacity of the grid circuit when it is opened and closed. Fig. 33 shows a sketch of the switch. A long thin nail made contact with a tip of a very small screw that was connected to the grid. By means of a silk thread the nail was raised or lowered. The change in capacity is very slight with the opening and closing of this switch. With the switch closed, the galvanometer was set at zero. Then the switch was opened and due to the time constant of the grid circuit, it took the galvanometer about fifteen seconds to assume a position of deflection. Knowing the deflection of the galvanometer in terms of the input voltage from previous calibration and knowing the value of the large resistor, the ionization current was computed. Table 34 shows the ionization current measured first with 10^{12} resistor and with the uranium nitrate two centimeters away from the plates of the condenser. The resistor was of the Victoreen type. There is a limit to the small magnitude of current that can be measured due to the increase in time constant and to the low voltage sensitivity of the electrometer circuit. Then the ionization current was measured with the uranium nitrate 4 cms. away from the plates of the condenser.

The measurement of current by the drift method depends upon the capacity of the grid circuit. Even though the capacity between the grid and filament of the tube itself is 3×10^{-12} farad, the capacity of the grid circuit is increased when something is connected to the

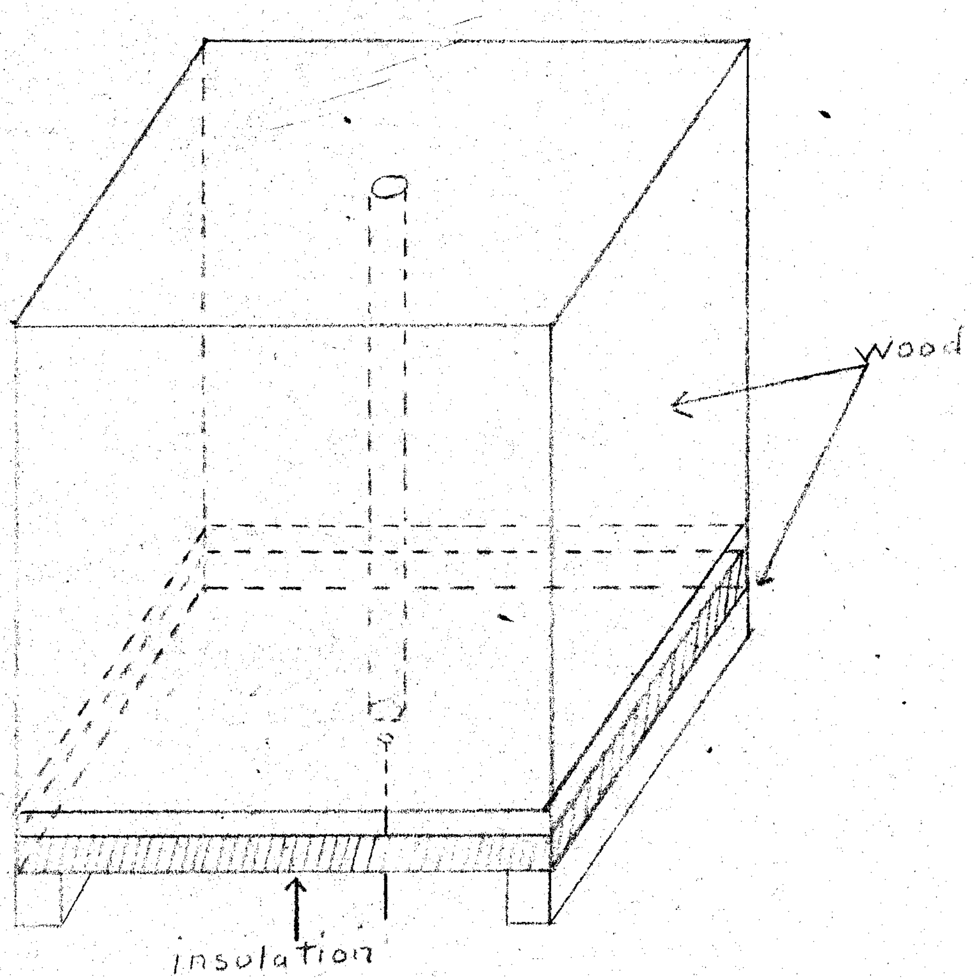


Fig. 33

grid. The method that was used to measure the capacity of the grid circuit was as follows. With the uranium in position to ionize the air between the two plates and with switch open in the circuit of Fig. 31, the time it took the galvanometer to deflect five centimeters was noted. Then a condenser was placed across the grid, and the time for the galvanometer to deflect five centimeters was recorded. A precision condenser was first used but since its lowest reading was 54×10^{-12} farad, it could not be used very conveniently since the capacity of the grid circuit was much lower. An air condenser (E. Leybolds Nachfoldger A.G., N 123) with a minimum of 25×10^{-12} farad, and a maximum of 50×10^{-12} farad was used. If T_1 is the time it takes the galvanometer to deflect a certain number of centimeters when just the ionization chamber is in series with the grid, if T_2 is the time it takes the galvanometer to deflect the same number of centimeters, if C_x is the unknown capacity of the grid circuit, and if C_2 is the capacity of the condenser that is added, then from the equation

$$\frac{C_x}{T_1} = \frac{C_1 + C_x}{T_2}$$

C_x can be computed. It is seen that if T_2 is equal to $2T_1$ then the capacity of the grid circuit is equal to the capacity of the condenser that is added. Table 34 shows the value of the capacity of the grid circuit as calculated by the above equation.

