A STUDY OF THE VOLTAGE SENSITIVITY OF A DIRECT CURRENT AMPLIFIER

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FOREWORD

The rapidly increasing importance of the photo-electric cell, in many branches of scientific research as well as commercially, during the last few years has necessitated the development of a more sensitive method of measuring the very minute photo-electric currents. In the past, the only method of measurement was by the use of the quadrant electrometer. However the sensitivity of this instrument is not sufficient for most photo-electric problems, and in addition its manipulation requires great skill. Hence the necessity of constructing a more sensitive instrument for the measurement of photo-electric currents lead experimenters to concentrate their efforts on methods of amplifyimg these small direct currents. The results of their investigations were an instrument called "a direct current amplifier", employing in its construction the thermionic vacuum tube, and also the construction of a special thermionic tube, suitable for use in amplifiers, known as the FP 54.[(1)] Since then rapid strides have been made in the construction of other types of amplifiers, one of the best-known being the bridge amplifier type. Using commercial thermionic tubes designed for radio reception in this balanced circuit a voltage sensitivity of 10^{-5} volt/mm. has been obtained.[(2)] DuBridge[(3)] using two FP54's in the bridge circuit obtained a sensitivity of 4×10^{-6} v/mm.

(1) Physics Review, November 1930
(2) Razek and Mulder, J.O.S.A. and R.S.I. Dec. 1929.
(3) L.A.DuBridge, Phys. Rev. Feb. 1931.

The sensitivity of an amplifier is greatly reduced due to the fact that the plate current of the tube masks the comparatively small "amplification current" by necessitating a relatively insensitive meter in the plate circuit. However it has been found that considerable increase in sensitivity may be obtained by introducing into the simple circuit an auxiliary battery[(4)] in such a manner that it forces a current through the plate current meter equal to the plate current but in the opposite direction. Thus the sensitivity of the meter employed can be increased until irregularities in the plate current make the zero unsteady. A second method is by substituting the plate current of a second vacuum tube[(5)] for the current due to the auxiliary battery, then the fluctuations in the two tubes can be made to offset each other to a considerable extent allowing further increase in sensitivity to be obtained.

MacDonald and MacPherson[(6)] devised an amplifier employing ordinary commercial vacuum tubes, which they found to be extremely stable, rugged and to have a voltage sensitivity of 3×10^{-4} volt/mm. The fact that this type of amplifier showed such a high degree of stability suggested the possibility of greater sensitivity being obtained by applying the two methods of increasing the sensitivity mentioned above. The purpose of this paper, therefore, is to describe the steps taken in the

(4) Razek and Mulder J.O.S.A. and R.S.I. June 1929.
(5) J.M.Eglin, J.O.S.A. and R.S.I. 1929.
(6) Philosophical Magazine, Jan. 1933.

investigation of this problem and to indicate the degree of sensitivity which can be obtained with this type of amplifier.

CHAPTER 1.

History of Direct Current Amplification.

Since the foundation of all direct current amplifiers is the thermionic vacuum tube, a knowledge of the development, construction and characteristics of the vacuum tube is essential before making a study of the amplifier.

1. Development of the Vacuum Tube.

About 1884 Edison discovered that if inside an exhausted incandescent electric lamp of the ordinary type, containing a filament whose two ends were connected to two wires insulated from each other, there was introduced a third wire insulated from the filament connections and maintained at a potential positive with respect to the filament, then a current would flow across the vacuum inside the tube from the third wire to the filament as long as the filament was incandescent, but that the current ceased as soon as the filament became cold. In 1896 J.A.Fleming [7] also studied this phenomenon but it was left to J.J.Thomson [8] and O.W.Richardson to give a true understanding of what took place inside the tube. They showed that negative electricity was given off from the hot filament in the form of electrons. In 1901 Richardson [9] showed that the electrons were emitted solely by virtue of their kinetic energy and need no chemical reaction at the surface of the filament. When Richardson gave his explanation of the mechanism of the emission of

(7) Phil.Mag. Volume 42, 1896.
(8) Phil.Mag. " 48, 1899.
(9) Proc. Camb.Phil. Soc. Vol. 2, 1901.

the emission of electrons from hot bodies, it was not thought of a contribution of practical value.

In 1905, his principle was applied by Fleming, when he conceived the idea of using the thermionic tube as a rectifier for the detection of electromagnetic waves. It was DeForest, in 1907, who first introduced the control grid, resulting in a device of tremendous potentialities. This at once introduced the possibility of amplification and it was immediately used as an amplifier and oscillator generator. By 1914, the three electrode tube was used as a repeater in the commercial system of telephone communication. Since then thermionic tubes have been constructed containing four, five, and even six electrodes. However only those tubes containing three and four electrodes have been applied to the direct current amplifier investigated in this paper.

2. <u>Construction of Thermionic Tubes</u>.

The simplest form of thermionic tube consists of an evacuated vessel usually of glass, containing a filament which is heated by passing a current through it and an anode usually in the form of a plate or two plates, or a cylinder surrounding the filament.

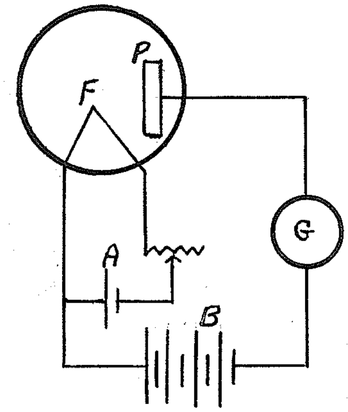


Figure 1.

Figure 1 indicates how such a tube is connected. The filament is heated by means of the current from the battery A and emits electrons which are drawn to the anode or plate P under the influence of a potential difference, maintained by the battery B, between the filament and the plate, positive with respect to the filament.

The next step in the development of the thermionic tube is the three electrode tube. This type contains, in addition to the filament and plate, a third electrode known as the control grid. The control grid is placed between the filament and plate and is in the form of a wire mesh or grid. The function of the control grid is to control the flow of electrons from the filament to the plate. This control is accomplished by applying potential variations to the grid and as a result of these variations the flow of electrons can be increased or decreased according as the grid is made positive or negative with respect to the filament. Figure 2 shows the position of the 3 electrodes and how they are connected in a circuit.

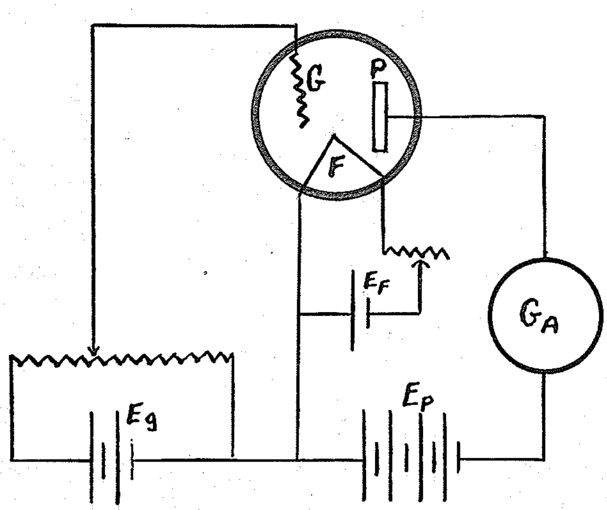


Figure 2.

A further step in the development was the introduction of a second grid, termed the screen grid, and its function ~~is~~ is also to control the plate-filament current by acting upon the space charge or free electrons. Figure 3 indicates the position of the screen grid and how it is connected in a circuit.

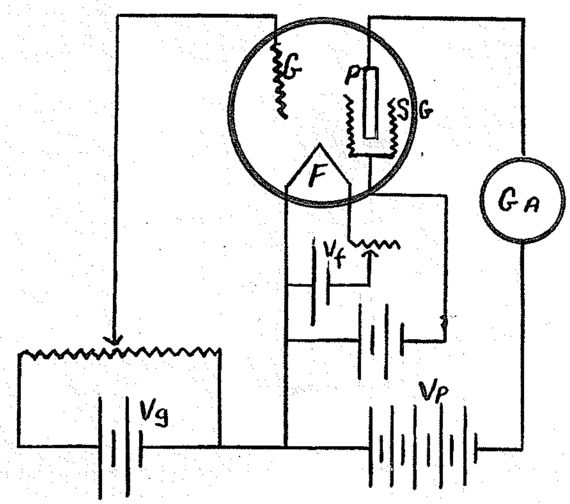


Figure 3.

3. Characteristics of Thermionic Tubes.

Two-electrode or diode tubes.

When the filament is heated to a definite temperature T_1 the current to the plate or anode for various potentials applied between cathode and anode,mresults in a curve as shown in Fig.4. Any increase in voltage over that at A_1 causes practically no further increase in the current and the upper section A_1B_1 is termed the saturation current. If the temperature of the cathode is increased to T_2 curve OA_2B_2 is obtained.

Next let a definite potential E_1 be applied between anode and cathode, and the anode current observed as a function of

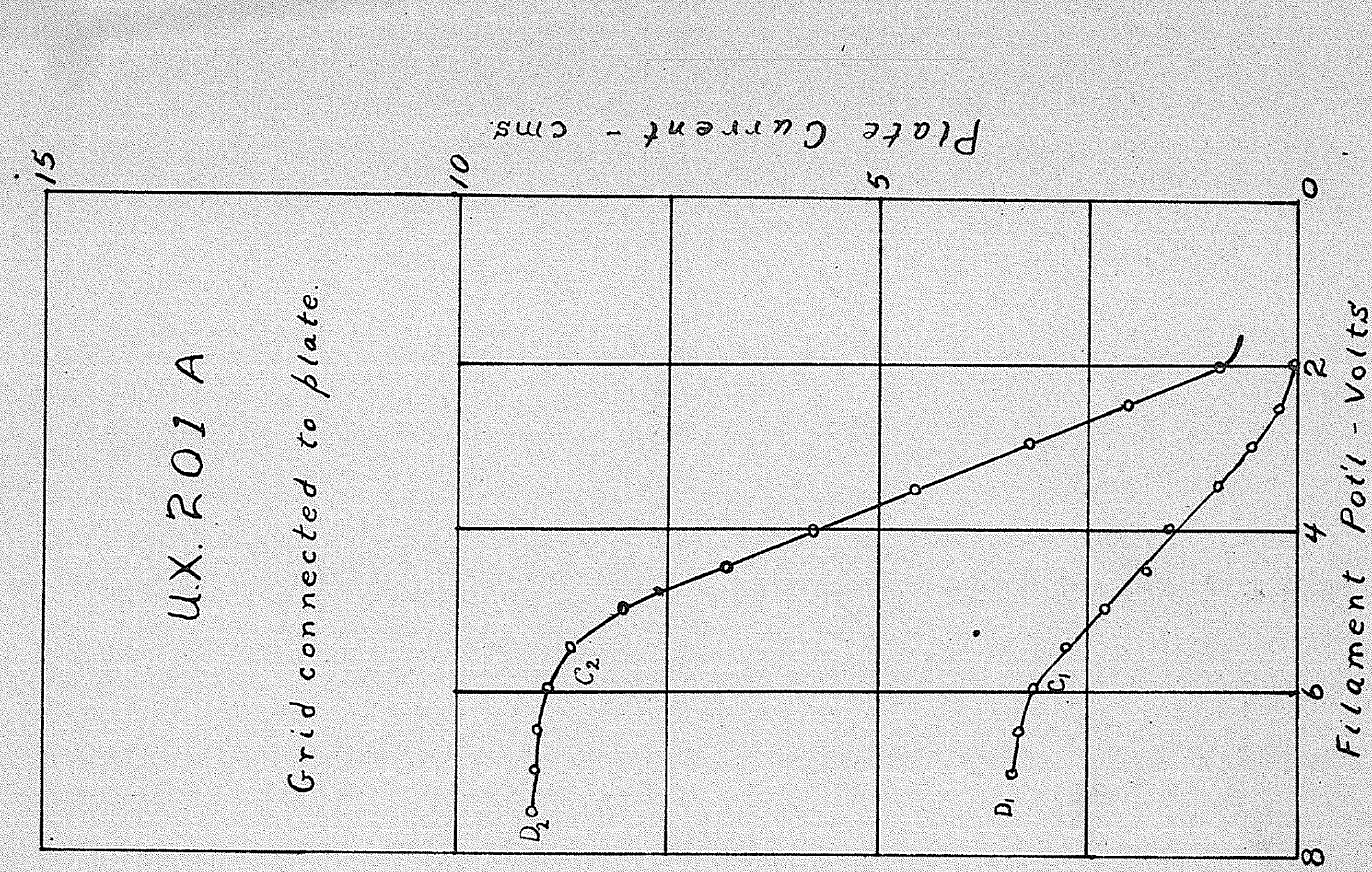


Figure 5.

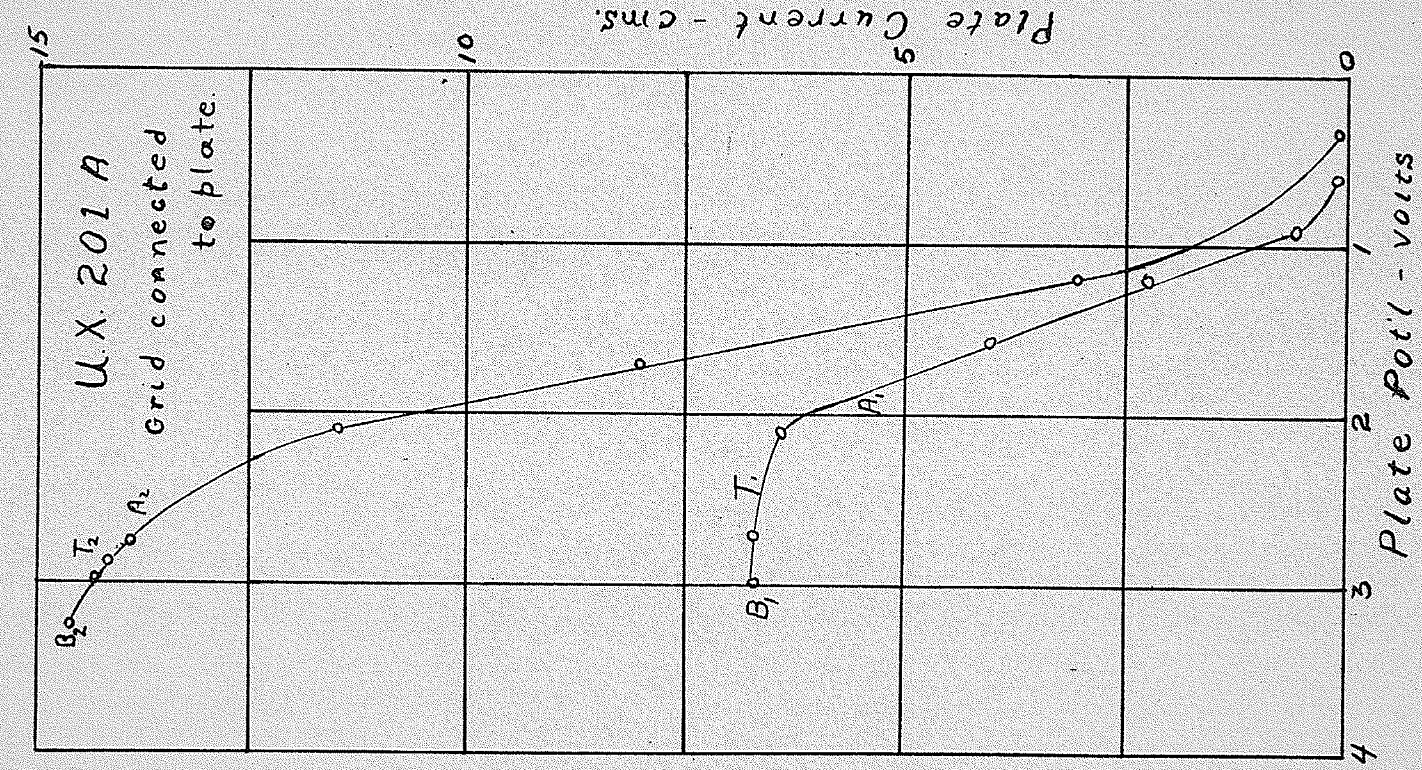


Figure 4.

the temperature of the filament. A typical curve is shown in Figure 5.

The current increases until it reaches a value C_1, any additional increase of the cathode temperature causes no further increase in the anode current (C_1D_1). This condition is defined as temperature saturation. The reason that there is no further increase in the current is that at the cathode temperature greater than that corresponding to ~~that~~ C_1, so many electrons are emitted from the filament that the resulting volume density of their charges causes all other electrons to be repelled and returned to the cathode.

If the potential is increased to E_2, the current increases since more electrons are attracted to the anode. Thus the temperature must be raised to C_2 before full space charge effect can be exerted. The result is that the higher the applied voltage, therefore the higher the cathode temperature must be to obtain full space charge effect.

Three electrode tubes or triodes.

The fundamental characteristic curves of a triode used as an amplifier consist of two families of curves: the grid potential-grid current family and the grid potential-plate current family.

A. Grid Current-Grid Potential.

Figure 6 represents a typical grid current-grid potential curve obtained from a UX222. The method of measurement is shown in Figure 7.

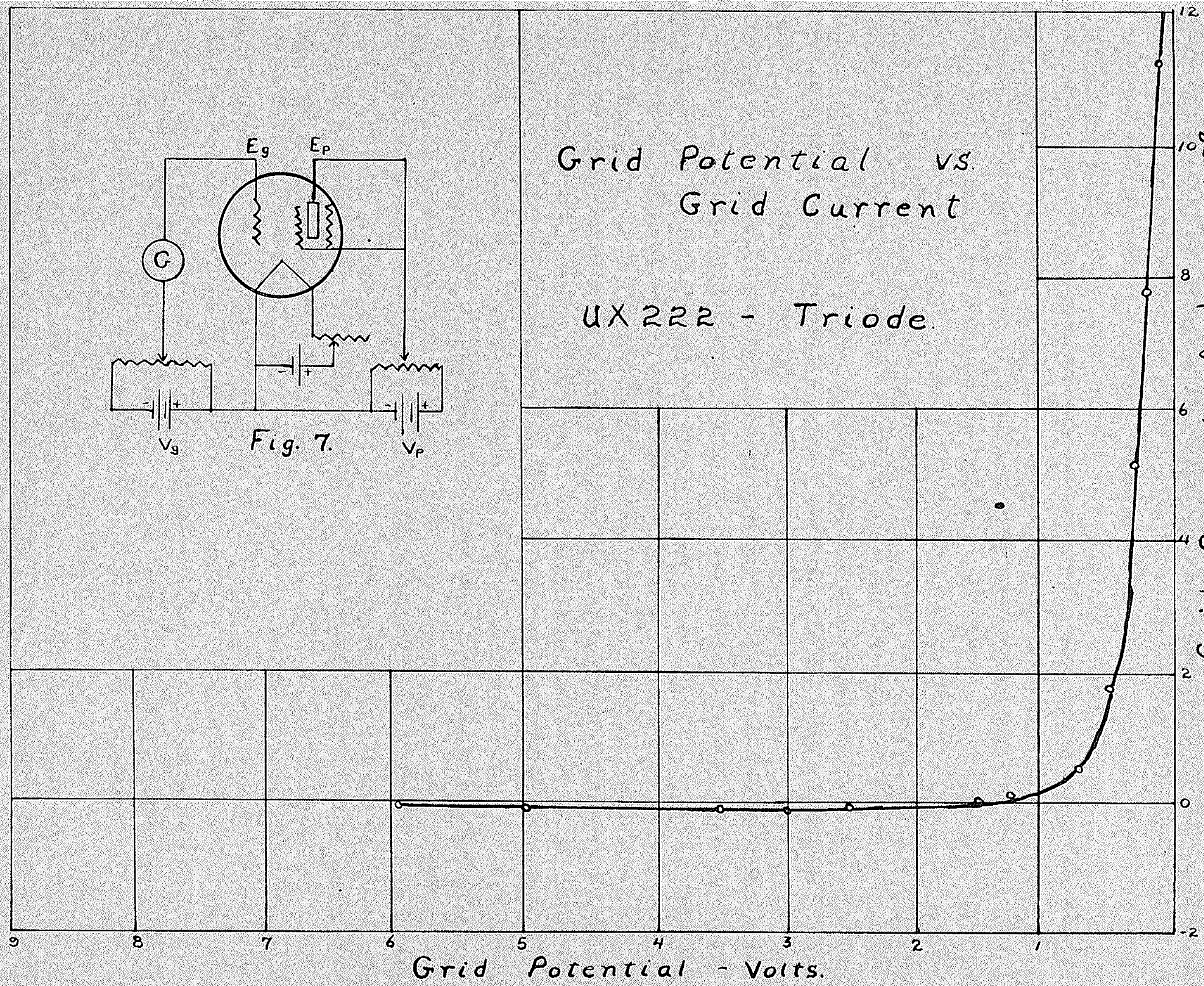

Grid Potential vs. Grid Current
UX222 - Triode.
Grid Current - Amperes x 10^{-7}
Grid Potential - Volts.
12
10
8
6
4
2
0
-2
9
8
7
6
5
4
3
2
1
E_g
E_P
G
V_g
V_P
Fig. 7.