The actual measurement of ionization current was done in the following manner. With the uranium nitrate two centimeters away from the two plates (the one being the metal of the grid lead) the

STEADY DEFLECTION METHOD

	Resistance of grid resister in ohms	Deflection of Gal. in cms. = D	Sv = Voltage Sensitivity	E = input voltage = D x Sv	$i = \frac{E}{R}$
A	10^{12}	5.47	$\frac{.084\text{ volt}}{19.3\text{ cm.}}$	.0238 volt	2.38×10^{-14} ampere
B	10^{12}	.92	$\frac{.084\text{ volt}}{19.3\text{ cm.}}$	.004 volt	4×10^{-15} ampere

DRIFT METHOD

	Measured Capacity of grid circuit in fareds	Sv = Voltage Sensitivity	Time rate of deflection $\left(\frac{D}{T}\right)_a$ of gal. at floating grid potential	$\left(\frac{dE}{dT}\right)_a = \left(\frac{D}{T}\right)_a \times S_v$ at floating grid potential	Time rate of deflection of gal. when ionization current was being measured $= \left(\frac{D}{T}\right)_b$	$\left(\frac{dE}{dT}\right)_b = \left(\frac{D}{T}\right)_b \times S_v$ When ionization current was being measured	Ionization current = $C\left[\left(\frac{dE}{dT}\right)_b - \left(\frac{dE}{dT}\right)_a\right]$ in amperes
A	14.4×10^{-12}	$\frac{.084\text{ volt}}{19.3\text{ cm.}}$	$\frac{5\text{ cm.}}{40\text{ sec.}}$	$.000544\ \frac{\text{volt}}{\text{sec.}}$	$\frac{5\text{ cm.}}{10\text{ sec.}}$	$.00218\ \frac{\text{volt}}{\text{sec.}}$	2.35×10^{-14}
B	14.4×10^{-12}	$\frac{.084\text{ volt}}{19.3\text{ cm}}$	$\frac{5\text{ cm.}}{40\text{ sec.}}$	$.000544\ \frac{\text{volt}}{\text{sec.}}$	$\frac{5\text{ cm.}}{2.9\text{ sec.}}$	$.00075\ \frac{\text{volt}}{\text{sec.}}$	2.9×10^{-15}

THE ABOVE TABLE SHOWS THE RESULTS OF MEASURING TWO DIFFERENT IONIZATION CURRENTS BY THE DRIFT AND STEADY DEFLECTION METHODS USING THE FP-54 IN THE BARTH CIRCUIT.

TABLE 34

time rate of deflection of the galvanometer was observed which was designated as $\left(\frac{dE}{dT}\right)_b$; with the rod containing the uranium removed but with another rod of the same shape (with no uranium nitrate in its tip) in its place, the time rate of deflection of the galvanometer was observed. From the equation

$$i = C\frac{dE}{dT} = C\left[\left(\frac{dE}{dT}\right)_b - \left(\frac{dE}{dT}\right)_a\right]$$

i can be determined. The $\left(\frac{dE}{dT}\right)_a$ and the $\left(\frac{dE}{dT}\right)_b$ are determined from the calibration of the galvanometer deflection in terms of the input grid voltage. In table 34, two values of ionization currents were determined; the one when the uranium nitrate was two centimeters from the plates and the other when the uranium was four centimeters away.

2. The Western Electric D-96475 Tube

The Western Electric electrometer tube was used in the Barth circuit as shown in Fig. 35. The various resistances are indicated in the figure. The procedure in general was that used with the FP-54 tube.

The characteristics of the D-96475 tube are as follows:

Filament current, I_A	0.27	amperes
Plate voltage, E_B	4	volts
Inner grid voltage, E_N	4	volts
Control grid voltage, E_C	-3	volts

Under these conditions, a typical tube has approximately the following characteristics:

Filament voltage, E_A	1.0	volt
Plate current, I_B	85	microamperes
Inner grid current, I_N	520	microamperes
Mutual conductance, G_M	40	microamperes/volt
Control grid current, I_C	10^{-15}	amperes
Input resistance	10^{16}	ohms
Control grid capacity to ground	4.5×10^{-12}	farads

The Barth circuit with the D-96475 tube was balanced only with difficulty. The reason why the circuit was hard to balance was that it takes between twenty-five to thirty minutes for the tube to reach equilibrium after the filament current is changed. This is due to the large filament current of .270 ma. required by the tube.

The author allowed twenty-seven minutes to elapse between readings when he was getting the balanced conditions. With the FP-54 tube, the resistance R_3 was varied until there was a reversal of the galvanometer deflection and after having found the approximate values of R_3 and the filament current, then very accurate readings were taken. It takes the FP-54 tube about three minutes to reach equilibrium after the filament current is changed. But with the D-96475 tube, it was not possible to get the galvanometer to reverse its direction by slowly and steadily changing the filament current in one direction. It might be remarked that the author was not able to balance the circuit with R_3, R_2 and the plate lead as connected in Fig. 27. But with the arrangement of Fig. 35 a balance was obtained.

The procedure used in obtaining a balance was as follows. The resistances were adjusted so that the proper plate, screen and grid voltages were 4, 4, and -3 volts respectively with a filament current approximately 258 ma. (No balance could be obtained with a filament current of 270 ma. the recommended value.) With the shunt at 10% sensitivity, the resistances were varied while an electrometer voltmeter was measuring the plate and screen voltages. When these two voltages were approximately 4 volts, then the galvanometer was set at full sensitivity and the resistance R_8 was adjusted to place the galvanometer on zero. Then R_4 was steadily changed. The rate of deflection of the galvanometer was noted. Then R_3 was slightly changed and the rate of deflection of the galvanometer was noted as R_4 was steadily changed. This was repeated for a number of different

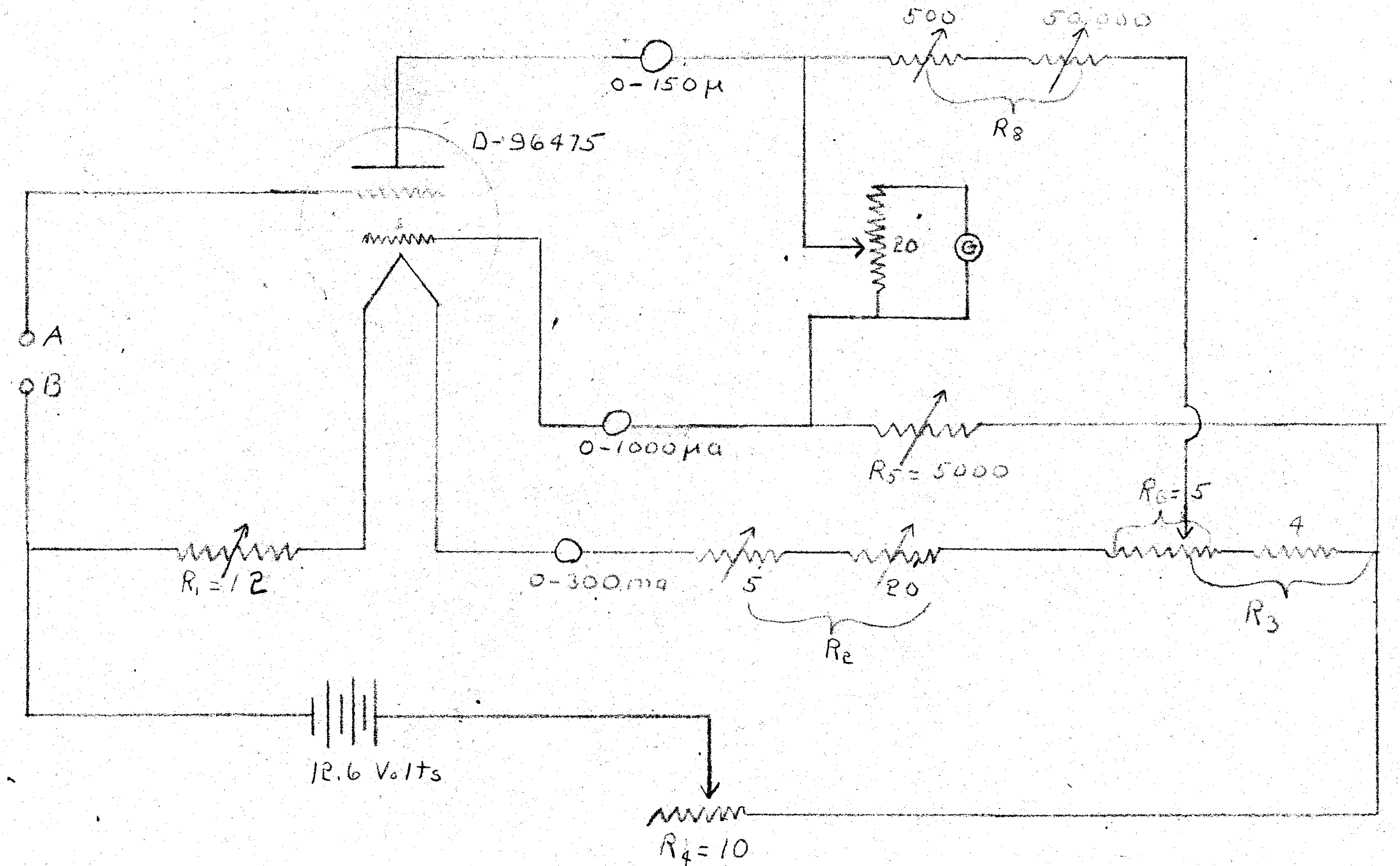

500
50,000
R8
0-150μ
D-96475
20
G
A
B
0-1000μa
R5 = 5000
R6 = 5
4
R1 = 12
0-300ma
5
20
R2
R3
12.6 Volts
R4 = 10

Fig. 35

values of R_3 and with various combinations of values of R_2 and R_3. In balancing the Barth circuit with the D-96475 tube, it is better roughly to get the balancing point by finding that value of R_3 and R_2 such that the rapidity of the deflection of the galvanometer is the smallest. This method has to be used because the deflection of the galvanometer will not reverse itself with a steady change of R_4 (that is, with a steady change of filament current). After having found the approximate values of R_3, R_2 and filament current, then exact readings are taken with an interval of at least twenty-five minutes between readings. During all these readings, the grid, of course, is shorted, that is A and B are connected as shown in Fig.35.

Curve 1 of Fig. 37_1 is plotted. This curve reverses its direction and is fairly flat between the range of 255 and 265 ma. With the filament current set at 258 and with R_3 set at 4.5 ohms and R_2 at 23.3 ohms, the deflection of the galvanometer was noted after each hour. Fig. 38 shows the stability curve. Fig. 37_2 shows curves obtained for various values of R_3. Then the input voltage was changed to .084 and .164 volt and the filament current was varied. The curves 2 and 3 of Fig. 37 show the results. It is to be noted that the flat part of these curves do not appear above one another as in Fig. 28 for FP-54 tube.

Fig. 36 shows the voltage calibration of the circuit. In comparison to the FP-54 (see Fig. 30) the Barth circuit with the D-96475 tube has a greater voltage sensitivity than with the FP-54 tube.

Fig. 39 shows the detailed data involved in the measurement of two different ionization currents by the drift and steady deflection methods.