Figure 6.

The current flowing through the galvanometer for any given value of the grid battery V_g and the plate battery V_p is made up of several components which will be given below. If the galvanometer has a low resistance, the grid potential E_g will be practically equal to V_g, but V_g and E_g will not be the same when a high resistance is introduced into the circuit.

The grid current may be considered as made up of the following componentes.[(10)]

(a) Grid to filament leakage current.

(b) Plate to grid leakage current.

(c) Positive ion current, due to the ionisation of the residual gas in the tube and the emission of ions from the filament.

(d) Electron current to grid. When the grid is only slightlynegative with respect to the negative end of the filament, a certain number of electrons are able to overcome the adverse negative potential between the filament and the grid because of the high initial K.E. of these electrons due to the high temperature of the filament.

These four factors are the main ones which make up the grid current as measured by the galvanometer and produce a curve such as is shown in Figure 6. From this curve arise two quantities (grid impedance and grid conductance) which are defined as follows.

(10) Nottingham, Jour. Franklin Inst. 209, 1930.

Grid Impedance.

This quantity is defined as equal to the reciprocal of the slope of the grid current curve at some particular point.

Thus $$Z_g = \frac{\partial E_g}{\partial I_g} \qquad \text{...............(1)}$$

Where Z_g = grid impedance.

∂E_g = small change in grid potential.

∂I_g = small change in grid current.

From Figure 6 it is seen that the grid impedance is positive for small negative values of E_g and negative for larger negative values of E_g.

Grid Conductance.

It is the slope of the grid current-grid potential curve.

Thus $$G_g = \frac{\partial I_g}{\partial E_g} \qquad \text{...............(2)}$$

Where G_g = grid conductance

B. Plate Current - Grid Potential.

The measurement of the plate current is similar to that of the grid current. Figure 8 represents schematically the circuit used in the measurement while Figure 9 represents a typical curve obtained from a UX222.

Mutual Conductance.

The slope of the grid potential-plate current curve at a constant plate potential is defined as the mutual conductance.

Hence $$G_m = \left(\frac{\partial I_p}{\partial E_g}\right)_{E_p \text{ CONSTANT}} \qquad \text{...............(3)}$$

Where G_m = mutual conductance

∂I_p = change in plate current due to

∂E_g = the small change in grid potential.

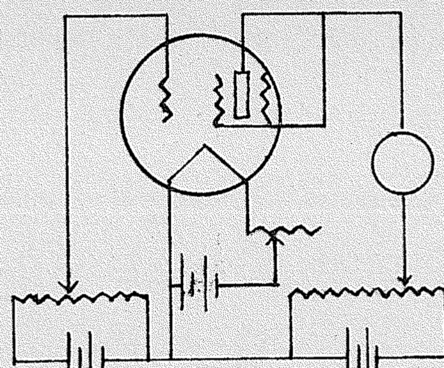


Figure 8

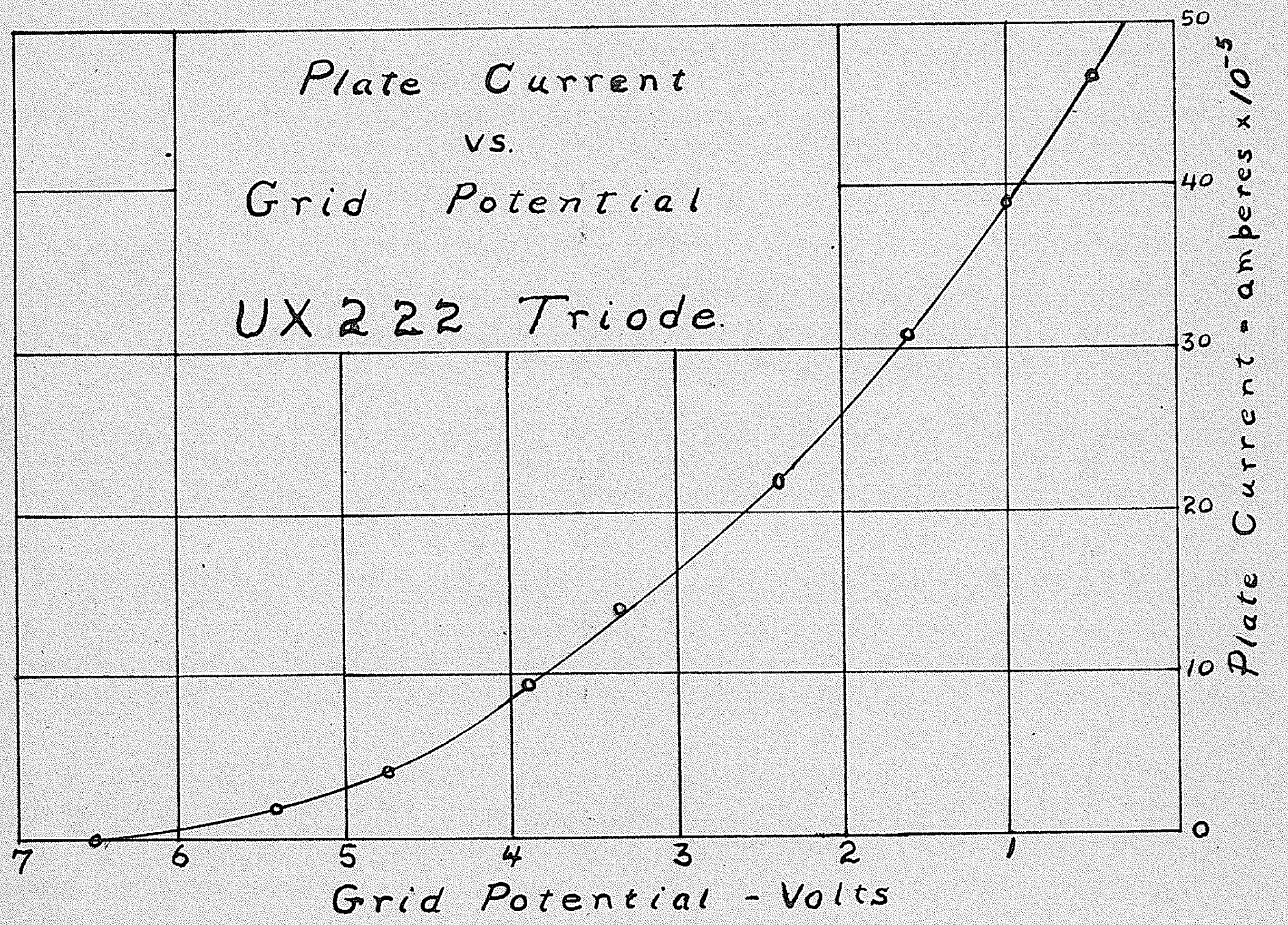


Figure 9.

The mutual conductance is a measure of the effect of the grid potential on the plate current and therefore it is desireable to have as large a mutual conductance as possible, while on the other hand the grid conductance should be a minimum to obtain sensitivity in an amplifier. In other words, the input current must raise the potential of the grid as much as possible, and this must alter the plate current a maximum extent.

Plate Impedance.

The plate impedance is defined as the reciprocal of the slope of the plate current-grid potential curve.

Thus $\frac{1}{Z_p} = \frac{\partial I_p}{\partial E_g}$ or $Z_p = \frac{\partial E_g}{\partial I_p}$ ....(4)

Amplification Constant.

The amplification constant represents the maximum voltage amplification obtainable for any tube. It depends only on the mesh of the grid, the diameter of the grid wire, and the distance between the plate and grid. It is defined algebraically by - $\mu = \partial E_p / \partial E_g$ ....(5)

The preceding discussion will give some idea of the theory and characteristics of the modern thermionic tube, leading up to a consideration of its use in direct current amplification circuits.

4. The Simple Circuit Amplifier.

Figure 10 represents the simple amplifier circuit, using a photo-cell as a source of current to be amplified.

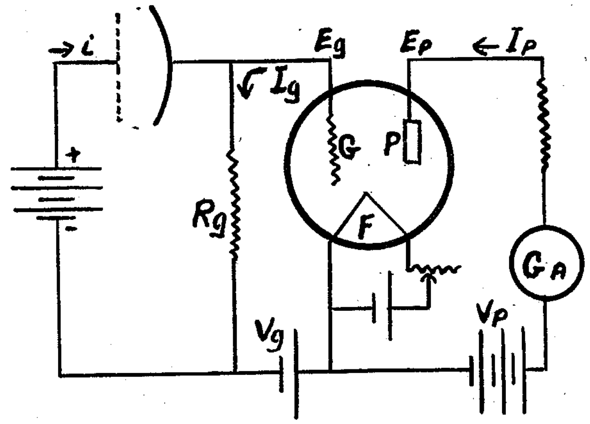


Figure 10.

This simple circuit constitutes the basis of practically all direct current amplifiers. In this circuit the steady plate current flows through the circuit PGF causing a deflection of the galvanometer G_A. When a current is forced through the input resistance Rg with an external e.m.f. it raises the potential of G relative to F, causing an increase in the plate current and a correspondingly greater deflection of the galvanometer. A study of the grid potential-plate current and the grid potential-grid current curves, with the operating resistance in the plate circuit, enables the prediction of the manner in which the plate current of the tube depends on the grid potential i.e. the sensitivity of the circuit can be determined. The sensitivity is defined as the change in the plate current corresponding to a small change in the grid potential.

$$S_v = \frac{\partial I_p}{\partial E_g} \qquad \text{...............(6).}$$

Where S_v = sensitivity to voltage.

∂I_p = change in the plate current.

∂E_g = change in the grid potential.

The Computation of Sensitivity to Voltage.

The expression for the plate current in a vacuum tube circuit is given by[11]

$$I_p = \frac{1}{Z_p}\left(E_p + \mu E_g + E_o\right) \qquad \ldots\ldots\ldots\ldots(7)$$

Where E_p = plate potential

E_g = grid potential

E_o = constant.

μ = voltage amplification.

Z_p = plate impedance.

The Kirchoff Law equation fo~~t~~r the plate circuit is

$$E_p = V_p - R_p I_p \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Where V_p = "B" battery potential.

R_p = resistance in the plate circuit.

E_p = plate potential

I_p = plate current.

From equation (7)

$$E_p = I_p Z_p - \mu E_g - E_o$$

(11) Nottingham, J.O.F.I. 209, 1930.

Substitutimng for E_p in equation (8)

$$I_p Z_p - \mu E_g - E_o = V_p - R_p I_p$$

$$I_p(Z_p + R_p) = V_p + \mu E_g + E_o$$

$$I_p = \frac{V_p + \mu E_g + E_o}{Z_p + R_p}$$

$$= \frac{1/Z_p(V_p + \mu E_g + E_o)}{1 + R_p/Z_p}$$

Differentiate

$$S_v = \frac{\partial I_p}{\partial E_g} = \frac{\frac{\mu}{Z_p}}{1 + \frac{R_p}{Z_p}} = \frac{G_m}{1 + \frac{R_p}{Z_p}} \quad \text{.....(9)}$$

μ , Z_p and E_o have been treated in the above as constants, the legitimacy of which being based on the fact that the final equation and the experiments check for small variations. If R_p is very small compared with Z_p the sensitivity is equal to the mutual conductance G_m but if R_p is not small then the sensitivity is less than G_m because Z_p is always positive.

If we suppose that a drop in potential across the grid resistance R_g is caused, it will, of course, be impressed on the grid of the vacuum tube. The resulting change will cause a deflection "d# of the galvanometer which has a sensitivity of S_g mms./ampere.

$$\text{Then } \frac{d}{S_g} = \Delta i_p = G_m \Delta E_g \quad \text{.............(10)}$$

where Δi_p and ΔE_g are the changes in the plate current and grid potential respectively.

The sensitivity to voltage in mm/volt of this amplifier is therefore $S_V = \dfrac{d}{\Delta E_g} = \neq G_m S_g$ ....(11)

Thus to get a high sensitivity to voltage a vacuum tube having a high mutual conductance should be used with a sensitive galvanometer.

The sensitivity of an amplifier is limited by its freedom from irregular disturbances[12]. These arise from three causes.

<u>Sources of Irregularities</u>.

(1) External to Apparatus.

The circuit is very sensitive to high frequency disturbances. This source can be removed by enclosing the apparatus completely in a conducting shield preferably earthed; but the enclosure must be complete, and, in the last resort, must contain the whole apparatus including the batteries.

(2) Batteries.

Changes in the potential between the grid and the filament will be amplified; whether they are caused by the current from the photo-cell or by changes in the voltage of the batteries. The constancy of the grid bias battery is most important, the filament battery scarcely less so. Changes in the filament battery produce changes in the effective grid voltage, partly because this depends somewhat on the velocity of the emission of the

(12) Campbell and Ritchie, Photo-Electric Cells 138.

thermionic electrons, which depends on the temperature but more because the cathode is not all at the same voltage, but covers the whole range of voltages applied to it. Variations in the plate voltages are somewhat less important for these are reduced effectively by the magnification factor of the valve.

Slow, regular variations of the voltages as the batteries run down are unavoidable, but usually of little importance. Trouble arises only from rapid and irregular changes.

(3) Thermionic Emission of Valve Filament.

This effect is caused by minute changes in the surface residual gas. Any alteration of the electric field or the temperature of the filament may shift this gas to or from the surface of the filament and change the emission of all or part of it, and therefore, change the relation of plate current- grid potential or grid current-grid potential. The anode current is determined by past as well as present conditions and when the amplifier is first put into action or started again after rest, it may change continually for a period of many hours.

5. <u>The Simple Circuit with Battery Compensation.</u>

It will be apparent that in order to use a circuit of this type, the increment of the galvanometer deflection caused by the current through the grid resistor must be sufficiently great to be perceptible. That is, the amplified current must approximate the same order of magnitude as the plate current, hence the smaller the plate current the more sensitive the amplifier, all other factors being constant.

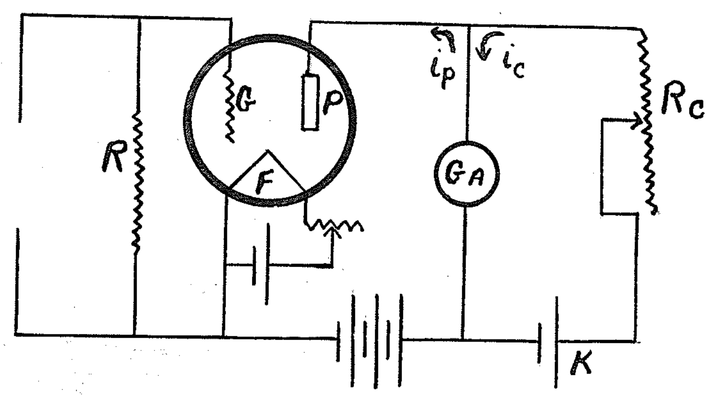


Figure 11.

The usual method of reducing the plate current flowing through the galvanometer is to hold all other factors constant and apply a back e.m.f. to this instrument from an auxiliary source. Figure 11 shows a circuit exhibiting in its simplest form this principle. The auxiliary battery K causes a current, the magnitude of which is controlled by the resistance R_c, to flow through the galvanometer in the opposite direction to the plate current, which is thus balanced out of the circuit allowing the galvanometer to record only the amplified current. As a result this instrument may then be increased in sensitivity, a limit being placed only by the degree of exactitude and constancy of the balance.

6. <u>Wheatstone Bridge Circuit.</u>

Another method of arranging an amplifier circuit so that no current flows through the galvanometer for the zero condition but does flow when this condition is disturbed comes directly from the simple Wheatstone Bridge circuit.

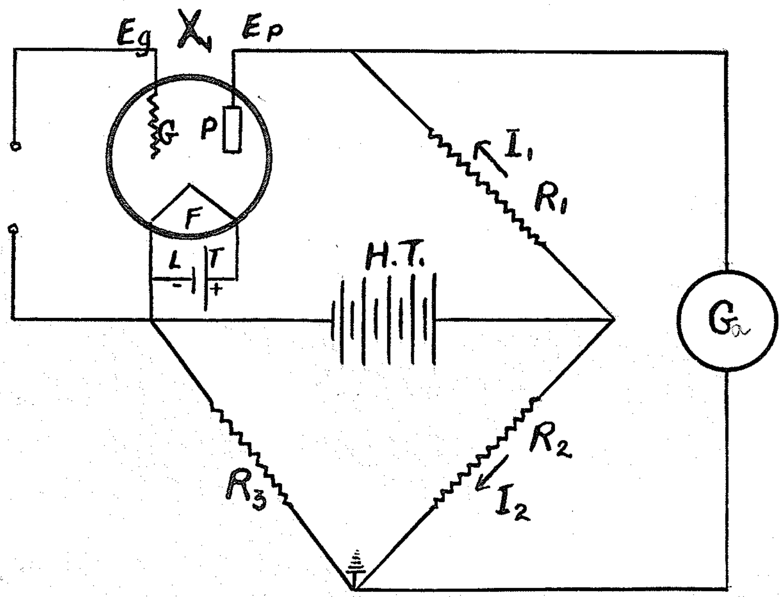


Figure 12.

The usual circuit employed[13] is shown in Figure 12. In series with the plate P of the valve is placed a resistance R_1, of the order 10^4 ohms, while two other variable resistances, R_2 and R_3 are connected in series across the high tension battery H.T., supplying the plate current. The input circuit is connected to the grid, and the negative of the low tension battery L.T., supplying the filament heating current, is usually connected to earth. The galvanometer, G_a, is connected between the plate and the junction of R_2 and R_3.

Denoting the currents in R_1 and R_2 by I_1 and I_2, the galvanometer will be undeflected if the relation $R_1I_1 = R_2I_2$ is satisfied. Alternatively, denoting the impedance of the valve

(13) Proc. Camb. Phil. Soc. Vol.XX111 1927.

to the plate current by X_1, and regarding the system as a Wheatstone Bridge, balance will be obtained when

$$R_1/R_2 = X_1/R_3 = I_2/I_1.$$

Any change in the potential of the grid alters the value of I_1 (or of X_1) and so throws the system out of balance giving rise to a galvanometer deflection which, it can be shown, is proportional to the change of grid potential.

While such a system has a large current amplification factor, an early limit is set to the minimum current that can be measured by it by the unsteadiness of the zero, and no advantage is to be gained by using an extremely sensitive galvanometer unless the system can be stabalized.

The unsteadiness of the zero is mainly due to the small changes of the plate current I_1 produced by small fluctuations of the voltage of the low ~~an~~ high tension batteries. In other words, the impedance X_1 of the valve is not constant, but a function of these batteries. Hence if R_1, R_2 and R_3 are constant any change in X_1 produced by battery voltage fluctuations will result in the system becoming unbalanced.

This unsteadiness can be overcome to a certain extent by using another valve as shown in Figure 13, similar to the first, and of impedance X_2 to replace R_3 of Figure 12. The first valve only is used as an amplifier, the second being idle. With two perfectly matched valves, the debalancing effects produced by battery fluctuations would cancel out. No two valves, however,

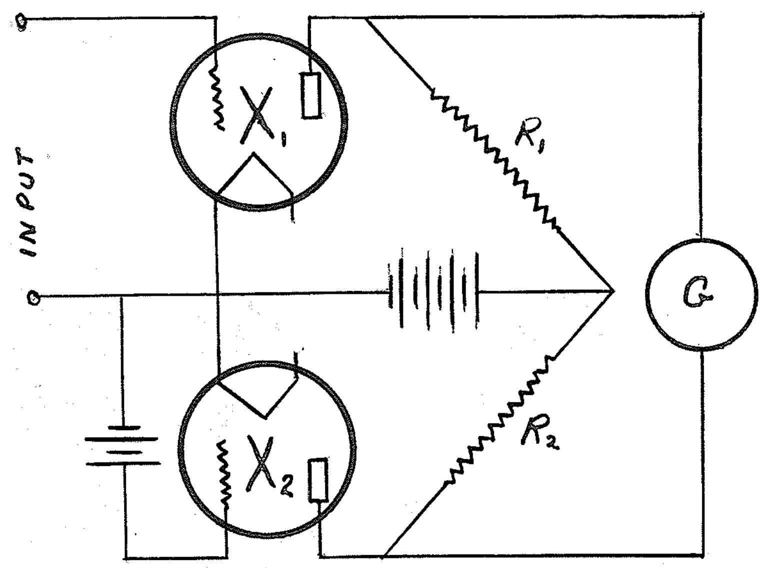


Figure 13.

have characteristics sufficiently similar to give perfect compensation in this manner, although this circuit is a decided improvement over that shown in Figure 12.

The bridge circuit differs from that of the battery compensation method only in that the plate current of a second v valve has been substituted for the current of the auxiliary battery.

In the next chapter a discussion of the changes and improvements of the bridge circuit will be given in detail.

7. Resistance - Impedance Circuit.

The battery compensation and bridge methods of balancing out the plate current enable S_g in equation (11) to be increased, the G_m, however, remains constant. In 1933 MacDonald and MacPherson[14] described a circuit in which G_m has been in-

(14) Phil. Mag. vol. XV. Jan. 1933.

creased and S_g kept constant.

The phenomenon upon which they based their new circuit is that the direction of flow of the grid current alters at a definite value of the grid potential, that is, at a certain negative potential of the grid relative to the negative side of the filament, the grid current is zero, with more positive values, the electron flow is from the filament to the grid, while with greater negative potentials the direction of flow is reversed. This phenomenon is due to a flow of positive ions to the grid and the repulsion by it of the filament electrons.

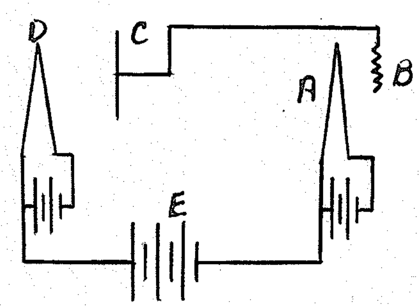
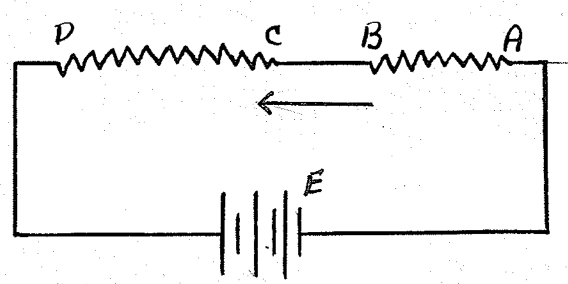
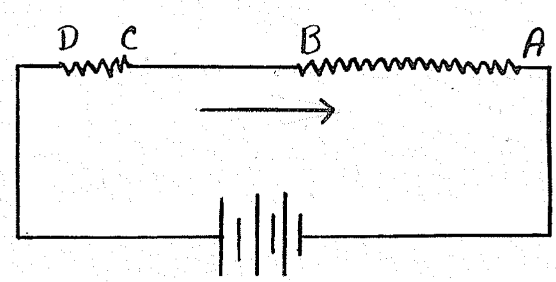


Figure 14 a



14 b



14 c.

Suppose we have a circuit such as shown in Figure 14 (a) where AB represents the filament and grid of the above tube and CD the plate and filament of a second tube which will allow the electrons to flow from D to C but not in the reverse direction. If the potential of B is greater than the potential when there is no grid current, the direction of current flow will be that of Figure 14 (b) since the electrons flow from the filament A to the grid B and encounter the maximum resistance between plate C and filament D. However if B is given a potential less than the zero grid current potential, the current is reversed in direction, the positive ions flowing to the grid being equivalent to a flow of electrons from B to A. The resistance of DC to electrons moving in this direction is relatively low, while that of BA is increased. Thus in Figure 14 (b) the major drop in potential of the battery E is across DC, while in Figure 14 (c) it is practically all impressed between the grid and filament of the first tube. The manner in which a small potential change at B may control the location of the potential drop due to E in such a circuit was investigated with the result that a stable amplifier, shown in Figure 15, of high voltage sensitivity was obtained.

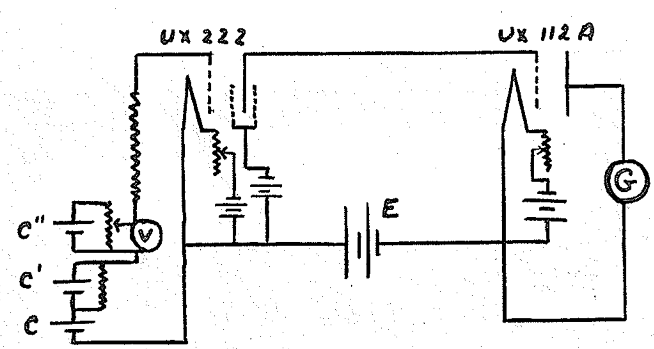


Figure 15

CHAPTER II

DEVELOPMENT OF DIRECT CURRENT AMPLIFICATION .

The previous chapter has been devoted to a brief outline of the types of direct current amplifiers and their principles. In this chapter the recent developments of each type will be given in detail together with additional theory wherever necessary for a complete understanding of their theory and operation. The first part of chapter 1 was devoted to a discussion of thermionic vacuum tubes, their characteristics, construction and function. It is logical, therefore, to begin this chapter by a discussion of a new thermionic tube, the FP 54, developed with the purpose of overcoming some of the difficulties encountered in the use of ordinary commercial tubes in direct current amplification.

1. The FP 54.

In the ordinary tube circuits the external resistance R_g is shunted by the grid resistance Z_g, of the tube itself, and hence the total resistance cannot be made greater than Z_g. Also at ordinary operating voltages Z_g is not greater than a few hundred megohms, due to the insulation leakage in the tube and to the collection of positive ions by the grid. Therefore the first requirement of a tube for direct current amplification is that the input resistance is high or that the grid currents in the tube, under normal operating conditions, are very small. It was this condition that Metcalf and Thompson[15] in the con-

(15) Phys. Rev. Nov. 1st. vol. 36, 1930.

struction of the FP 54 were able to satisfy.

The grid current in a high vacuum tube, when the grid is sufficiently negative to repel all electrons may be due to any or all of the following causes:

(1) Leakage over glass or insulation.

(2) Ions formed by gas present in the tube.

(3) Thermionic grid-emission due to heating of grid by filament power.

(4) Ions emitted by the filament.

(5) Photo-electrons emitted by the control grid under action of soft X-rays, produced by the normal anode current.

Leakage over insulation is relatively small compared to the other currents and may be reduced to a minimum by the usual methods. It was found thatvwith the highest obtainable vacuum the positive current was greater than 10^{-13} ampere, if operating above ionisation potential. If the voltage was below 8 volts no ionisation current was produced. Any effects of the grid heating could be eliminated by using low filament power.

Smith(16) and Wahlen (17) showed that positive ions are emitted by a hot filament in large numbers. These ions are drawn to the negative control grid and may amount to as much as 10^{-12} ampere from a small tungsten filament. To overcome this positive space charge, a grid is placed between the filament and control grid which repels all ions since it is operated at a positive

(16) Phys. Rev. 35, 1930.
(17) Phys. Rev. 34, 1929.

potential. This space charge grid, as it is called, also increases the mutual conductance of the tube.

Under action of light from the filament, no photo-electrons are emitted by pure nickel or molybdenum grids, but there is invariably enough contamination to cause an appreciable current. This effect is greatly reduced by using thoriated filaments operated at a low temperature. Also by using low anode voltages, the currents produced by the effect of soft X-rays are reduced to an inappreciable value.

The tube finally developed by Metcalf and Thompson, after taking all these considerations into account, is a space charge grid tube. The control grid is brought out at the top of the bulb while the other elements terminate in the base. The control grid is mounted on quartz beads, shielded to prevent contamination of the surface. The filament is of thoriated tungsten and consists of two legs in parallel to keep the voltage low.

The most desireable operating characteristics of the tube are as follows:

Filament voltage	2.5	Amplification factor	1
Plate voltage	6.0	Plate resistance	40000 ohms
Control grid voltage	-4.0	Sensitivity;	10^{-17} amp
Space charge grid	4.2		2.56^{-6} mm/volt
Filament current	100 ma		
Mutual conductance	25 ua/v		
Plate current	40 ua.		

2. The Simple Circuit.

In 1930 L.A.DuBridge [18] examined the standard amplifier circuits then in existence using the FP 54 to investigate its possibilities and limitations under actual working conditions. The first circuit examined was the simple circuit described in chapter 1. Slight modifications were necessary due to the fact that the FP 54 is a four-element tube. In addition to modifying the circuit he shunted the galvanometer with an Ayrton shunt and balanced out the plate current through the galvanometer by means of an auxiliary battery and rheostat.

Figure 16 shows the circuit as used by DuBridge and indicates the changes required to use an FP 54.

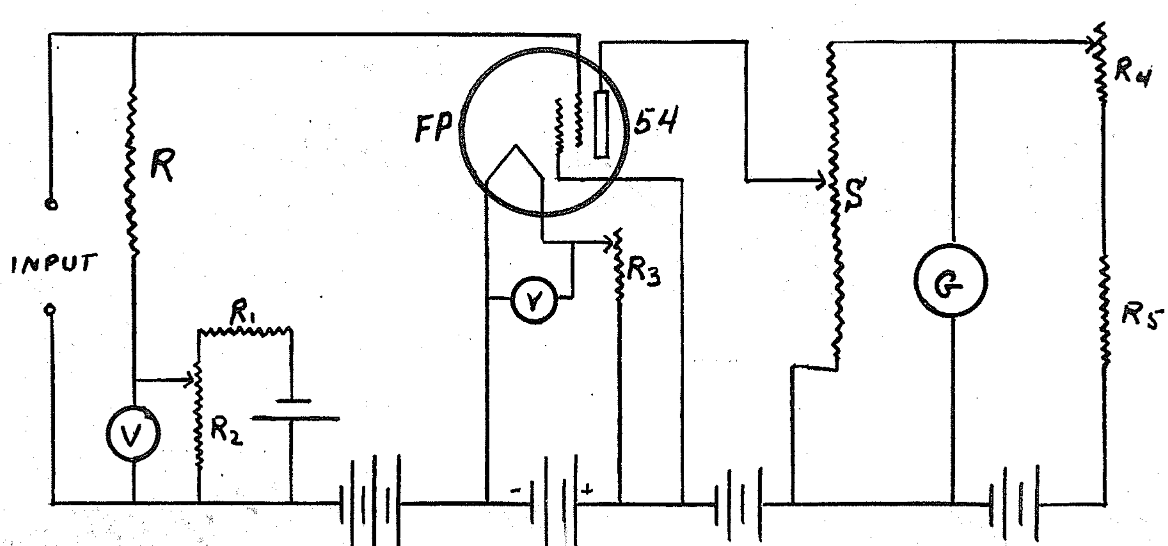


Figure 16.

(18) Phys. Rev. vol. 37, 1931.

The method of operation is as follows; with the tube operating at normal voltages the galvanometer is made to read zero by adjustment of the rheostat R_4. The voltage sensitivity of the circuit is then determined by applying to the control grid a series of known voltages by means of the potential divider, R_2 and observing the corresponding deflections. If the deflection is then measured for an unknown input current i, the magnitude of i can at once be determined if R is known. There is a linear relation between galvanometer deflection and input voltage as long as the latter does not exceed 300 millivolts, in spite of the fact that the tube does not operate on the straight portion of its characteristic.

The highest voltage sensitivity which can be obtained with such a circuit is limited by the fluctuations due to changes in battery voltages and other causes. By using large storage batteries for the voltage supply and by careful shielding it has been found possible, with a very sensitive galvanometer, to obtain a voltage sensitigity in excess of $2x10^{-5}$ v/mm. The drift in such a circuit was found normally to be very constant and approximately 7.7 mm/sec.

From what has already been said of direct currents it will be apparent that the controlling factor for voltage sensitivity with this type of amplification is the magnitude of the plate current which should be as small as possible. However in examining the work of investigators with direct currents it is noticed that in practically all cases the operating constants used with valves are those recommended by the manufacturers for alternating-current work. In this field, since the relative magnitudes of the plate and amplified currents are of no particular importance, large operating potentials would be used in order to obtain the maximum output.

MacDonald and Tweed [18] investigated the simple circuit, using commercial vacuum tubes, with the purpose of showing that there exist operating constants which give a great deal higher sensitivity than is usually obtained. In addition they demonstrated a method of using large input resistances with radio valves of the screen grid type.

The sensitivity to voltage of the simple circuit is given by

$$S_v = G_m S_g.$$

where S_v is the voltage sensitivity, G_m the mutual conductance and S_g the galvanometer sensitivity.

With this circuit the galvanometer sensitivity must be adjusted to suit the plate current and in this case was always kept such that the initial plate current caused a 50% deflection of the total scale length. In computing the sensitivity in amps/mm. a total scale length of 50 cms. was employed, the value of the plate current used, being the lowest it was possible to obtain and remain in the region of linear mutual conductance.

(18(Physics Mag. page 178, May 1933.

Under these conditions a factor proportional to the voltage sensitivity will be given by substituting the reciprocal of the plate current for the galvanometer sensitivity in the above equation. However, while the mutual conductance is determined by the mechanical constants of the valve, it is also a function of the filament and plate potentials, in general decreasing as they decrease. The sensitivity on the other hand, being inversely proportional to the plate current, increases with lower operating potentials, so that the maximum voltage sensitivity will be obtained when the quotient of the mutual conductance by the plate current is a maximum. Examination of this quantity was made and it was found that the galvanometer sensitivity increased more rapidly than the mutual conductance decreases, as the operating potentials are lowered.

The investigators employed a UX222 of the four-element screen grid type with the control grid at the apex. This tube can be operated with the screen grid connected to the filament, at a potential positive to the filament or tied to the plate.

(a) Screen Grid Tied to the Plate.

They found that the effect of decreasing the filament voltage at any one plate potential was in general to increase the voltage sensitivity. The effect was most marked at the extremities of the permissible range of variations and thus in order to obtain maximum efficiency with stability, it is desireable to operate at potentials slightly in excess of the lower extreme. Having thus determined the most desireable filament potential for any plate potential they determined by examination the most efficient plate potential, the results being shown in Figure 17. They discovered that the lower the plate voltage the greater the sensitivity of the unit save with zero volts on the plate where the sensitivity drops off slightly. With the particular tube examined the sensitivity was found to rise from 3×10^{-2} volt/mm. at 90 volts on the plate to 5×10^{-4} v/mm. with 1.5 volts on the plate.

(b) <u>Tube as a Screen Grid. Plate at Zero Potential</u>.

A family of grid potential vs. plate current curves were run for different screen grid potentials with no battery in the plate circuit. These curves were found to shift to regions of lower negative bias with increasing screen grid potential. From an examination of these curves shown in Figure 18 it was apparent that increasing the screen grid potential does not alter the value of the maximum mutual conductance but that it does cause this section of the curve to shorten. An upper limit is thus placed on the value of the potential that may be employed and it was found to be slightly in excess of 6 volts.

The manner in which the screen grid affected the grid current curve was then examined and this curve was found to be moved toward the origin as the screen grid potential was increased although not to the same extent that the plate current curve was moved away. These two findings showed the value of employing a screen grid, and an amplifier constructed on the

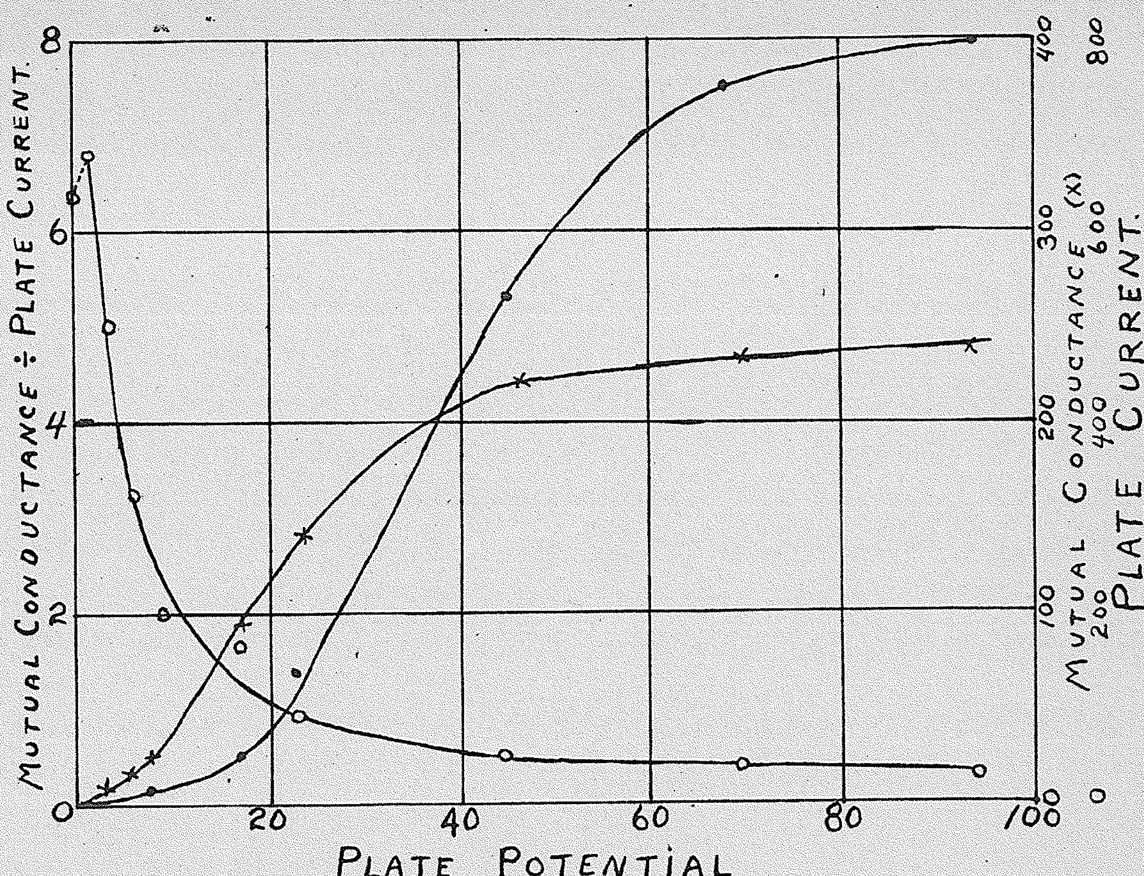


FIGURE 17.

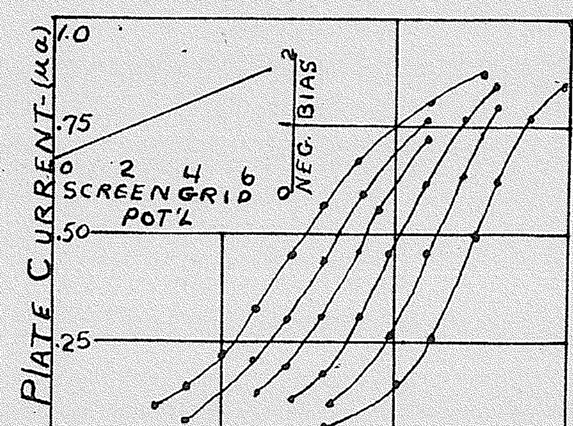


FIGURE 18.

above lines gave a voltage sensitivity of $4x10^{-3}$ v/mm. The constants of such an amplifier are :

Screen grid	6 volts	Input resistance	10^{-10} ohms.
Filament	2 "	Mutual conductance	$.36x10^{-6}$ amp/volt.
Plate	0 "	Current sensitivity	$4x10^{-13}$ amp/mm.
Control grid	-2 "		

(c) Higher Plate Potentials.

With a small potential applied to the plate the effect of the screen grid potential on the plate current was found to be different from that when no plate potential was applied. As the screen grid was made more positive both the plate current and the mutual conductance were increased. An examination of the relative rates of increase showed that with higher values of the screen the ratio of the mutual conductance to the plate current decreased. Hence, provided the plate potential is less than the screen grid potential, the screen grid in a four-element tube alters the plate characteristics in the same manner as did the plate potential discussed in part (a). Thus in order to retain high voltage sensitivity, low screen grid potentials must be employed to give a low plate current in order to work on the linear section of the curve. The use of a high screen potential to obtain a high grid-filament resistance is thus prohibited.

A further investigation lead to the conclusion that, with a small potential applied to the plate, increasing the screen grid potential does not alter the voltage sensitivity provided that in this case the negative bias is increased sufficiently to offset the resulting increase in plate current, which means that the valve is not operated on its linear section of plate current.

Operating the valve in this manner, that is on the negative end of the plate current curve allows the same ratio of slope to plate current to be obtained with high screen grid potentials as with low and the high input resistance resulting from high screen grid values is retained.

The constants of an amplifier operated on this primciple are:

Filament potential	1.25 volts
Plate potential	1.5 "
Screen grid pot'l.	12 "
Galvanometer sensitivity	2.8×10^{-10} amp/mm.
Mutual conductance	$.35 \times 10^{-6}$ amp/volt.
Input resistor	10^{12} ohms.
Voltage sensitivity	8×10^{-4} volt/mm.

This investigation leads to the conclusion that ordinary radio valves are quite satisfactory for many types of direct current amplifiers provided suitable operating constants are used, these constants being considerably lower than those recommended by the manufacturer.

3. The Bridge Amplifier.

Wold[19] in 1916 first recognized the principle of compensating the plate current of an amplifying valve by the plate current of a second similar tube, the grid of which is main-

(19) U.S. Patent No. 1232879, 1916-17.

tained at a fixed potential, when he described an amplifier consisting of a Wheatstone Bridge arrangement, the amplifying tube in one arm and the balancing tube in the other. In 1921 J.Bretano [20] published a paper in which he described a method of measuring ionization currents by means of three-electrode valves in a bridge circuit, the measurements being made by the steady deflection galvanometer method. The advantages of measuring ionization currents by means of valves had been previously pointed out by Malassez [21].

Figure 19 represents schematically the arrangement of Bretano's apparatus which is similar to that described in chapter 1 and is equivalent in all essential points to the circuits of this same principle developed later.