Input Voltage in Volts	Deflection of Gal. in Cms.	Sensitivity of Gal.
.002	1.0	Full Sensitivity
.012	4.1	"
.025	6.9	"
.040	11.0	"
.048	15.1	"
.064	22.4	"
.103	15.5	50%
.139	20.9	"
.175	14.5	25%
.203	16.7	"
.238	21.7	"
.286	24.4	"
.333	14.1	12%
.375	16.1	"
.421	18.1	"
.468	20.5	"
.52	23.4	"

VOLTAGE CALIBRATION FOR BARTH CIRCUIT WITH

WESTERN ELECTRIC D-96475 TUBE

Fig. 36

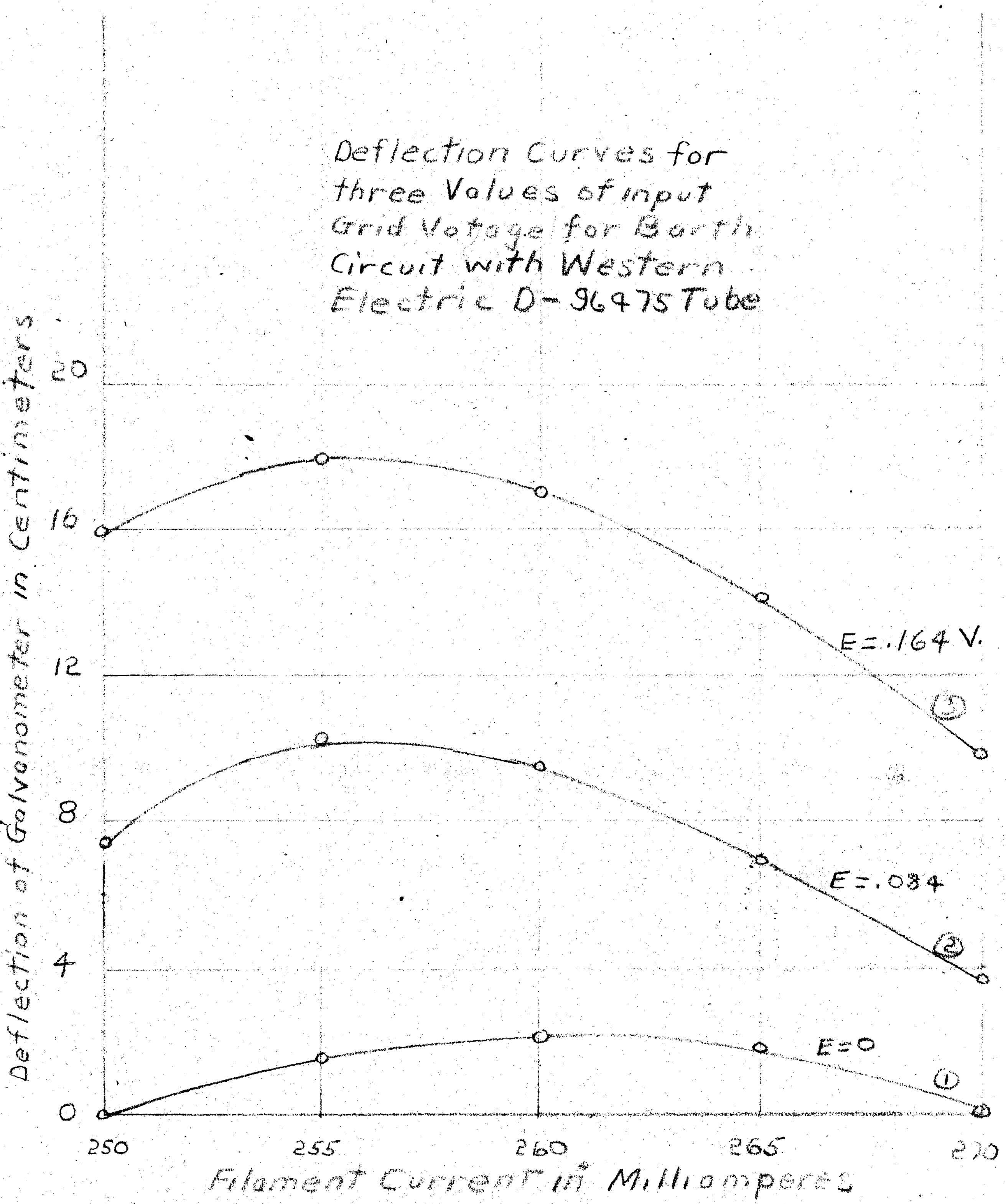

Deflection Curves for
three Values of input
Grid Votage for Barth
Circuit with Western
Electric D-96475 Tube
Deflection of Galvanometer in Centimeters
0
4
8
12
16
20
250
255
260
265
270
Filament Current in Milliamperes
E=.164 V.
③
E=.084
②
E=0
①