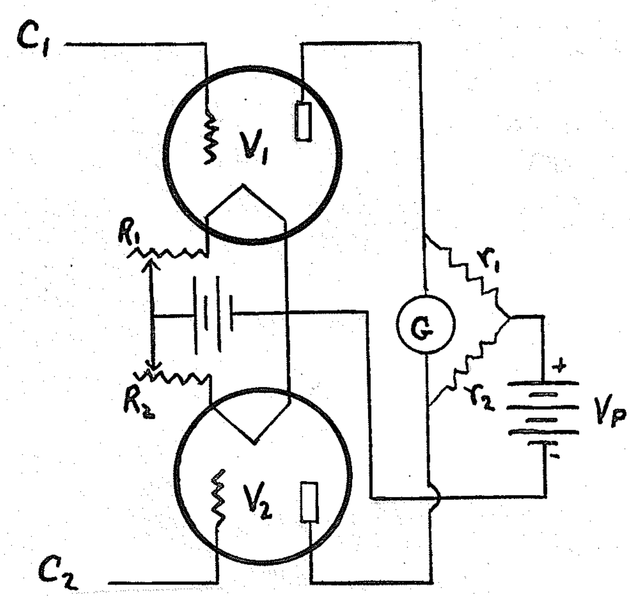


Figure 19.

(20) Nature, December 22, 1921.

(21) Comptes Rendus, vol.172, 1921.

The plates of the valves V_1 and V_2 are connected through equal resistance r_1 and r_2. One terminal of each of these resistances is connected to the positive pole of the battery V_p, the other terminals are connected through the galvanometer G. The resistances R_1 and R_2 regulate the heating currents through the filaments. Each grid can be connected to the positive plate of an ionization chamber through the leads C_1 or C_2.

The heating currents are set so as to give equal plate currents through both valves when the grids are insulated. When, owing to the ionization current, one grid receives a charge, the plate current through the corresponding valve is altered and the galvanometer is deflected. Then an ionization current acting on the grid of the balancing tube causes a deflection of the galvanometer in the opposite direction. Inequalities in the valves can be corrected by interposing an e.m.f. in one of the valve circuits by means of a battery and resistance. When used in this way, fluctuations in the heating currents and in the plate potentials are reduced owing to the fact that the heating currents for the filaments and plate voltages are supplied from the same source for both valves.

With this circuit Bretano obtained a current sensitivity of 3×10^{-13} amp/mm. and a voltage sensitivity of 1.2×10^{-4} v/mm. in spite of the fact that only soft tubes were used.

In 1927, six years later, Wynn-Williams[22] published a description of a bridge amplifier "capable of giving useful

(22) Proc. Camb. Phil. Soc. vol. XX111, 1927.

consistent results for a variety of purposes where an electrometer would normally be used." This circuit, as illustrated in Figure 20, is similar to that shown in Figure 19. In his circuit Wynn-Williams modified that of Bretano by the substitution of 30 cms. of Eureka wire EF connected to the filaments, for the variable resistances R_1 and R_2 of Figure 19.

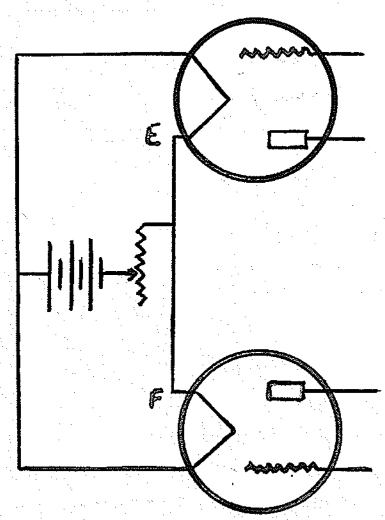


Figure 20.

In 1928 Williams[23] published a modification of his circuit giving certain precautions as to shielding etc., in order that the circuit could be applied to the ,easurement of any direct current of the magnitude $10^{-12} - 10^{-13}$ ampere no matter what their source. His method as stated before, was almost identical to that of Bretano's, the current sensitivity was not increased, being only $10^{-12} - 10^{-13}$ ampere and the scale was found not strictly linear. However, the slide wire resistance which he used to replace R_1 and R_2 of Figure 19 gave greater ease of adjustment for filament battery fluctuations.

(23) Phil. Mag. August 1928.

In 1929 Brentano[24] criticized Wynn-Williams' publication of August 1928, in which Williams stated his improvement of Brentano's circuit was one of vital importance. However his results were no better than Brentano's who claimed that the so-called improvement was only a question of technical execution. Brentano stated that the limits of sensitivity obtained by Williams were actually imposed by the unsteadiness of the arrangement. Wynn-Williams neglected the increase of the capacity of the one grid when connected to the ionization chamber. These capacities obviously should be of the same order of magnitude the exact values depending upon the characteristics and insulation of the grids.

In the same publication Brentano described a bridge amplifier using hard vacuum tubes, which were not available at the time of his work in 1921. With this circuit, shown in Figure 21, he obtained a voltage sensitivity of 2×10^{-5} volt/mm. and a current sensitivity of 4×10^{-14} amp./mm.

The essential changes of this circuit compared with former ones are; the use of valves of the screen grid type to get greater stability; the inner grid of the compensating tube is connected to a potentiometer through a high resistance, and a condenser of variable capacity is placed in parallel to compensate for the capacity effect produced by external fields.

In 1929 J.M.Eglin[25] published a paper in which he described

(24) Phil. Mag. Page 685, 1929.

(25) J.M.Eglin, J.O.S.A. 1929.

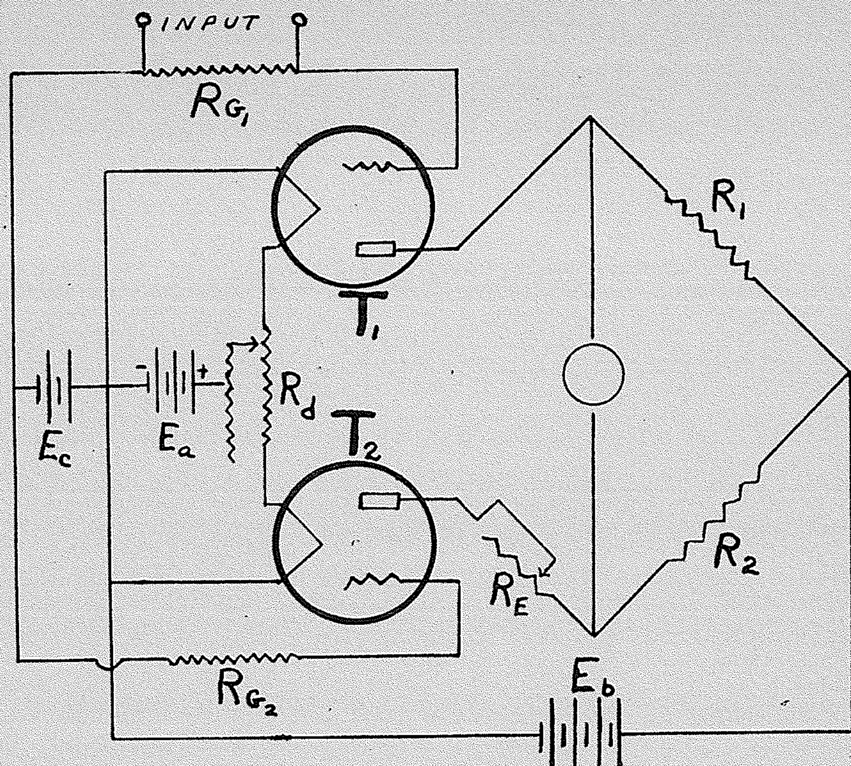


FIGURE 22

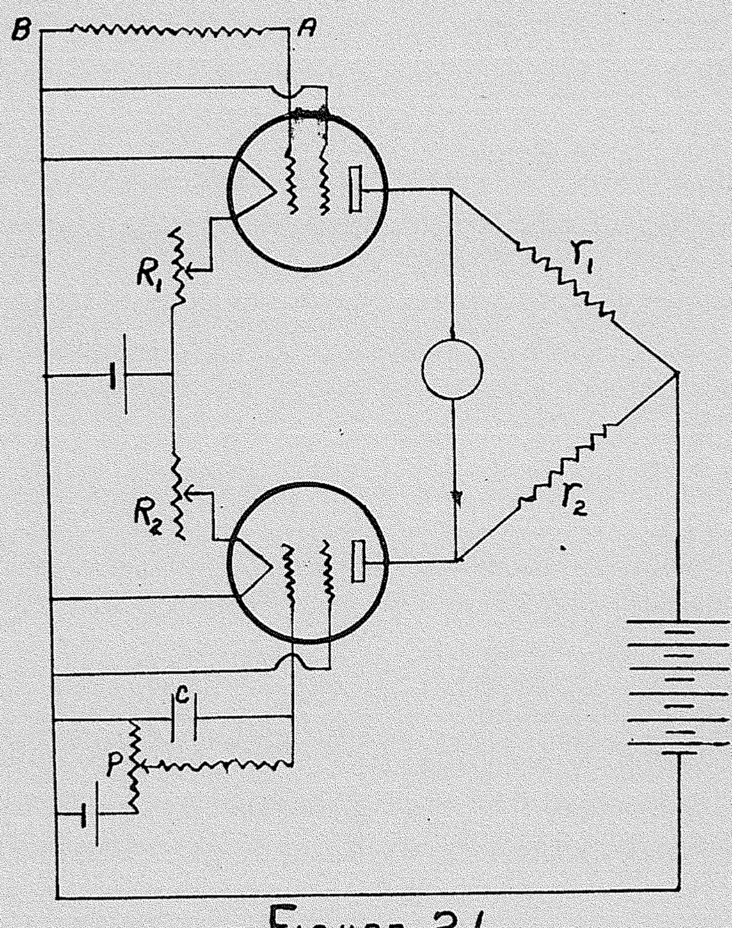


FIGURE 21.

a bridge amplifier offering further improvements over previous amplifiers of the same type using ordinary radio valves. The improvements are a result of the following modifications:

(1) The insertion of a resistance in series with the tube in one arm of the bridge to compensate for variations in plate and grid battery voltages.

(2) The suspension of the tubes to protect them from mechanical vibrations.

(3) The use of tubes with pure tungsten filaments to avoid changes in contact potentials, and with plates enclosing the filaments completely to lower the effects of wall charges.

Figure 22 is a schematic diagram of his circuit. In the circuit Wynn-Williams chose to employ, he connected one terminal of the input to the grid of one tube, and the other terminal to the filament of that tube. This essentially made the leakage between grid and filament a portion of the input circuit. Eglin preferred to have a known and definite resistance introduced by the amplifier into the input circuit, especially since it is possible at the same time to set the grid at a definite negative voltage. This can be done by the use of a grid resistance R_{g1} and a grid battery E_c as shown in Figure 22. The same grid battery and a similar resistance R_{g2} are used with the other tube.

The tube T_1 takes a voltage obtained from a small current passing through a high resistance in the grid circuit, and effectively transfers this voltage (amplified by the action of the tube) to the plate circuit. In this latter circuit, which has a much lower resistance, a much larger current is thereby produced.

The grid battery E_c is made sufficiently large so that the electron current to the grid is negligible. Eglin considered this grid current too small to necessitate a consideration of the changes in the grid current produced by changes in the grid voltage, which would result in the amplifier depending for the constancy and reliability of its amplification factor upon a grid current-grid voltage characteristic. Then the variation of the plate current would be due only to the departure from linearity of the plate current-grid voltage characteristics of the tubes, and the fluctuations of the potential supplies.

The changes in the filament voltage may vary the effective grid voltage with respect to different parts of the filament. These changes are compensated for by the insertion of a resistance R_d. Plate voltage fluctuations are compensated for by a resistance R_e in series with the second tube.

Razek and Mulder[26] further improved the above circuit by the addition of special high grid resistors, made of xylol and alcohol sealed in glass tubes, in the grid circuit of each tube. The advantages of this type of bridge amplifier, called the grid resistor amplifier are;

(1) It employs ordinary commercial tubes selected only for

(26) J.O.S.A. and R.S.I. vol.19, 1929.

high internal insulation.

(2) It allows these tubes to be operated at any point on their characteristics.

(3) It makes use of the ionization currents to obtain high sensitivity.

(4) It allows complete and readily attainable compensation for all battery voltage fluctuations.

Eglin's circuit permitted compensation only for filament and plate battery fluctuations while Razek and Mulder went one step further by permitting grid battery compensation by the addition of the high grid resistors.

The voltage sensitivity obtained with this circuit was 10^{-5} volt/mm. and the current sensitivity 7×10^{-15} amp/mm.

It is evident from what has already been said about bridge amplifiers, that considerable success has been obtained with the use of ordinary radio tubes in these amplification circuits. The difficulties encountered are due largely to the fact that all thermionic tubes have been designed for the amplification of rapidly varying currents, and therefore possess characteristics undesireable for direct current work.

When Metcalf and Thompson designed the FP 54 (described at the beginning of this chapter) investigators examined its possibilities in the existing types of direct current amplifiers. L.A.DuBridge [27] used it in the bridge circuit with signal success obtaining a voltage sensitivity of 4×10^{-6} volt/mm.,

(27) Physical Rev. vol 37, 1931.

and a current sensitivity of 4 x 10^{-16} amp/mm. In addition he found that currents as small as 5 x 10^{-18} amp/mm. could be detected although not accurately measured.

The circuit used by L.A.DuBridge was essentially that used by Brentano and Eglin (which have already been described) except for the slight modification required because of the space charge grid.

4. Resistance - Impedance Circuit.

MacDonald and Campbell[28] while investigating the circuit published by MacDonald and MacPherson[29] discovered that if the grid filament system of a second thermionic tube be substituted for the resistance R_p, Figure 23, of the simple circuit amplifier, that a two tube amplifier of high voltage sensitivity, using ordinary radio valves, would result.

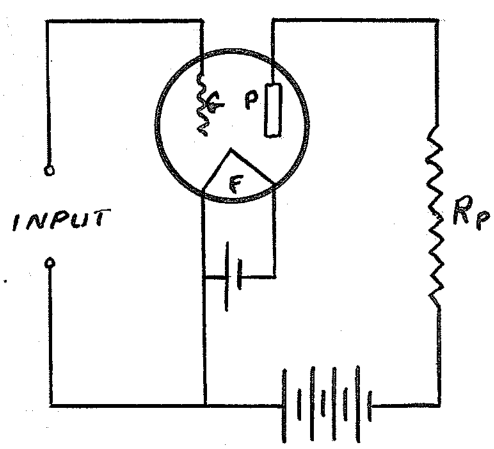


Figure 23.

(28) Physics, July, 1933.

(29) Phil. Mag. vol. 15, 1933.

The analytical expression for the change in plate current resulting from a change of the potential impressed upon the control grid of a thermionic tube connected as in Figure 23 is

$$\frac{\partial I_p}{\partial I_g} = \frac{G_m}{1 + \frac{R_p}{Z_p}} \qquad \ldots\ldots(9)$$

where i_p is the plate current, E_g the grid potential, G_m the mutual conductance of the tube, Z_p the filament-plate resistance of the tube and R_p the value of the resistance in the plate circuit.

Then, if as in Figure 24, the grid-filament system of a second tube be substituted in place of the ohmic resistance R_p of Figure 23 it will be possible to give R_p a negative value by

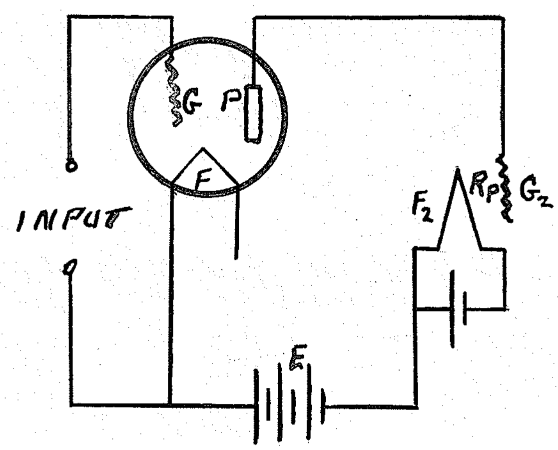


Figure 24.

adjusting the constants of the circuit in such a way that this second grid-filament system operates on the positive ion section of its grid potential vs grid current curve.

If R_p is made negative and numerically equal to Z_p in the above equation, then the numerical value of the equation becomes very great and a small change in the input potential E_g will cause a very great change in i_p, thus impressing a large voltage change on the second grid-filament system G_2F_2.

MacDonald and MacPherson[30] had based their circuit on this principle though at the time they did not attribute the high sensitivity to the negative sign of R_p butnto the change in the potential distribution of the circuit brought about by the substitution of the positive ion for the electron grid current of the output tube, a condition which MacDonald and Campbell found could not be brought about with the circuit just described.

The properties of the circuit described by MacDonald and MacPherson, obtained by using a UX222 as an input tube and a 112A as the output tube, are:

(1) The plate current of the output tube may be controlled by the potential of the control grid of the input tube. When the circuit is too sensitive to be stable, the sensitivity can be reduced by lowering the filament and plate potentials of the output tube.

(2) The negative bias of the control grid of the input tube, at which the mutual conductance of the unit is a maximum is directly proportional to the screen grid potential of the input tube.

(3) The grid conductance of the input tube is for practical purposes independent of the screen grid potential.

(4) No appreciable drift with a voltage sensitivity of

(30) Phil. Mag. vol. 15, 1933.

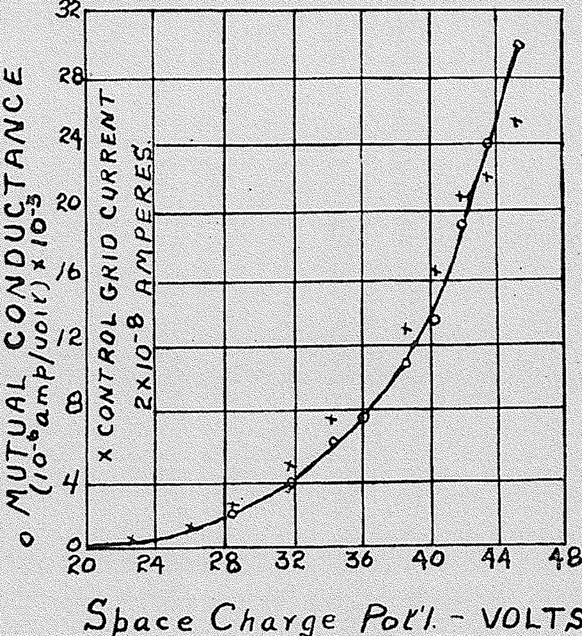


Figure 25.

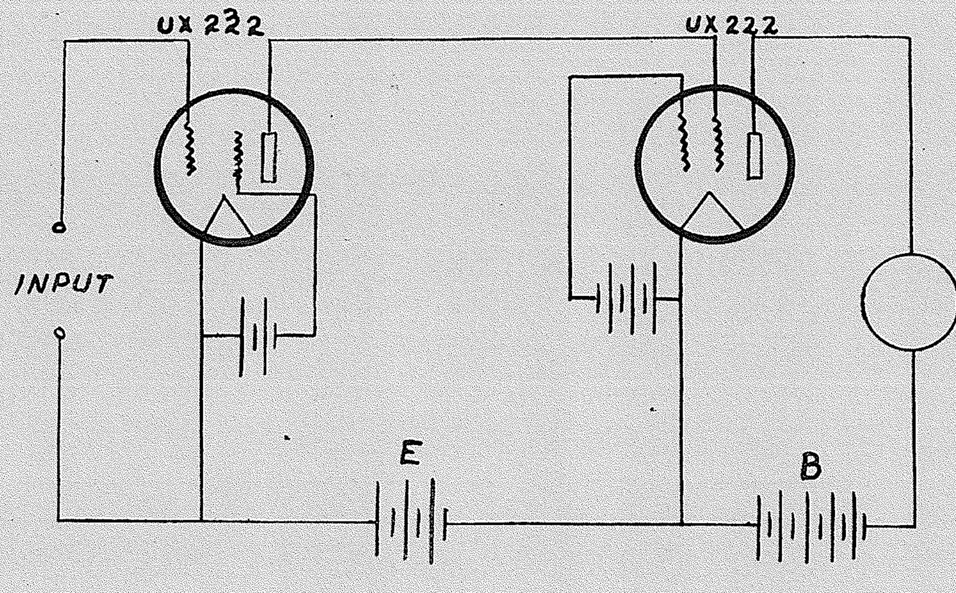


Figure 26.

Use of Additional Plate Resistance to Gain High Sensitivity.

If Rp is compounded of a positive and negative resistance in series, their algebraic sum may be adjusted to any desired value.

By opening the circuit in Figure 24 between P and G_2 and a resistance of suitable value inserted, the value of Rp may be kept negative and made to approach arithmetic equality with Z_p with a resulting increase in the voltage sensitivity.

MacDonald and Campbell made use of this possibility using a UX222 as a triode for the input tube and a 112A for the output. They found that this method of sensitivity adjustment to be both direct and simple.

The preceding two chapters have been an attempt to outline briefly and at the same time clearly, the history and the development of direct current amplifying circuits from the first application of thermionic tubes to the amplification of minute direct currents. In addition, a brief survey of the function, characteristics and development of thermionic tubes, as applied to the amplification of direct currents has been given. It is hoped that sufficient has been said to make the subject understandable to any reader no matter what his previous experience on the subject.

CHAPTER 111.

1. CONSTRUCTION of the UNIT.

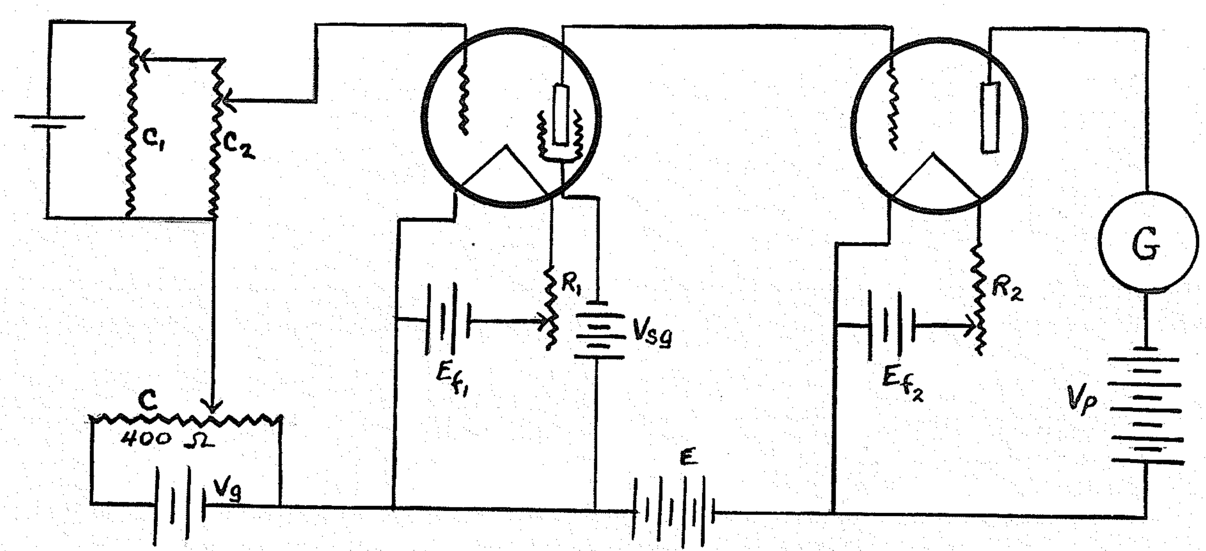


Figure 27.

Figure 27 represents a schematic diagram of the circuit used in the following investigation. The current through the filaments is supplied by two 6-volt wet batteries E_{f1} and E_{f2}, the potentials being altered to any desired value by means of 25-ohm variable resistances R_1 and R_2. The screen grid potential of the input tube is maintained by dry cells of 1.5 volts each, the potential being altered by the addition or subtraction of these cells. Dry cells also supply the potential of the E battery. The grid bias potential system consists of a 4-volt wet battery (part of the battery E_{f1}) placed across a 400-ohm variable resistance C. The sliding contact of this resistance is connected to a resistance box C_2 having a total resistance of 1110 ohms and capable of being varied by 1 ohm. The resistance box is connected in parallel with one end and the sliding contact of a second 400-ohm variable resistance C_1, C_1 being connected across a 1.5-volt battery (dry cell). This system provides a ready control of the grid potential and is capable of very small changes in the potential. The plate potential is supplied by a 90-volt "B" battery V_p. The whole apparatus including batteries is completely enclosed in a large wooden box completely covered with galvanized iron, and the shielding grounded.

The properties of the circuit, shown in Figure 27, were investigated by MacDonald and MacPherson[31] and were found to be;

(1) The negative potential of the control grid of the output tube is directly proportional to the potential applied at E.

(2) The plate current may be controlled by the potential of the control grid of the input tube.

(3) The negative bias of the control grid of the input tube, at which the mutual conductance of the unit is a maximum, is directly proportional to the screen grid potential.

(4) The grid conductance of the input tube is for practical purposes independent of the screen grid potential.

(5) The mutual conductance may be controlled by either the plate or filament potential of the output tube.

(6) The filament voltage of the input tube has no effect on the mutual conductance of the unit.

(31) Phil. Mag. vol. 15, 1933.

MacDonald and MacPherson obtained a voltage sensitivity of 3×10^{-4} volt/mm. with this circuit and it is the purpose of this paper to investigate just how far this sensitivity can be increased by the methods of battery and bridge compensation described in the preceding chapter.

Experimental Investigation.

The circuit described at the beginning of this chapter was first examined using a 230 as the output tube and a 232 as the input tube. The working constants were as follows;

E-potential .... 9.0 volts

Screen grid pot'l of the 232 ...... 6.0 volts

Filament potential of the 232 ..... 1.2 volts.

The circuit was examined for various plate and filament potentials as regards sensitivity and stability.

It was found that with 90 volts on the plate no control of the plate current could be obtained with filament potentials on the 230 ranging from 1.8 to 1 volt. For 67.5 volts on the plate of the 230 and a filament potential of 1.2, a certain amount of control was obtained but the drift was very rapid. With 1 volt on the filament the control improved but the drift remained very rapid. The plate potential was then reduced to 45 volts and the filament to 1 volt. This gave a sensitivity of 10^{-3} volt/mm. but did not improve the drift. Using these same working potentials, the screen grid was connected to the filament, the result of this being a decrease in the sensitivity and no improvement in the drift.

The persistence of the rapid drift, even with decreased filament and plate potentials, and also the nature of the drift hinted at the possibility of mechanical instability, most likely in the grid circuit. The nature of the drift was such that it was always in the direction of the change in potential, a fact that pointed to mechanical rather than electrical instability.

The circuit shown in Figure 27 fot the control of the grid potential contained two 400-ohm radio type variable resistances. These were of very poor construction, and it was decided that these might be the cause of the drift.

The grid potential control circuit was reconstructed using a decade resistance, having a total resistance of 9999 ohms, in series with a 1000-ohm fixed resistance, and connected in the main circuit as shown in Figure 28

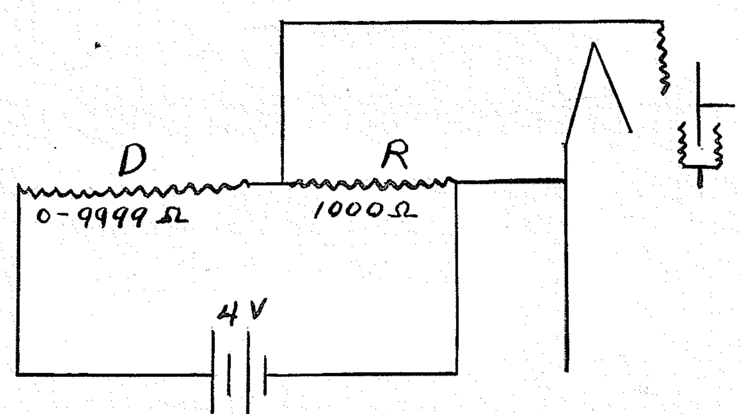


Figure 28.

The decade resistance consists of 4 sets of resistances connected in series, the first set 0 to 9 ohms, the second set 10 to 90 ohms, the third set 100 to 900 ohms and the fourth set

1000 to 9000 ohms and capable of having any value from 0 to 9999 ohms.

The functioning of this new unit is as follows. The decade was connected in series with the fixed resistance and a 4-volt wet battery. The leads to the control grid and the negative side of the filament of the input tube were tapped off, one from each end of the 1000-ohm resistance as shown in Figure 28. The potential applied to the grid will, therefore, be the drop in potential across the fixed resistance R. This fall in potential is varied by means of the decade resistance, that is, by way of illustration, if the resistance of the decade is zero the potential across R will be that of the battery, namely 4 volts, then if the value of D is made 1000 ohms, the potential across R applied to the grid will be 1000/2000 x 4 or 2 volts. Hence by changing the resistance of D, the potential applied to the grid may be altered, the changes being as large or as small as desired within certain limits defined by the voltage of the battery.

The circuit (Figure 27) was reconstructed, adopting the above method of grid control and also enclosing each wire in a rubber tube to insure good insulation, and as before the apparatus enclosed in a grounded metal box.

The circuit was then examined as before using a UX230 as the output tube or plate tube and a UX232 as the input tube or grid tube. Families of grid potential vs. plate current curves were obtained for various plate and filament potentials in order to observe the sensitivity variation with plate and filament potentials. The potentials of the E-battery and the screen grid were adjusted to bring the curves within the limits of the control grid battery.

DATA:

Operating Potentials (constants).

E-battery .... 4.5 volts.

Screen grid (232) .... 6.0 "

Filament (232) .... 1.2 "

230 Filament 1.5 volts.

(1) Plate 90 volts.

Plate current cms.	Grid pot'l volts	Plate current cms.	Grid pot'l volts
22	1.073	17	1.028
21.5	1.065	16	1.027
21	1.055	15	1.025
20	1.047	14	1.023
19	1.035	13	1.018
18	1.030	12	.908

(2) Plate 78 volts.

Plate current cms.	Grid pot'l volts	Plate current cms.	Grid pot'l volts
22	1.143	14	1.076
21	1.132	13	1.072
20	1.125	12	1.070
19	1.115	11	1.067
18	1.105	10	1.064
17	1.095	9	1.060
16	1.087	8	1.050
15	1.082	7.5	1.028

(3) Plate 67.5 volts.

Plate current cms	Grid pot'l volts	Plate current cms	Grid pot'l volts
18	1.333	10	1.075
16	1.133	9	1.073
15	1.121	8	1.067
14	1.110	7	1.064
13	1.095	6	1.055
12	1.087	5.5	1.050
11	1.082		

(4) Plate 55 volts.

Plate current cms	Grid pot'l volts	Plate current cms	Grid pot'l volts
13	1.333	7	1.155
12.5	1.290	6.5	1.146
11.5	1.250	6	1.143
11	1.242	5	1.130
10.5	1.230	4.5	1.125
10	1.216	4	1.120
9	1.195	3.5	1.117
8.5	1.186	3	1.111
8	1.177	2	1.095
7.5	1.163	1.5	1.081

(5) Plate 45 volts.

Plate current cms	Grid pot'l volts	Plate current cms	Grid pot'l volts
9.5	1.483	4	1.165
9	1.378	3.5	1.153
8	1.293	3	1.145
7.5	1.266	2.5	1.133
7	1.250	2	1.126
6.5	1.230	1.5	1.115
6	1.215	1	1.107
5.5	1.205	.5	1.095
5	1.193	0	1.000
4.5	1.173		

230 Filament 1.9 volts.

(6) Plate 90 volts.

Plate current cms	Grid pot'l volts	Plate current cms	Grid pot'l volts
22	1.081	16.5	1.036
20.9	1.067	15	1.033
20	1.058	13	1.028
19.1	1.050	10.2	1.010
17.8	1.042	9.75	1.000

(7) Plate 78 volts.

Plate current cms	Grid pot'l volts	Plate current cms	Grid pot'l volts
18.3	1.333	9.05	1.090
18.1	1.250	7.8	1.084
16.4	1.149	7.2	1.081
15	1.133	6.4	1.072
14	1.124	6.0	1.042
13.4	1.117	5.9	1.018
12	1.105	5.8	.930
10.5	1.096		

(8) Plate 68 volts.

Plate current cms	Grid pot'l volts	Plate current cms	grid Pot'l volts
14.45	1.250	7.9	1.090
14.1	1.176	6.75	1.084
13	1.140	6.1	1.081
12.2	1.130	5.1	1.075
11.4	1.120	4.35	1.070
10.25	1.108	4.0	1.058
9.6	1.102	3.8	1.026
8.4	1.093	3.75	1.000

(9) Plate 55 volts.

Plate current cms	Grid pot'l volts	Plate current cms	Grid pot'l volts
9.0	1.481	5.03	1.183
8.85	1.379	4.4	1.170
8.2	1.307	3.2	1.149
7.5	1.262	2.6	1.140
7.15	1.250	1.8	1.124
6.55	1.227	1.3	1.105
6.05	1.212	1.2	1.084
5.58	1.198	1.1	1.000

(10) Plate 45 volts.

Plate current cms	Grid pot'l volts	Plate current cms	Grid pot'l volts
6.2	1.600	1.5	1.156
5.95	1.429	1.05	1.143
5.5	1.356	.95	1.140
5.0	1.307	.75	1.133
4.4	1.266	.6	1.128
4.0	1.242	.5	1.124
3.6	1.223	.4	1.111
3.0	1.201	.3	1.053
2.1	1.173	.3	1.026

230 Filament 1.2 volts

(11) Plate 78 volts.

Plate current cms	Grid pot'l volts	Plate current cms	Grid pot'l volts
17	1.818	10.25	1.515
15.5	1.600	9.6	1.504
14.8	1.575	9.4	1.493
14.05	1.556	9.2	1.471
13.3	1.544	9.0	1.423
10.8	1.521	8.9	1.379

(12) Plate 55 volts.

Plate current cms	Grid pot'l volts	Plate current cms	Grid pot'l volts
12.5	1.905	5.5	1.606
11	1.762	4.6	1.594
10.1	1.717	3.2	1.575
9.05	1.681	1.8	1.550
8.05	1.653	1.4	1.521
6.8	1.626	1.25	1.429
		1.2	1.333

(13) Plate 67.5 volts.

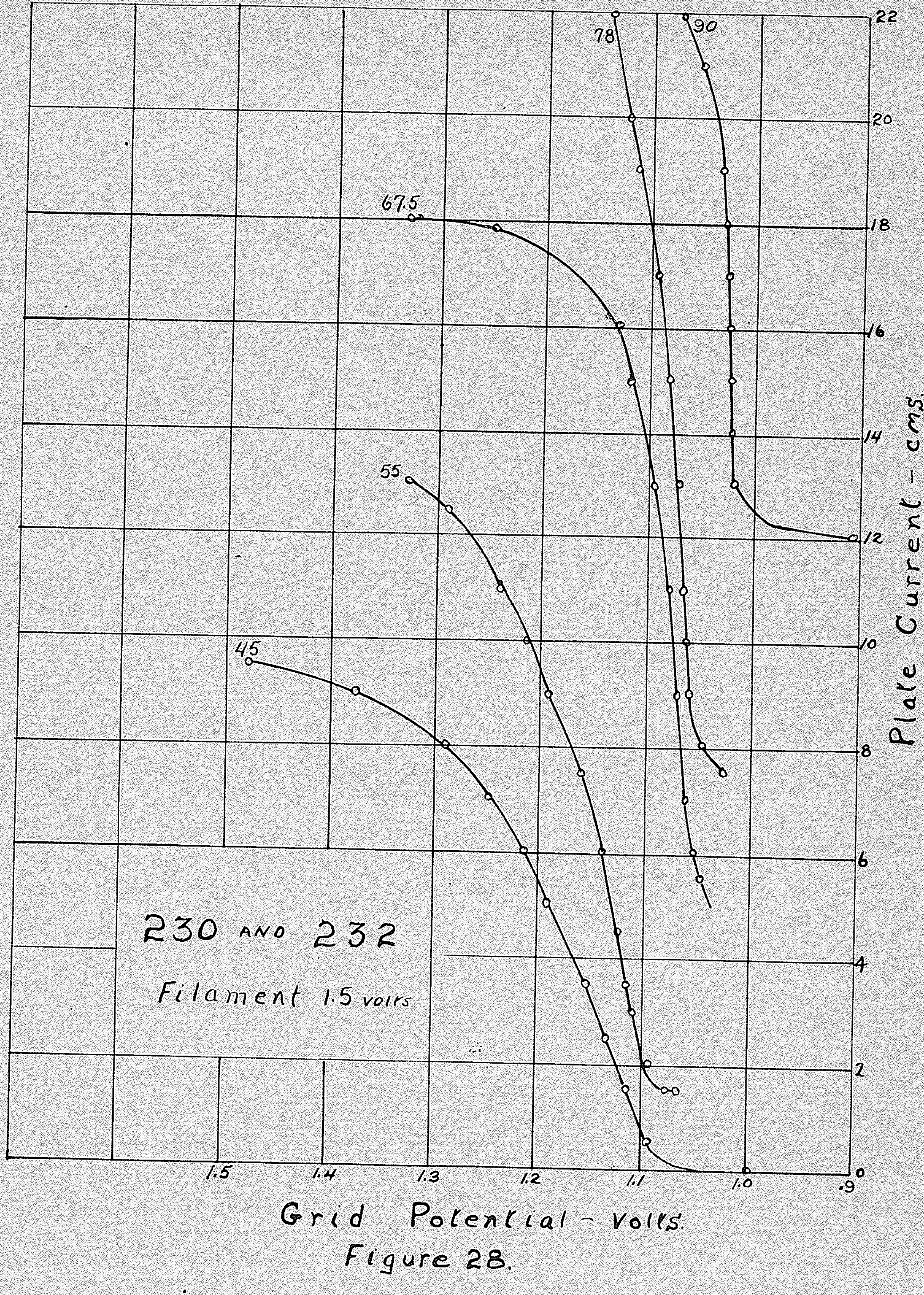
Plate current cms	Grid pot'l volts	Plate current cms	Grid pot'l volts
14	1.818	6.8	1.533
13.3	1.695	6.0	1.509
12.5	1.619	5.8	1.487
12.05	1.600	5.6	1.434
11.05	1.575	5.5	1.370
10.2	1.563	5.5	1.333

(14) Plate 45 volts.

Plate current cms	Grid pot'l volts	Plate current cms	Grid pot'l volts
6.95	1.810	2.9	1.639
6.05	1.754	1.6	1.606
5.95	1.747	1.33	1.600
4.95	1.702	.5	1.575
4.75	1.695	.2	1.544
3.9	1.667	.13	1.481

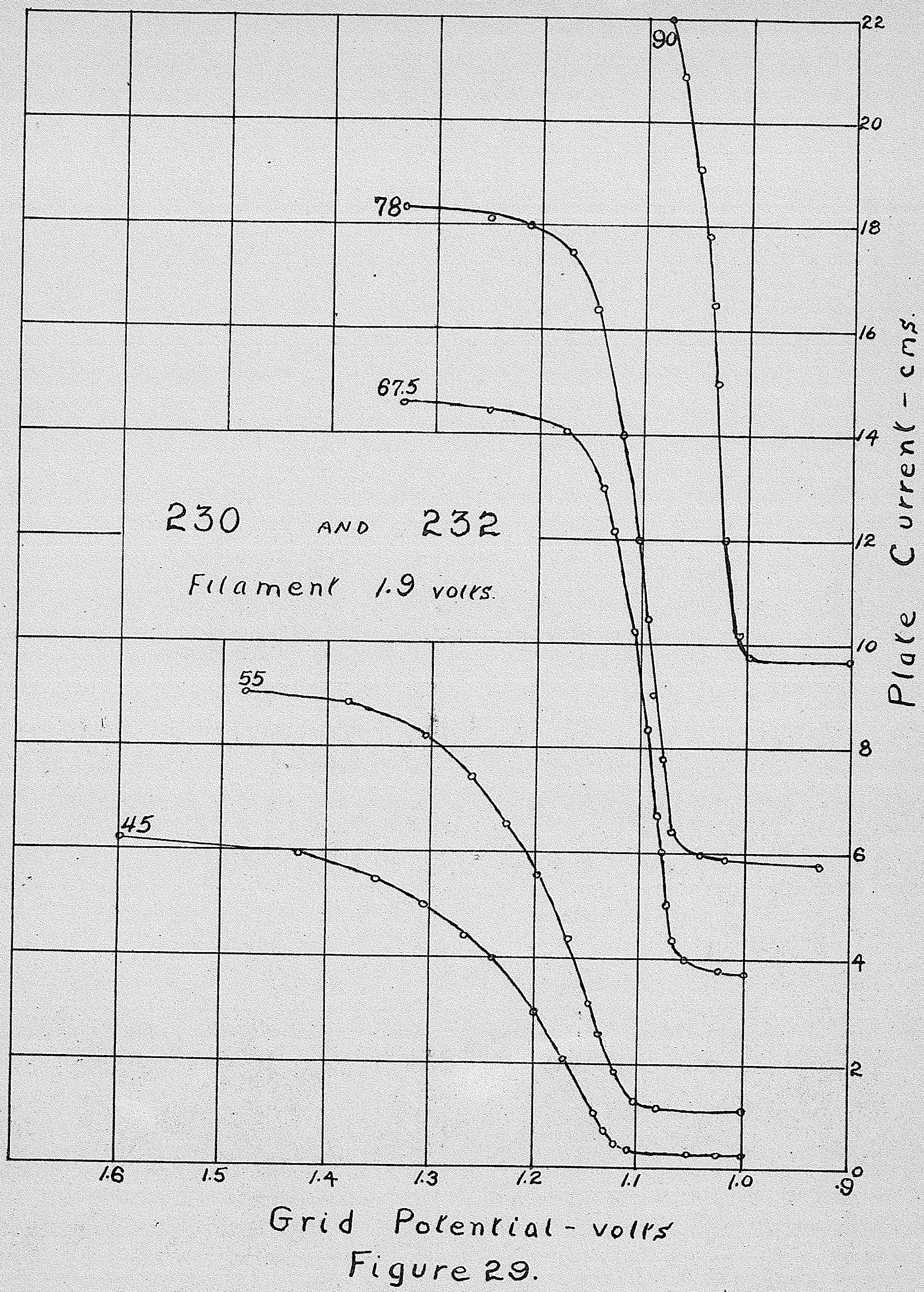
(15) Plate 32 volts.