Fig. 37,

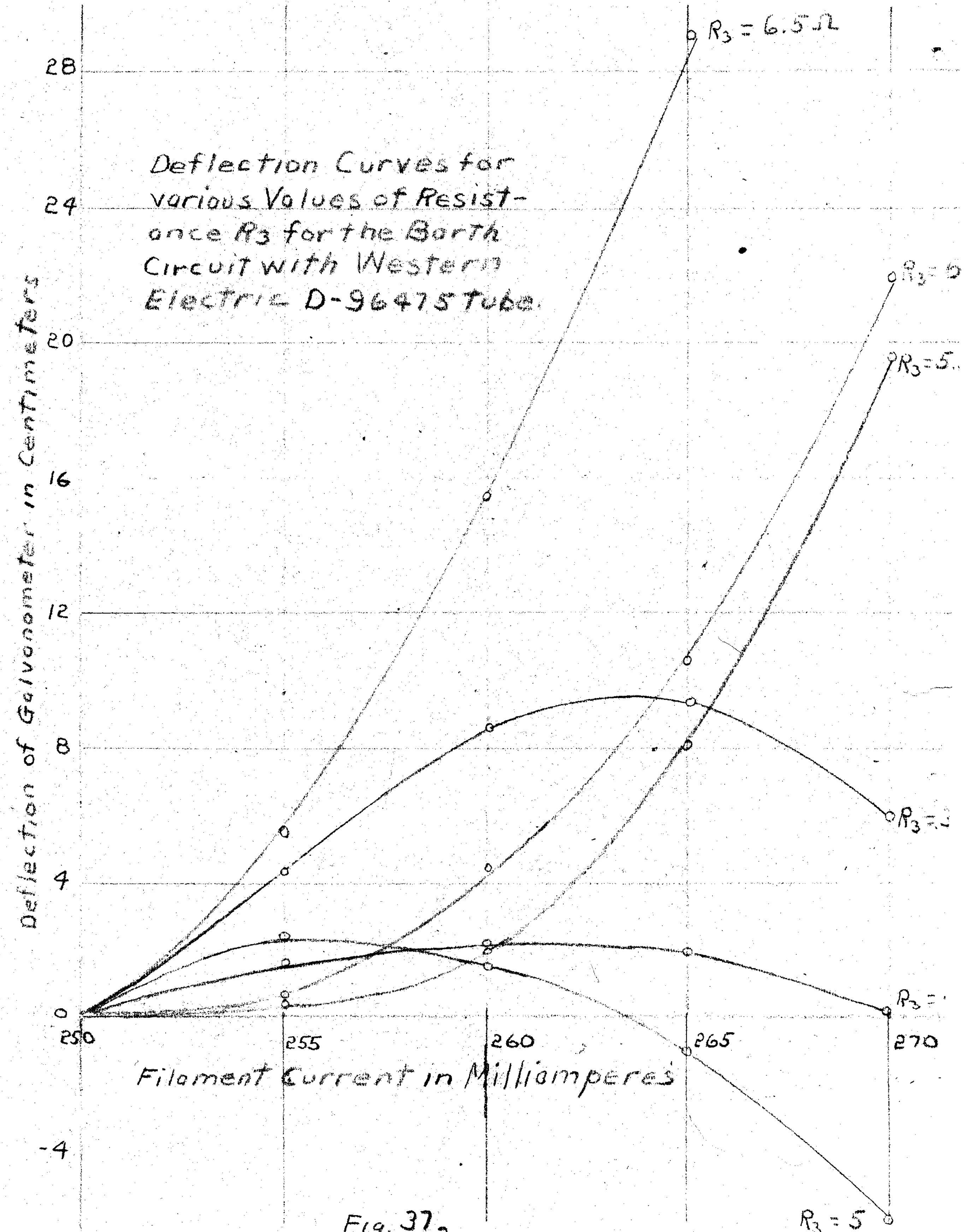
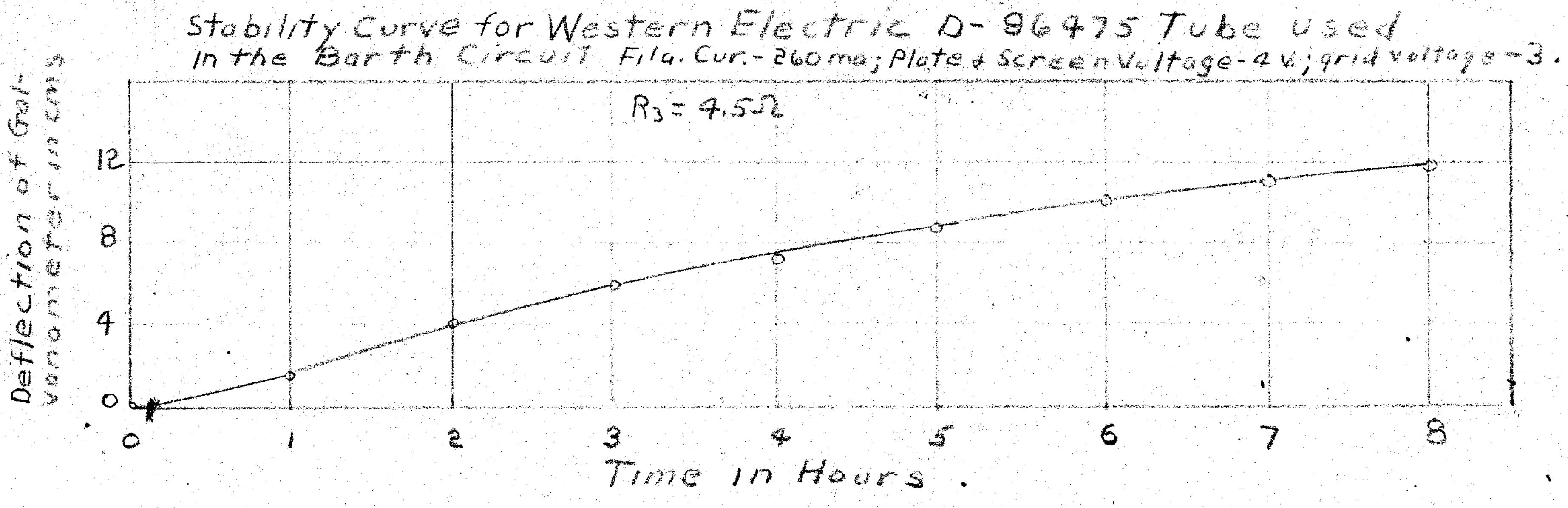

Deflection Curves for various Values of Resistance R_3 for the Borth Circuit with Western Electric D-96475 Tube.
Deflection of Galvanometer in Centimeters
Filament Current in Milliamperes
28
24
20
16
12
8
4
0
-4
250
255
260
265
270
R_3 = 6.5 Ω
R_3 = 6
R_3 = 5.
R_3 = 3
R_3 =
R_3 = 5

Fig. 37_2



Stability Curve for Western Electric D-96475 Tube used in the Barth Circuit Fila. Cur.-260 ma; Plate + Screen Voltage-4 V.; grid voltage -3.