Plate current	Grid pot'l	Plate current	Grid pot'l
1.65	2.000	.5	1.724
1.45	1.905	.3	1.695
1.00	1.802	0	1.600
.7	1.754		



22
20
18
16
14
12
10
8
6
4
2
0
78
90
67.5
55
45
1.5
1.4
1.3
1.2
1.1
1.0
.9
Plate Current - cms.
230 AND 232
Filament 1.5 volts
Grid Potential - volts.

Figure 28.



230 AND 232
Filament 1.9 volts.
90
78
67.5
55
45
22
20
18
16
14
12
10
8
6
4
2
0
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
Plate Current - cms.
Grid Potential - volts

Figure 29.

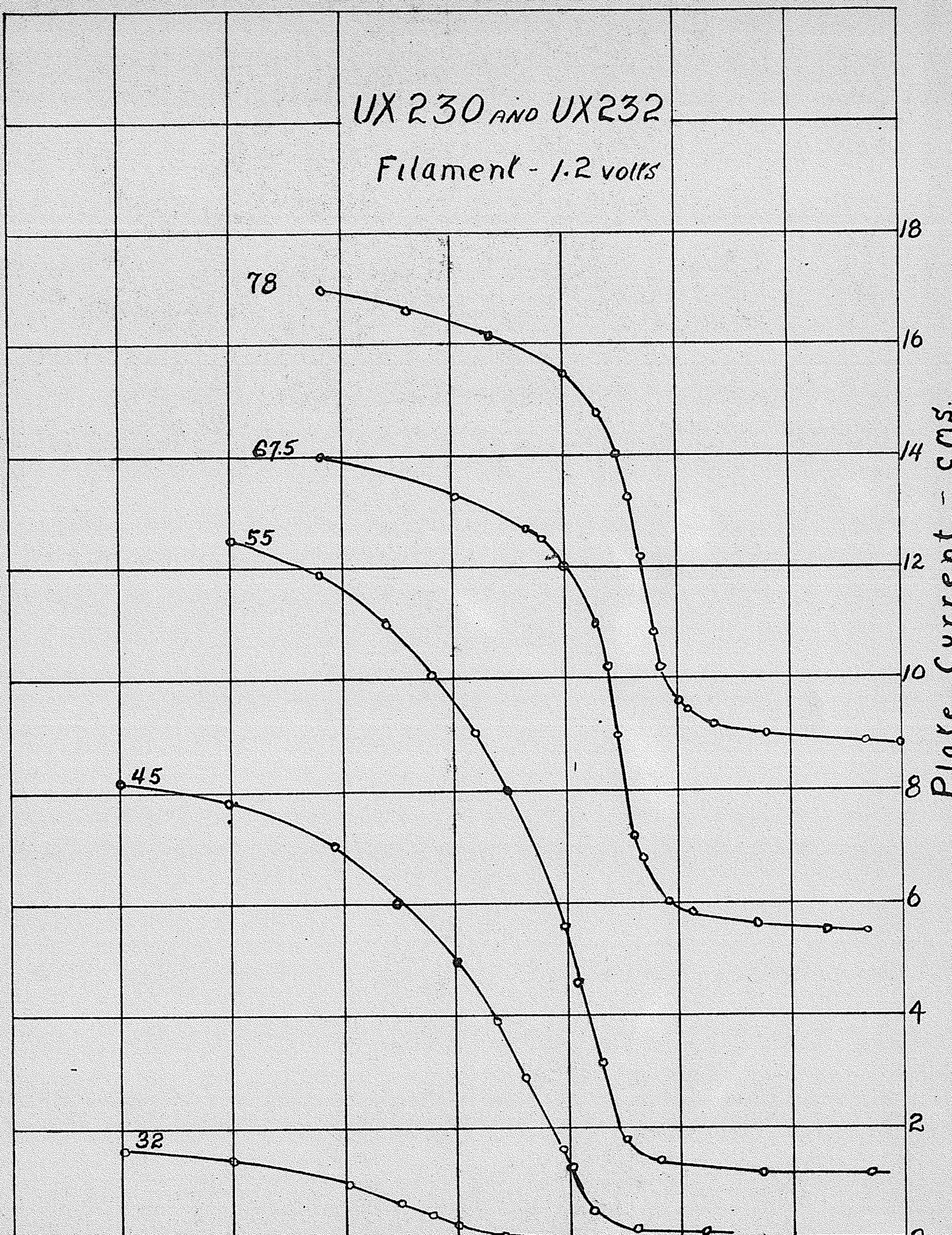

UX 230 AND UX 232
Filament - 1.2 volts
78
67.5
55
45
32
18
16
14
12
10
8
6
4
2
0
Plate Current - cms.
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
Grid Potential - volts.

Figure 30.

These curves are plotted in Figures 28, 29 and 30. They are the characteristic plate current-grid potential curves of this circuit. From these three families of curves it was observed;

(1) That the mutual conductance decreases with a decrease in the plate potential.

(2) That the mutual conductance decreases with a decrease in the filament potential.

(3) The plate current decreases with the plate potential.

(4) The maximum sensitivity was found to be 2.5×10^{-4} volt/mm., obtained with 90 volts on the plate and 1.9 on the filament.

The control as evidenced by the curves was very good and the drift slow. The substitution of the decade and the fixed resistance for the control of the grid potential of the grid tube, combined with better insulation of the wiring, reduced the drift to a very negligible value.

The sensitivity of the unit increased from 2.5×10^{-3} volt/mm. with 1.5 on the filament and 45 on the plate to 2.5×10^{-4} volt/mm. with 1.5 on the filament and 90 volts on the plate. This shows that it is possible to increase the sensitivity by increasing the plate potential.

The circuit was next examined using a UX112A as the plate tube and a UX222 as the grid tube. As with the 232 and the 230 families of curves were run for various plate and filament potentials to observe the sensitivity and stability with this combination of tubes.

DATA:

Operating potentials (constants).

E-battery .... 4.5 volts

Screen grid potential (222) ... 6.0 "

Filament potential (222) ...... 1.2 "

112A Filament 3.5 volts.

(1) Plate 90 volts.

Plate current mms.	Grid pot'l volts	Plate current mms	Grid pot'l volts
238	2.000	144	1.681
232	1.709	130	1.633
229.5	1.695	128	1.594
220	1.688	125.25	1.481
200	1.683	124	1.379
		121.3	1.000

(2) Plate 67.5 volts.

Plate current mms.	Grid pot'l volts	Plate current mms.	Grid pot'l volts
153	2.000	85	1.869
150	1.968	62	1.843
143	1.932	50	1.799
129	1.914	49	1.667
122	1.905	48	1.600
104.5	1.887	47	1.429

(3) Plate 77 volts.

Plate current mms.	Grid pot'l volts	Plate current mms.	Grid pot'l volts
192	2.000	129.5	1.789
190	1.905	100	1.784
184	1.818	82	1.747
170	1.802	77	1.667
160.5	1.798	75	1.538
145	1.793	74	1.428

(4) Plate 54 volts.

Plate current mms.	Grid pot'l volts	Plate current mms.	Grid pot'l volts
56	2.150	26	1.961
52	2.116	22	1.923
40	2.041	20.5	1.905

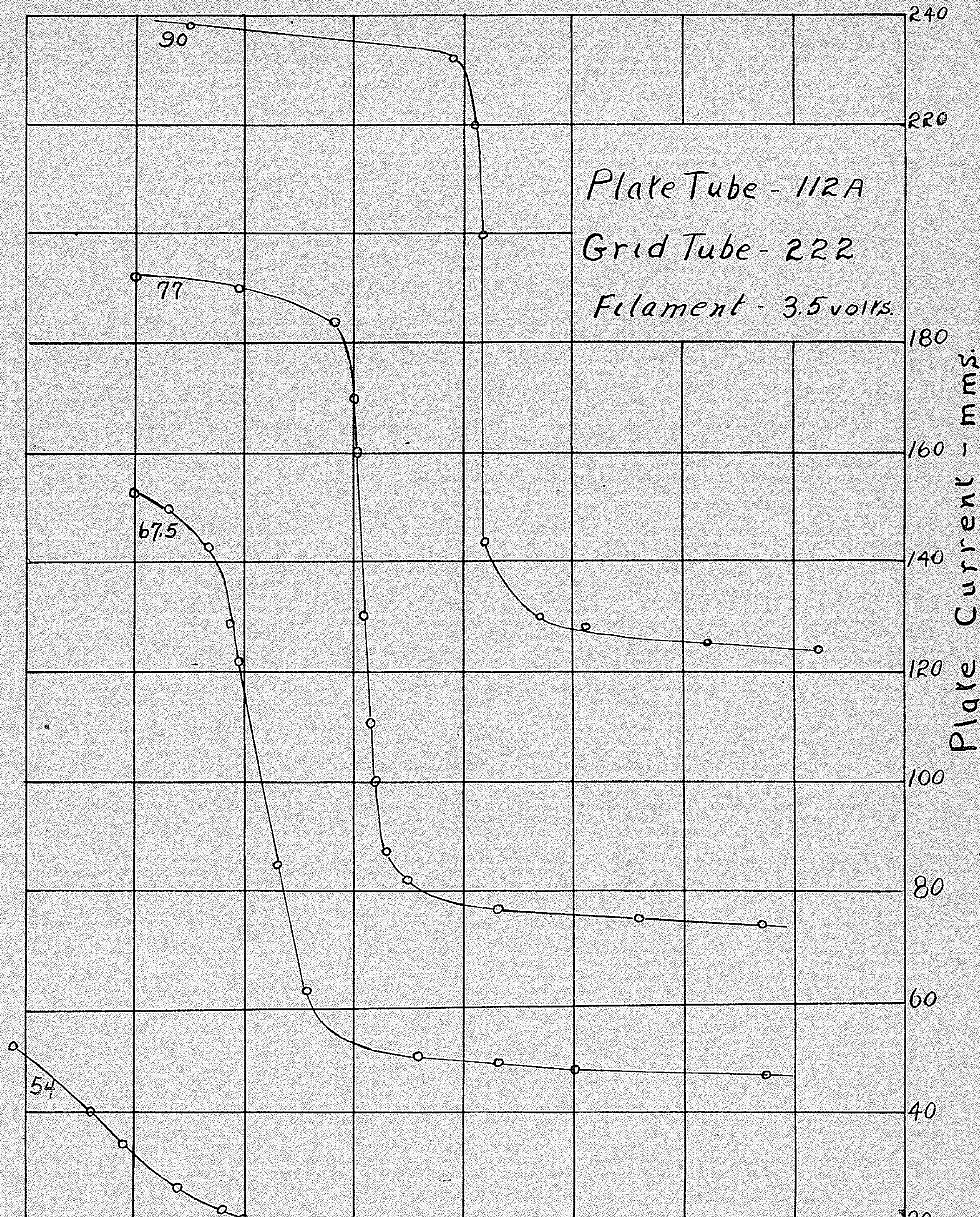


Plate Tube - 112A
Grid Tube - 222
Filament - 3.5 volts.
90
77
67.5
54
240
220
180
160
140
120
100
80
60
40
20
Plate Current - mms.
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
Grid Potential - volts

Figure 32.

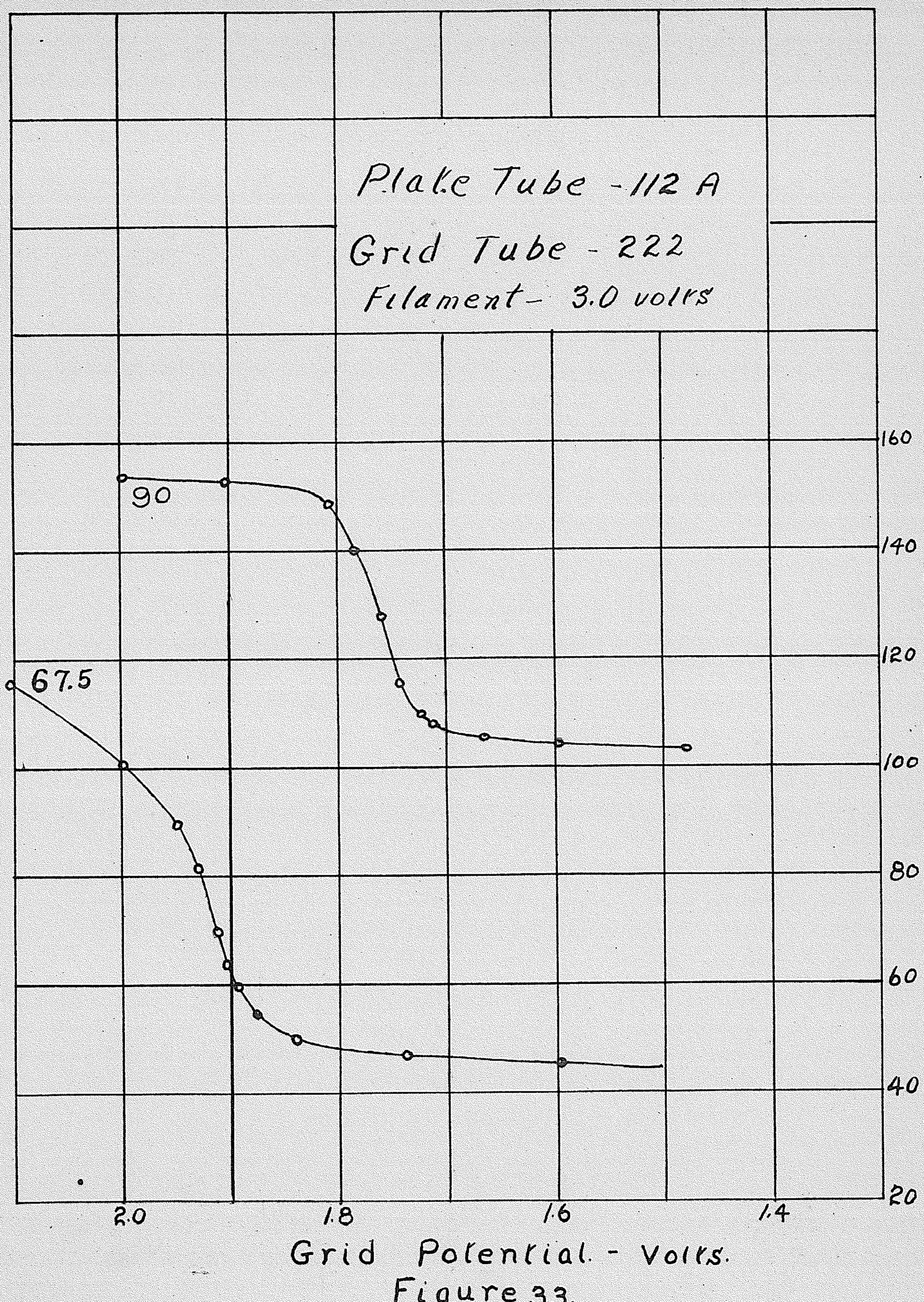


Plate Tube - 112 A
Grid Tube - 222
Filament - 3.0 volts
90
67.5
160
140
120
100
80
60
40
20
Plate Current - mms.
2.0
1.8
1.6
1.4
Grid Potential - Volts.

Figure 33.

112A Filament 3 volts.

(1) Plate 90 volts.

Plate current mms.	Grid pot'l volts	Plate current mms.	Grid pot'l volts
154	2.000	109.5	1.724
153.5	1.905	108	1.717
149	1.810	105.5	1.667
140.5	1.786	104	1.600
128	1.762	103	1.481
115.5	1.747	102.5	1.333

(2) Plate 67 volts.

Plate current mms.	Grid pot'l volts	Plate current mms.	Grid pot'l volts
116	2.105	64	1.905
101	1.990	60	1.896
90	1.951	50	1.843
82	1.932	47	1.739
69.5	1.914	45.5	1.600

Figures 32 and 33 represent the curves plotted from the above data. The curves for 90 volts on the plate and 3.5 volts on the filament shows a sudden drop indicating that the sensitivity was much too great to enable the plate current to be controlled by the grid potential. The measured slope of the curve with 77 volts on the plate and 3.5 volts on the filament gave a sensitivity of 2.5×10^{-4} volt/mm. The sensitivity of the instrument when the filament potential was reduced to 3 volts with 90 volts on the plate reduced the sensitivity from infinite to 10^{-3} volt/mm. These two sets of curves indicated much more clearly the variation of sensitivity with changes in the plate and filament potentials.

Plate Potential	Filament Potential	Sensitivity
90	3.5	infinite
90	3.0	10^{-3} volt/mm.
77	3.5	2×10^{-4} "

Plate Potential	Filament Potential	Sensitivity
67.5	3.5	7×10^{-4} volt/mm.
67.5	3.0	1.2×10^{-3} "

The observed drift of the instrument using 77 volts on the plate and 3.5 volts on the filament was only 6 mms. in 60 minutes, showing the drift to be very slow, with no irregular fluctuations.

The investigation so far has been confined to a study of the variation of sensitivity with plate and filament potentials of the output tube, and of the control and stability of the circuit at high plate and filament potentials. Only the data for two combinations of ordinary radio tubes are given, but in the following investigation the data for several other combinations will be given. The work so far shows that this circuit is a great improvement over the simple circuit. Although no ~~a~~ attempt has been made to balance out the plate current of the plate tube, the sensitivity has been increased approximately 10 times that of the simple circuit.

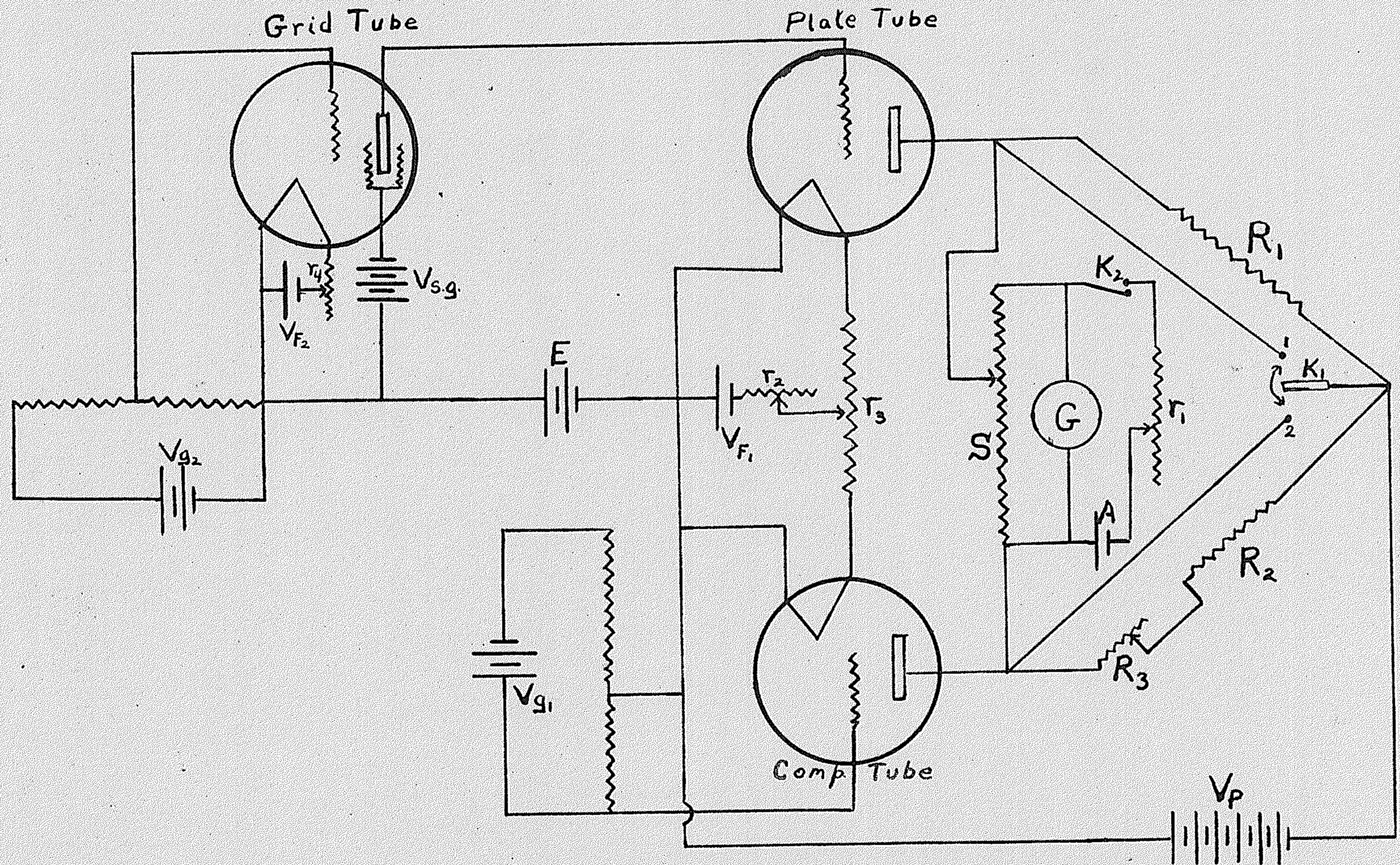
2. Plate Current Compensation.