Fig. 38

STEADY DEFLECTION METHOD

	Resistance of grid resistor in ohms	Deflection of Gal. in cms.= D	Sv = voltage sensitivity	E = input voltage = D x Sv. in volts	$i = \frac{E}{R}$
A	10^{12}	8	$\frac{.064 \text{ volt}}{22.4 \text{ cm.}}$	.023	2.3×10^{-14} ampere
B	10^{12}	1.93	$\frac{.064 \text{ volt}}{22.4 \text{ cm.}}$	.0055	5.5×10^{-15} ampere

DRIFT METHOD

	Measured capacity of grid circuit in farads	Sw = voltage sensitivity	Time rate of deflection of gal. at floating grid potential	at floating grid potential	Time rate of deflection of gal. when ionization current was being measured =	when ionization current was being measured	Ionization current = ampere
A	8.3×10^{-12}	$\frac{.064 \text{ volt}}{22.4 \text{ cm.}}$	$\frac{5 \text{ cm.}}{32 \text{ sec.}}$	$.00043 \frac{\text{volt}}{\text{sec.}}$	$\frac{5 \text{ cm.}}{8 \text{ sec.}}$	$.00177 \frac{\text{volt}}{\text{sec.}}$	1.1×10^{-14}
B	8.3×10^{-12}	$\frac{.064 \text{ volt}}{22.4 \text{ cm.}}$	$\frac{5 \text{ cm.}}{32 \text{ sec.}}$	$.00043 \frac{\text{volt}}{\text{sec.}}$	$\frac{5 \text{ cm.}}{18 \text{ sec.}}$	$.00079 \frac{\text{volt}}{\text{sec.}}$	5.72×10^{-15}

THE ABOVE TABLE SHOWS THE RESULTS OF MEASURING TWO DIFFERENT IONIZATION CURRENTS BY THE DRIFT AND STEADY DEFLECTION METHODS USING THE D-96475 TUBE IN THE BARTH CIRCUIT

Table 39

3. The Victoreen VW-41 Tube

The characteristics of the VW-41 tube are as follows:

Filament Current	0.010	amperes
Filament Voltage	1.5	volts
Plate Current	10	microamperes
Plate Voltage	6.0	volts max.
MU G-1	5.0	
MU G-2	1.0	
Transconductance	10	micromhos
Plate Resistance	125,000	ohms
Grid 1 Current	250	microamperes
Grid 2 Resistance	10^{16}	ohms - approx.
Grid 2 Current	Less than 10^{-14}	amp.
Grid 2 Voltage	1.0	minimum

Fig. 40 shows the circuit with the various resistances. The resistances were adjusted so that the plate voltage was 5 volts (the maximum voltage is 6 volts). The grid voltage was adjusted to -2 volts (the minimum voltage is -1 volt). R_7 was adjusted until the screen current was 250 microamperes. All these adjustments were made with .010 amperes flowing through the filament. The plate current was 10 microamperes.

By means of R_8 and R_5 the galvanometer was brought to zero. Then R_3 was set at a value of about 70 ohms and R_4 was steadily changed. No reversal of direction of the galvanometer occurred.

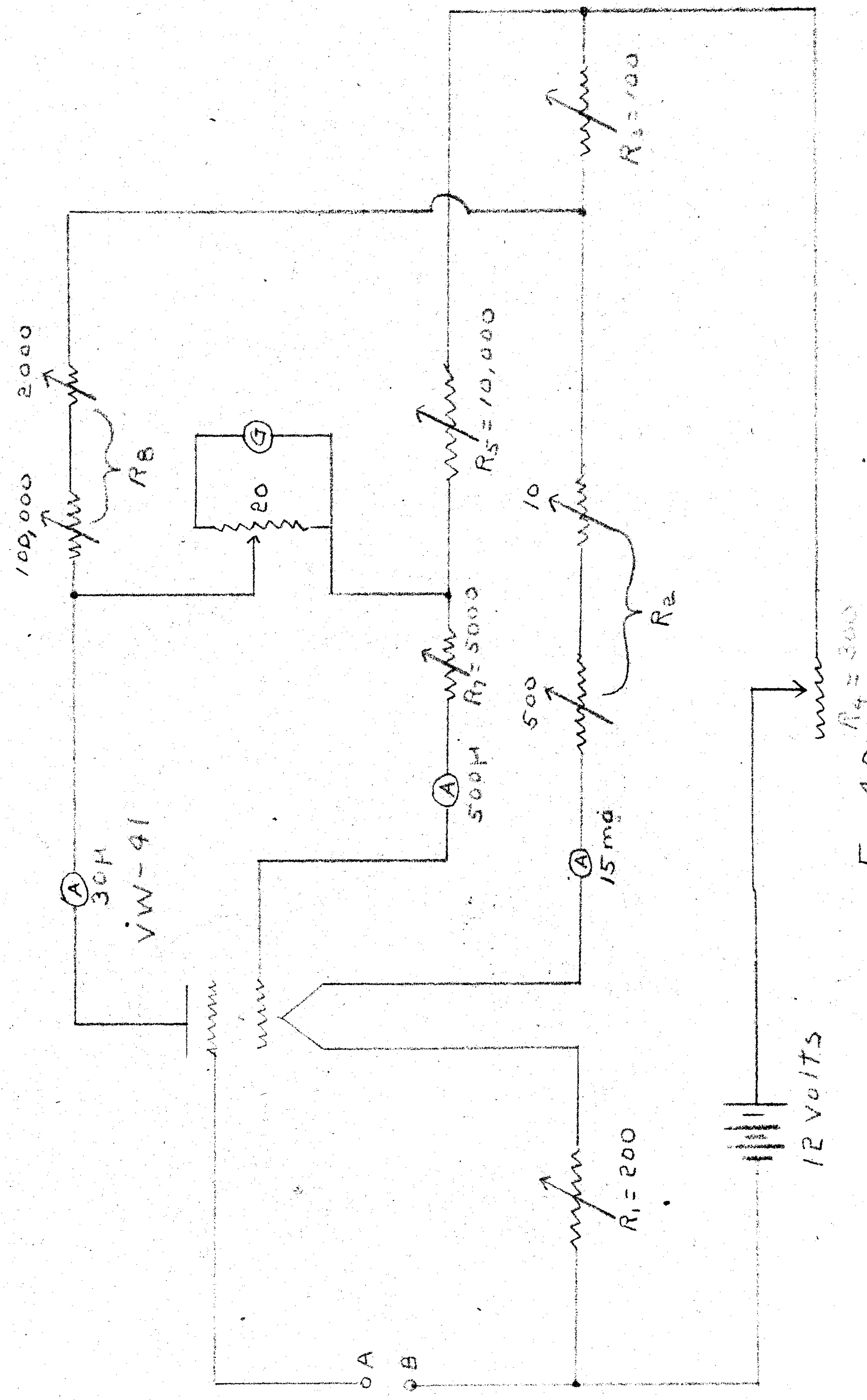

100,000
2000
R8
20
G
A
30H
VW-41
A
500H
R7 = 5000
R5 = 10,000
R3 = 100
10
500
R2
A
15 ma
R1 = 200
12 Volts
R4 = 300
A
B

Fig. 40

This step was repeated for different values of R_3 until there was a reversal of the deflection of the galvanometer. It may be necessary to vary R_2 and to see what combination of R_2 and R_3 will bring about this change in direction.

Fig. 41 shows the data for calibration of the Barth circuit with the VW-41 tube. It is readily seen that the voltage sensitivity of this circuit is not as good as the circuit with the FP-54 and D-96475 tubes.

With a plate voltage of 5 volts, a grid voltage of -2 volts, screen grid current of 225 microamperes and with a plate current of 11 microamperes, curve 1 of Fig. 42 was obtained. Then with three other input voltages curves 2, 3, and 4 were obtained. It is readily seen that the flat portions of the curves appear above each other. At first sight, it may appear that the stability of this circuit would not be very good since a change of 1 ma. in the filament current covers the entire curves. This is not true since the filament current changes vary little due to battery voltages ~~due to~~ because of the small magnitude of current drawn from the battery. Fig. 43 shows how stable the circuit was over a period of fourteen hours.

Table 44 shows the results of measuring an ionization current as explained above. Since there was no metal at the end of the grid lead the author attached a very thin copper plate to the grid lead and this served as the plate of the ionization chamber. The author was not able to measure down to 10^{-15} ampere with this small tube principally because the voltage sensitivity of the circuit was not as great as with the two previous tubes.

Input Voltage in Volts	Deflection of Gal. in Cms.	Sensitivity of Gal.
.002	.5	Full Sensitivity
.0125	3.7	"
.025	5.7	"
.040	8.6	"
.048	10.5	"
.0645	15.5	"
.103	25.5	"
.139	15.7	50%
.175	20.1	"
.203	24.4	"
.238	14.0	25%
.286	16.2	"
.333	18.8	"
.375	21.8	"
.421	24.9	"
.468	14	12%
.52	16	"
.57	18.3	"