The preceding investigation was sufficient to show the effect of increasing the plate and filament potentials on the sensitivity of the unit. The following investigation is to determine the increase in sensitivity to be obtained by (a) balancing out the plate current by means of an auxiliary battery and (b) balancing out the plate current by means of the plate current from a second tube of similar design. The examination includes several combinations of three and four element tubes both as plate and grid tubes.

The circuit used in the first part was dismantled and reconstructed as shown in Figure 34. The whole apparatus including batteries was enclosed in a grounded copper-shielded box, the tubes being placed in a similar copper box within the large one, and grounded to it. The galvanometer was also enclosed in a copper-shielded box and the leads to the rest of the apparatus enclosed in a brass tube connected at one end to the galvanometer box and at the other to the main box in such a way that the shielding effect was not destroyed. The negative side of the filament battery V_{f1} was also connected to the ground.

Description of the Apparatus.

R_1 is a fixed resistance of 10000 ohms forming one arm of the bridge while the other arm is composed of a high resistance box R_2 in series with a small variable resistance R_3 of 25 ohms. r_1 is a high variable resistance to control the current through the galvanometer from the auxiliary battery A



Grid Tube
Plate Tube
Comp Tube
$V_{s.g.}$
r_4
V_{F_2}
V_{g_2}
E
r_2
V_{F_1}
r_3
V_{g_1}
S
G
K_2
r_1
A
R_1
K_1
1
2
R_2
R_3
V_P

Figure 34.

while K_2 is a switch permitting the closing or opening of the auxiliary battery circuit as desired. K_1 is a single pole double throw switch enabling one or other of the bridge arms to be short-circuited as required. r_2 and r_4 are 30 ohm variable resistances of good construction to control the filament potentials of the grid and plate tubes. r_3 is a 6-ohm variable resistance used to adjust the current from the battery V_{f1} through the filaments of the plate and compensating tubes. V_{f2} is the filament battery supply for the grid tube. V_{g1} and V_{g2} are the batteries controlling the potentials of the controlgrids of the compensating and grid tubes respectively. V_{sg} is the screen grid battery and V_p is the plate battery. S is a variable shunt to control the sensitivity of the galvanometer, and equal to 22000 ohms, the value of the critical damping resistance of the galvanometer.

The method of investigation for each combination of tubes was as follows (1) a series of plate current-grid potential curves were plotted for various plate and filament potentials for the purpose of finding those potentials which gave the maximum sensitivity combined with maximum stability in the two tube circuit; (2) the plate current through the galvanometer was backed up by degrees by means of the current from an auxiliary battery, the plate tube being operated on those potentials found in part (1) above to give both maximum sensitivity and and stability; (3) the plate current through the galvanometer was balanced out by means of the plate current from a second similar tube, again operating the plate tube on those potentials found in part (1); (4) the plate current-grid potential curve was obtained for the plate tube operated on the potentials found in part (1).

For part (1) the compensating tube was left out of the circuit, K_1 was closed to the side 2 thus short-circuiting the resistances R_2 and R_3, while K_2 was left open to cut out the auxiliary battery circuit. Then by applying various potentials to the plate and filament of the plate tube, the plate current-grid potential curves were obtained, S being adjusted in order to set the sensitivity of the galvanometer to suit the plate current.

With the compensating tube still out of the circuit, K_1 was closed on the side 2 and K_2 closed so as to permit the plate current to be balanced out. The grid potential of the input tube was set so as to bring the circuit to the straight portion of the curve and the plate current balanced out by adjusting r_1. The sensitivity of the galvanometer was increased by means of S so that a small change in the grid potential of the grid tube caused a deflection over the whole scale of the galvanometer. After each deflection, the galvanometer was adjusted to the original starting point on the scale by changing r_1. By this method a series of deflections were obtained and the results plotted.

To balance out the plate current by means of a second tube the circuit was used as follows. K_2 was opened and K_1 set in the intermediate position thus placing both arms of the bridge in the circuit. The compensation was carried out as follows: the plate current was adjusted to the straight portion of the curve by adjustment of the grid potential of the grid tube. The galvanometer was adjusted to zero by changing the grid potential of the compensating tube. A small change in the potential of the plate battery was made and the galvanometer restored to zero by altering the resistances R_2 and R_3. This was continued until small changes in the plate potential caused no deflection of the galvanometer. Next the filament potential was altered and the galvanometer restored to zero by adjustment of the resistance r_3. Small changes were again applied to the filament potential and r_3 altered until finally a position was found such that any further change in the potential caused no change in the zero of the galvanometer. The grid potential of the input tube was then altered by a small amount and the deflection of the galvanometer noted. The sensitivity of the galvanometer was then increased by altering S until small changes in the grid potential caused a deflection of nearly the whole length of the scale. The sensitivity of the galvanometer was limited by the fluctuations. After each change in the grid potential the galvanometer was returned to the zero position by increasing the plate current of the compensating tube. In this way a series of deflections were obtained and curves drawn.

For the fourth part, that is the measurement of the plate current of the plate tube, the grid and compensating tubes were removed from the circuit. K_1 was moved over to the side 2, K_2 was opened and the leads to the E-battery joined together. Then by changing the lead from the grid of the grid tube to the grid of the plate tube a simple circuit was formed. The deflection of the galvanometer was noted for changes in the grid potential, the tube being operated at those potentials as found to be the most suitable in the first part of this investigation.

DATA:

(1) UX112A as Plate Tube and a UX222 as Grid Tube.

Operating Potentials (constants)

E-battery .... 6.1 volts

Screen grid potential of 222 .. 6.3 "

Filament potential of 222 ..... 1.2 "

Part (1)

The best working potentials for the plate tube (112A) were found to be; Plate 86 volts, Filament 3.0 volts. The plate current-grid potential of the unit for these potentials is shown in Figure 35.

Sensitivity of the galvanometer.... 15×10^{-6} amp/mm.

Slope of the curve 07/40

Voltage sensitivity................ 1.75×10^{-3} volt/mm.

Part (2)

The data for this part is plotted in Figure 36.

Sensitivity of the galvanometer.... 4.6×10^{-7} amp/mm.

Measured slope of the curve 07/1700

Voltage sensitivity................ 3.5×10^{-5} volt/mm.

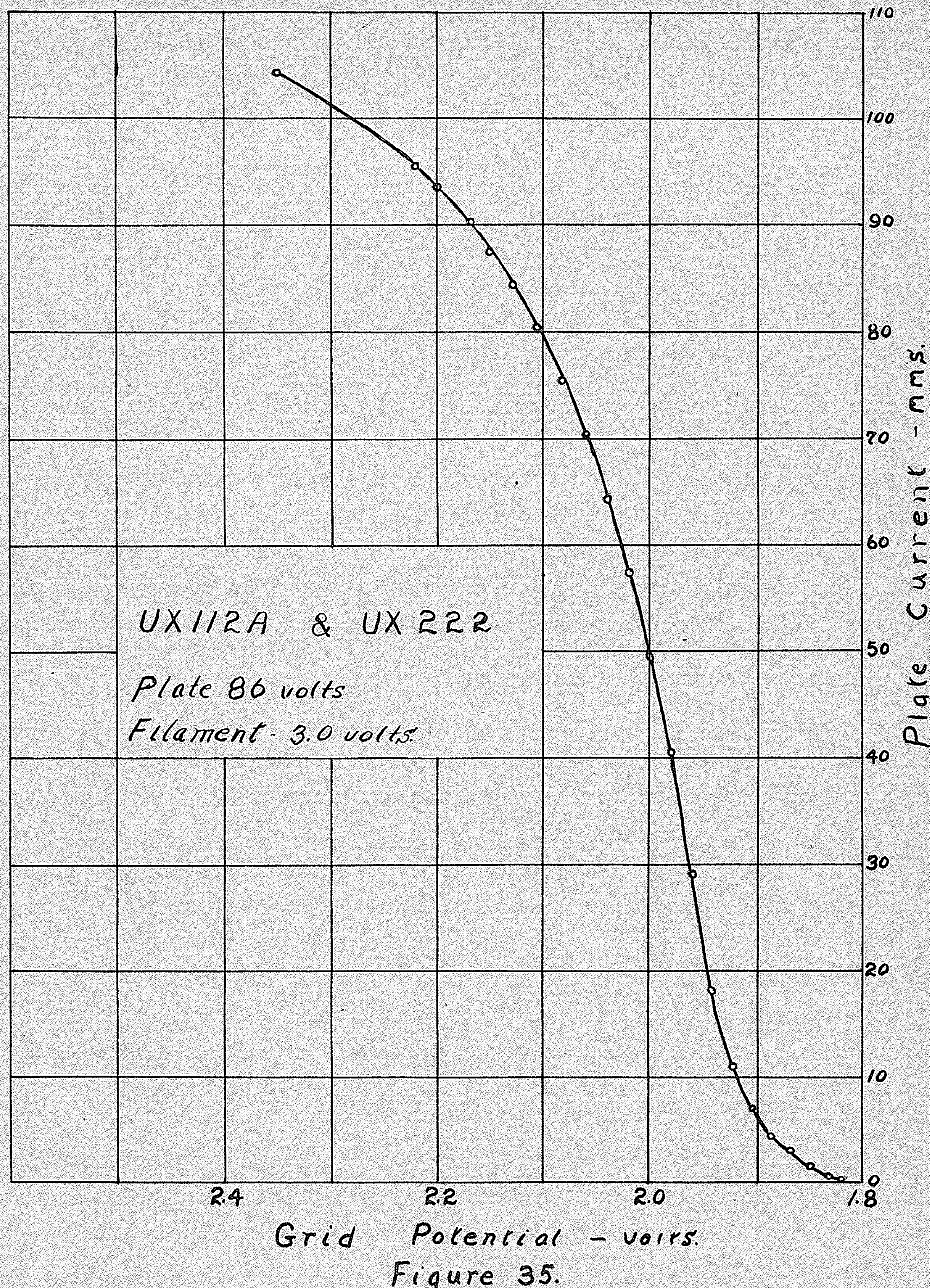
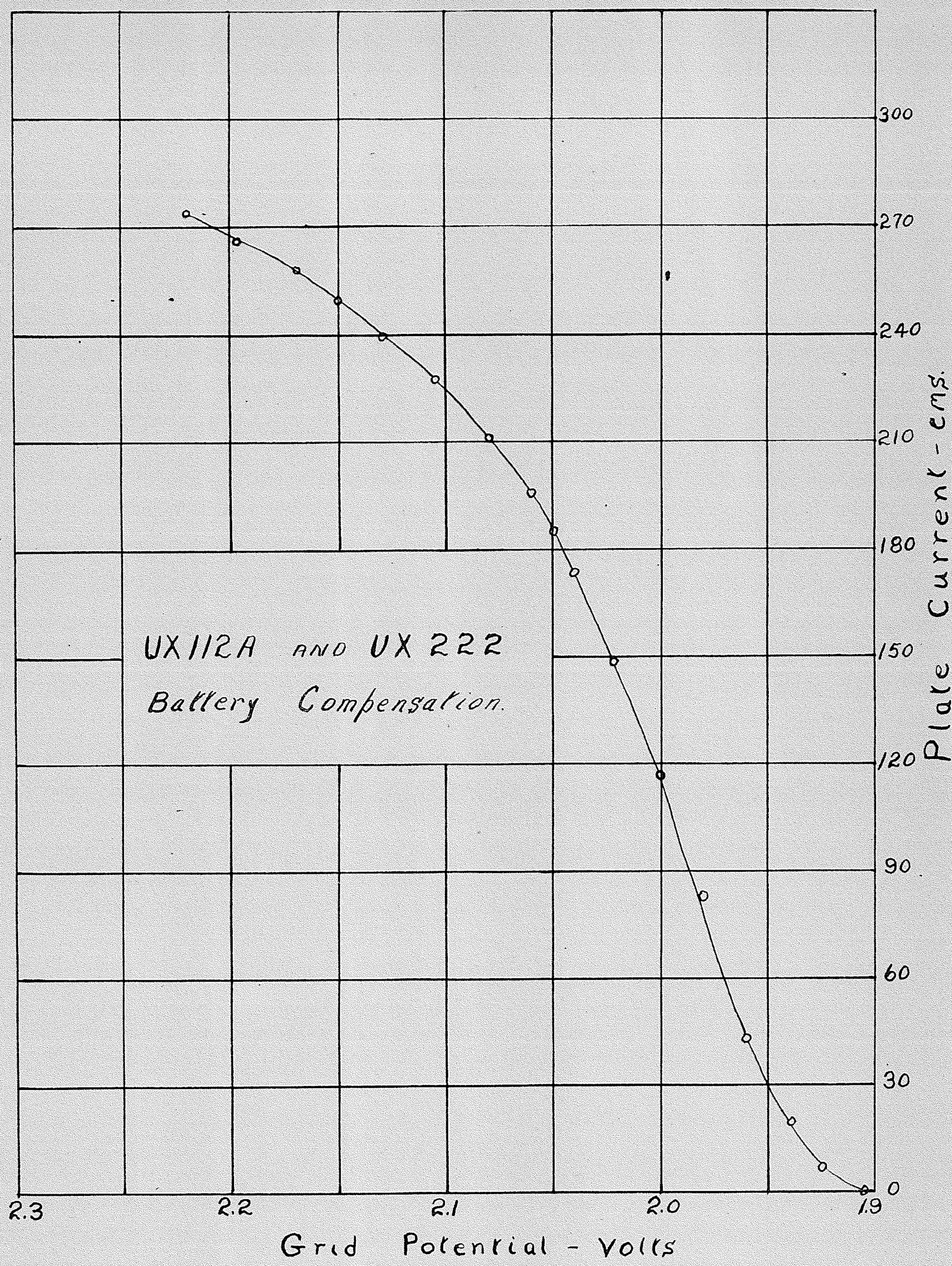
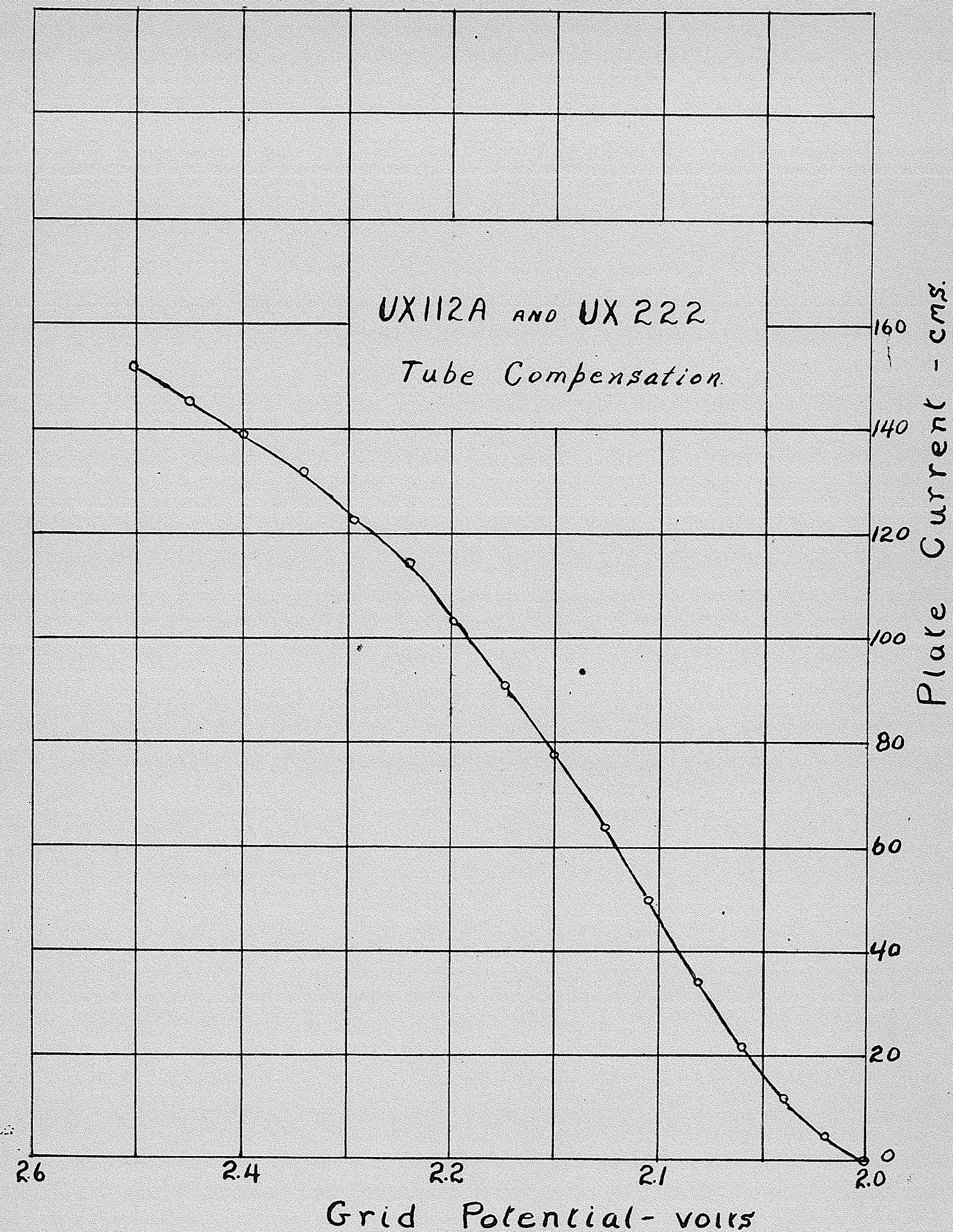

110
100
90
80
70
60
50
40
30
20
10
0
2.4
2.2
2.0
1.8
Plate Current - mms.
Grid Potential - volts.
UX112A & UX 222
Plate 86 volts
Filament - 3.0 volts

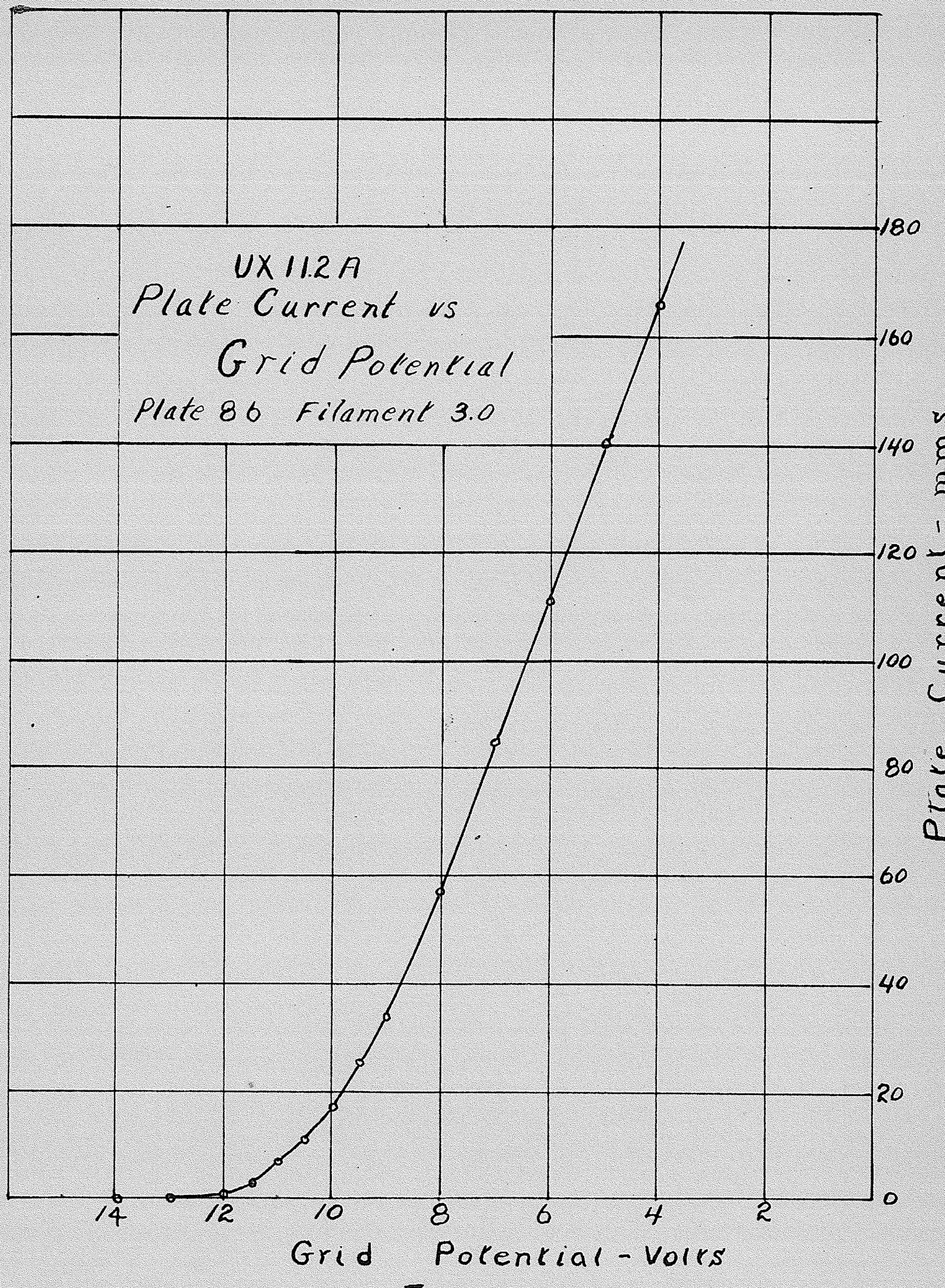
Figure 35.