VOLTAGE CALIBRATION FOR BARTH CIRCUIT WITH

VICTOREEN VW-41 TUBE

Fig. 41

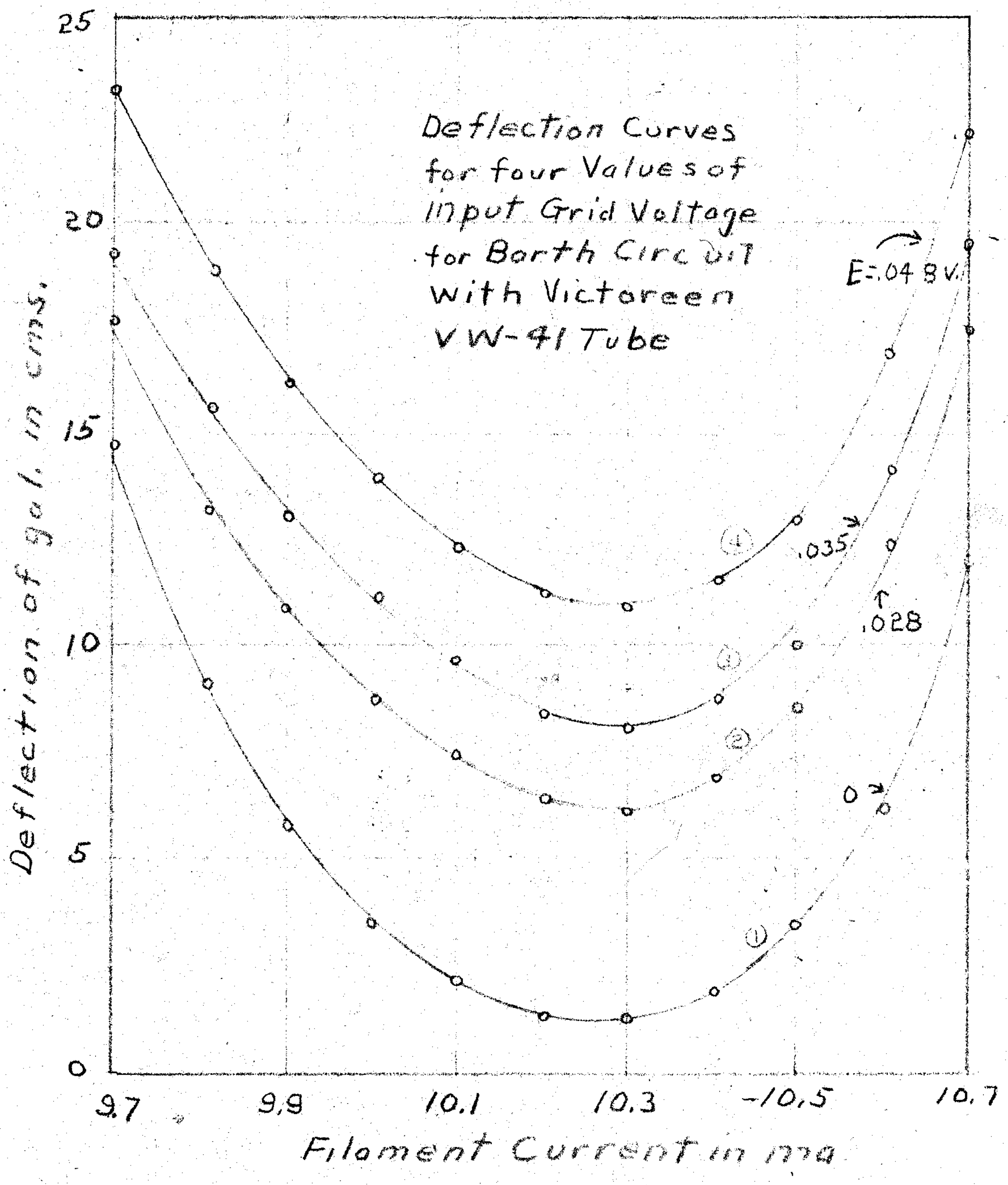

Deflection Curves for four Values of Input Grid Voltage for Borth Circuit with Victoreen VW-41 Tube
E=.048 V.
.035
.028
0
(1)
(2)
(3)
(4)
25
20
15
10
5
0
9.7
9.9
10.1
10.3
10.5
10.7
Deflection of gal. in cms.
Filament Current in ma

Fig. 42

Stability Curve for Victoreen VW-41 tube used in the Barth Circuit. Fila. cur. - .010 ma; plate voltage 4.2 volts; screen grid voltage 4.2 volts; grid voltage -1.4 volts.

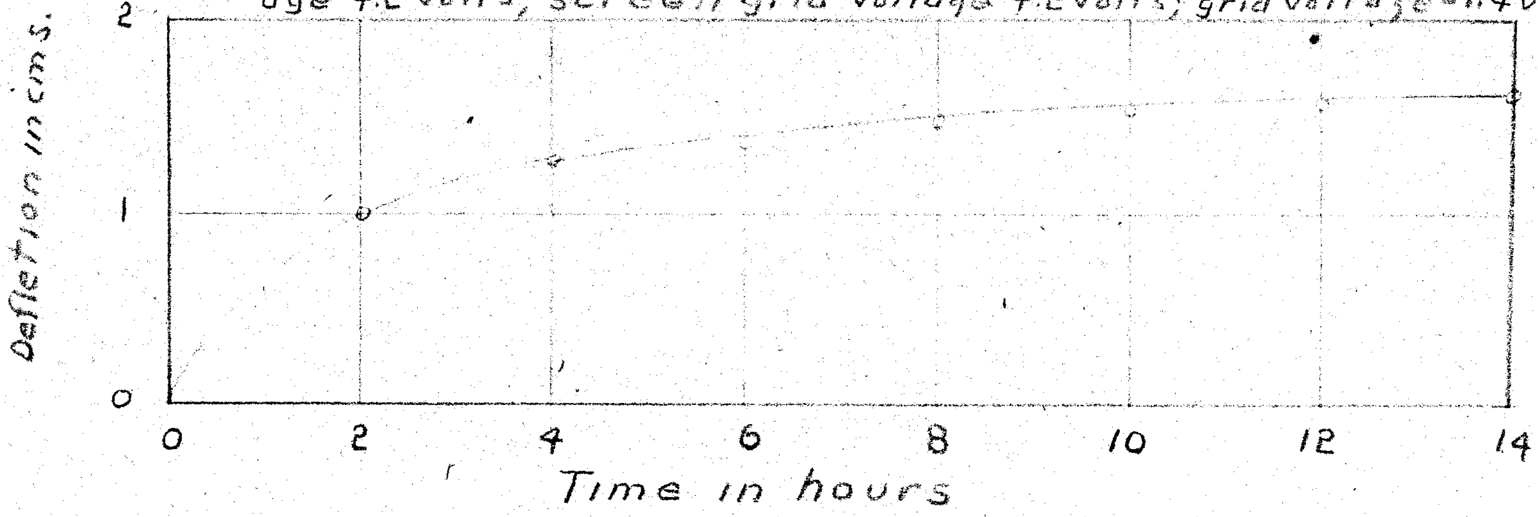


Fig. 43

STEADY DEFLECTION METHOD

Resistance of grid resistor in ohms	Deflection of gal. in cms.= D	Sv = voltage sensitivity	E = input voltage = D x Sv in volts	$i = \frac{E}{R}$
10^{12}	5.2	$\frac{.064 \text{ volt}}{15.5 \text{ cm.}}$	.0217	2.17×10^{-14}

DRIFT METHOD

Measured capacity of grid circuit in farads	Sv = voltage sensitivity	Time rate of deflection of gal. at floating grid potential	at floating grid potential	Time rate of deflection of gal. when ionization current was being measured =	when ionization current was being measured	Ionization current =
10×10^{-12}	$\frac{.064 \text{ volt}}{15.5 \text{ cm.}}$	$\frac{5 \text{ cms.}}{18.2 \text{ sec.}}$	$.00088 \frac{\text{volt}}{\text{sec.}}$	$\frac{5 \text{ cm.}}{5 \text{ sec.}}$	$.00418 \frac{\text{volt}}{\text{sec.}}$	2.17×10^{-14}

THE ABOVE TABLE SHOWS THE RESULTS OF MEASURING AN IONIZATION CURRENT

BY THE DRIFT AND STEADY DEFLECTION METHODS USING THE VICTOREEN VW-41

TUBE IN THE BARTH CIRCUIT

Table 44

Summary of Results

The voltage sensitivity of electrometer circuits is low, the current sensitivity is high.

The Barth circuit is the most stable of all compensating electrometer one tube bridge circuits.

The Barth circuit with the General Electric FP-54 tube is much easier to balance than the same circuit with the Western Electric D-96475 tube, or with the Victoreen VW-41 tube, and has a greater voltage sensitivity than the same circuit with the Victoreen VW-41 tube.

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