UX 112A AND UX 222
Battery Compensation.
300
270
240
210
180
150
120
90
60
30
0
Plate Current - cms.
2.3
2.2
2.1
2.0
1.9
Grid Potential - Volts
Figure 36.



UX112A AND UX 222
Tube Compensation
Plate Current - cms.
160
140
120
100
80
60
40
20
0
2.6
2.4
2.2
2.1
2.0
Grid Potential - volts

Figure 37.


UX 112 A
Plate Current vs
Grid Potential
Plate 86 Filament 3.0
180
160
140
120
100
80
60
40
20
0
Plate Current - mms.
14
12
10
8
6
4
2
Grid Potential - Volts
Figure 38.

Part (3)

The data for this part is shown in Figure 37.

Sensitivity of the galvanometer.... 2.7×10^{-7} amp/mm.

Measured slope of the curve........ .125/800

Voltage sensitivity................ 1.5×10^{-4} volt/mm.

Part (4)

The data is shown in Figure 38.

Sensitivity of the galvanometer.... 10^{-5} amp/mm.

Voltage sensitivity................ 3.5×10^{-2} volt/mm.

<u>Summary</u>.

Method	Voltage sensitivity
Single tube circuit	3.5×10^{-2} volt/mm.
Two tube circuit	1.75×10^{-3} "
Battery compensation	3.5×10^{-5} "
Bridge compensation	1.5×10^{-4} "

(2) <u>201 as Plate Tube and a 222 as Grid Tube</u>.

Operating Potentials (constants)

E-battery...................... 6.1 volts

Screen grid potential of 222... 6.3 "

Filament potential of 222...... 1.2 "

Part (1)

The best working potentials for the plate tube (201) were found to be; Plate 86 volts, Filament 4.5 volts. The plate current-grid potential curve for the unit operated at these potentials is shown in Figure 39.

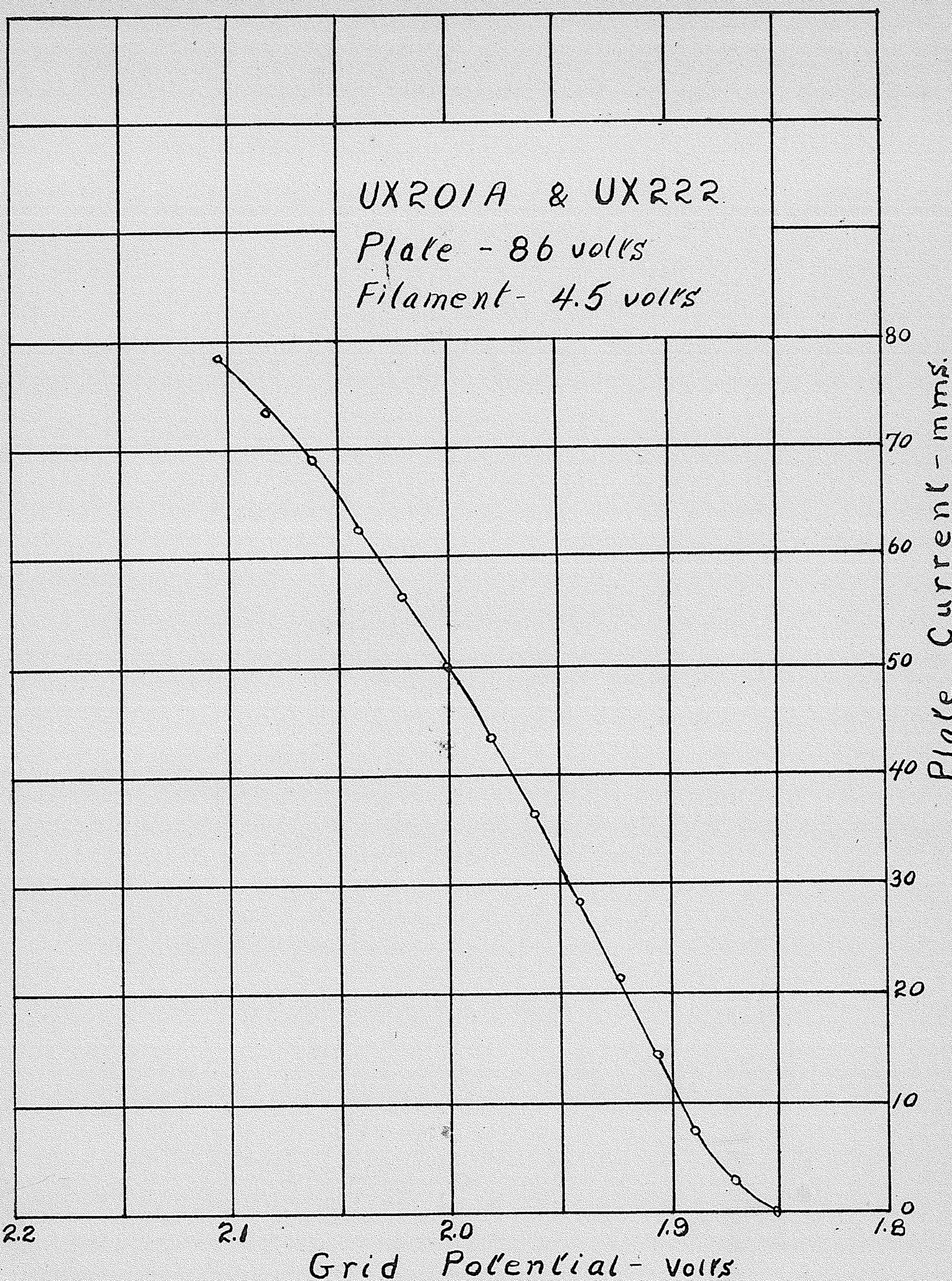
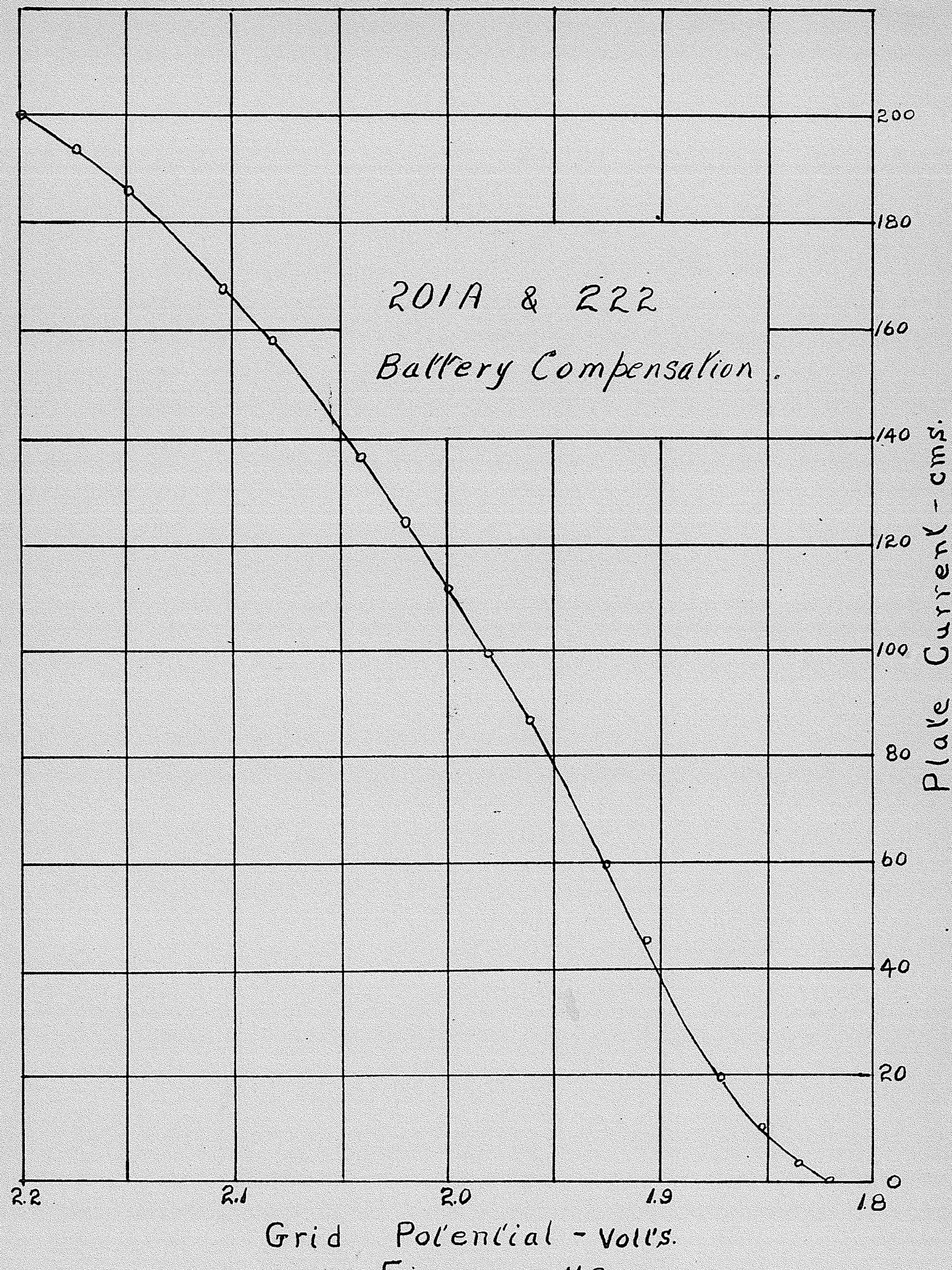
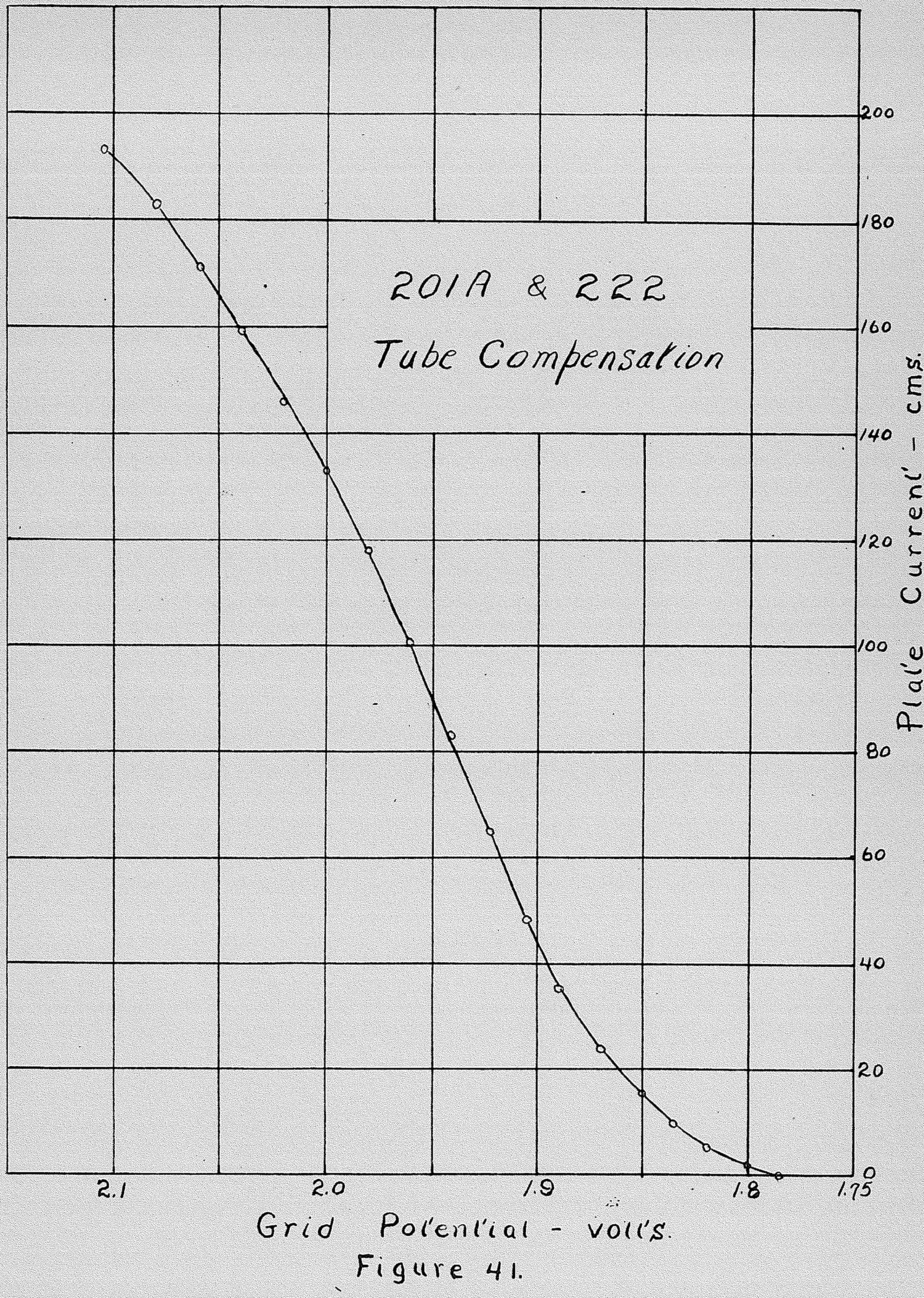

UX201A & UX222
Plate - 86 volts
Filament - 4.5 volts
80
70
60
50
40
30
20
10
0
Plate Current - mms.
2.2
2.1
2.0
1.9
1.8
Grid Potential - volts

Figure 39.



201A & 222
Battery Compensation.
200
180
160
140
120
100
80
60
40
20
0
Plate Current - cms.
2.2
2.1
2.0
1.9
1.8
Grid Potential - Volts.

Figure 40.



201A & 222
Tube Compensation
Plate Current - cms.
200
180
160
140
120
100
80
60
40
20
0
2.1
2.0
1.9
1.8
1.75
Grid Potential - volts.

Figure 41.

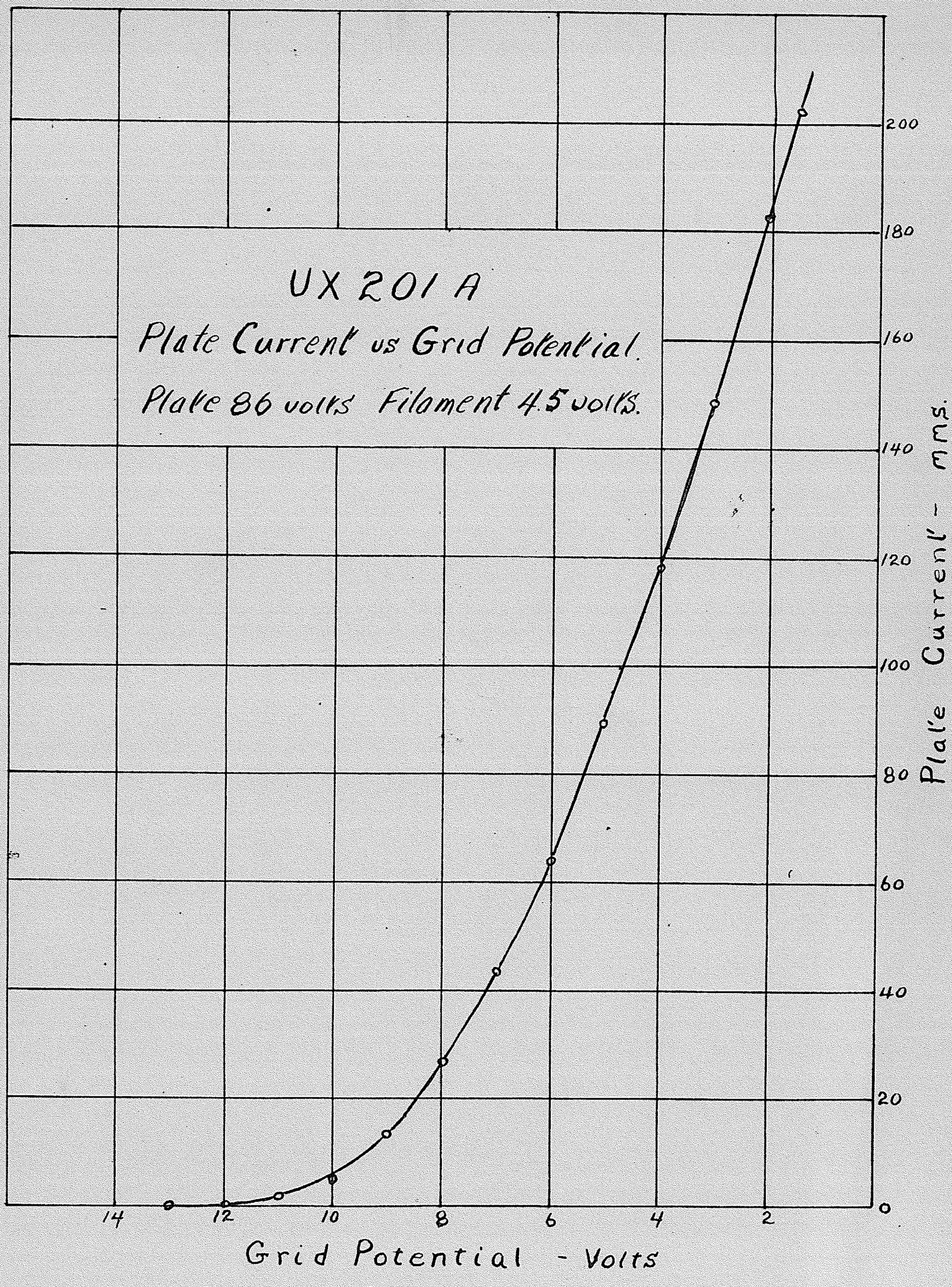

UX 201 A
Plate Current vs Grid Potential.
Plate 86 volts Filament 4.5 volts.
200
180
160
140
120
100
80
60
40
20
0
14
12
10
8
6
4
2
Plate Current - mas.
Grid Potential - Volts

Figure 42

Sensitivity of the galvanometer.... 8.6×10^{-6} amp/mm.

Measured slope of the curve........ .11/45

Voltage sensitivity............... 2.4×10^{-3} volt/mm.

Part (2)

The data is shown by the curve of Figure 40.

Sensitivity of the galvanometer.... 5×10^{-7} amp/mm.

Slope of the curve.................... .105/780

Voltage sensitivity............... 1.3×10^{-4} volt/mm.

Part (3)

The data is plotted in Figure 41.

Sensitivity of the galvanometer.... 1.5×10^{-7} amp/mm.

Slope of the curve................ .07/680

Voltage sensitivity............... 10^{-4} volt/mm.

Part (4)

The data for this part is shown in Figure 42.

Sensitivity of the galvanometer.... 2×10^{-5} amp/mm.

Slope of the curve................ 4.6 / 150

Voltage sensitivity............... 3×10^{-2} volt/mm.

Summary.

Method	Voltage sensitivity
Single tube circuit	3×10^{-2} volt/mm.
Two tube circuit	2.4×10^{-3} "
Battery compensation	1.3×10^{-4} "
Bridge compensation	10^{-4} "

(3) <u>201A as Plate Tube and a 232 as Grid Tube</u>.

Operating Potentials (constants)

E-battery .... 6.1 volts

Screen grid potential of 232... 6.3 "

Filament potential of 232...... 1.2 "

Part (1)

The best working potentials for the plate tube (201A) were found to be; Plate 85 volts, Filament 3.5 volts. The plate current-grid potential curve for the unit operated at these potentials is shown in Figure 43.

Sensitivity of the galvanometer.... 6×10^{-6} amp/mm.

Measured slope of the curve........ .033/45

Voltage sensitivity................ 7.5×10^{-4} volt/mm.

Part (2)

The data for this part is shown in Figure 44.

Sensitivity of the galvanometer.... 2.6×10^{-7} amp/mm.

Measured slope of the curve........ .052/1500

Voltage sensitivity................ 3.5×10^{-5} volt/mm.

Part #3)

The grid potential of the grid tube was adjusted to 1.4706 volts. At this potential the unit is at the most sensitive part of the curve. The plate current was balanced out by means of a compensating tube and the galvanometer adjusted to zero. The sensitivity of the galvanometer was measured and found to be 2.6×10^{-7} amp/mm. The deflection of the galvanometer was observed for a change in the grid potential of 5.4×10^{-3} volt. The

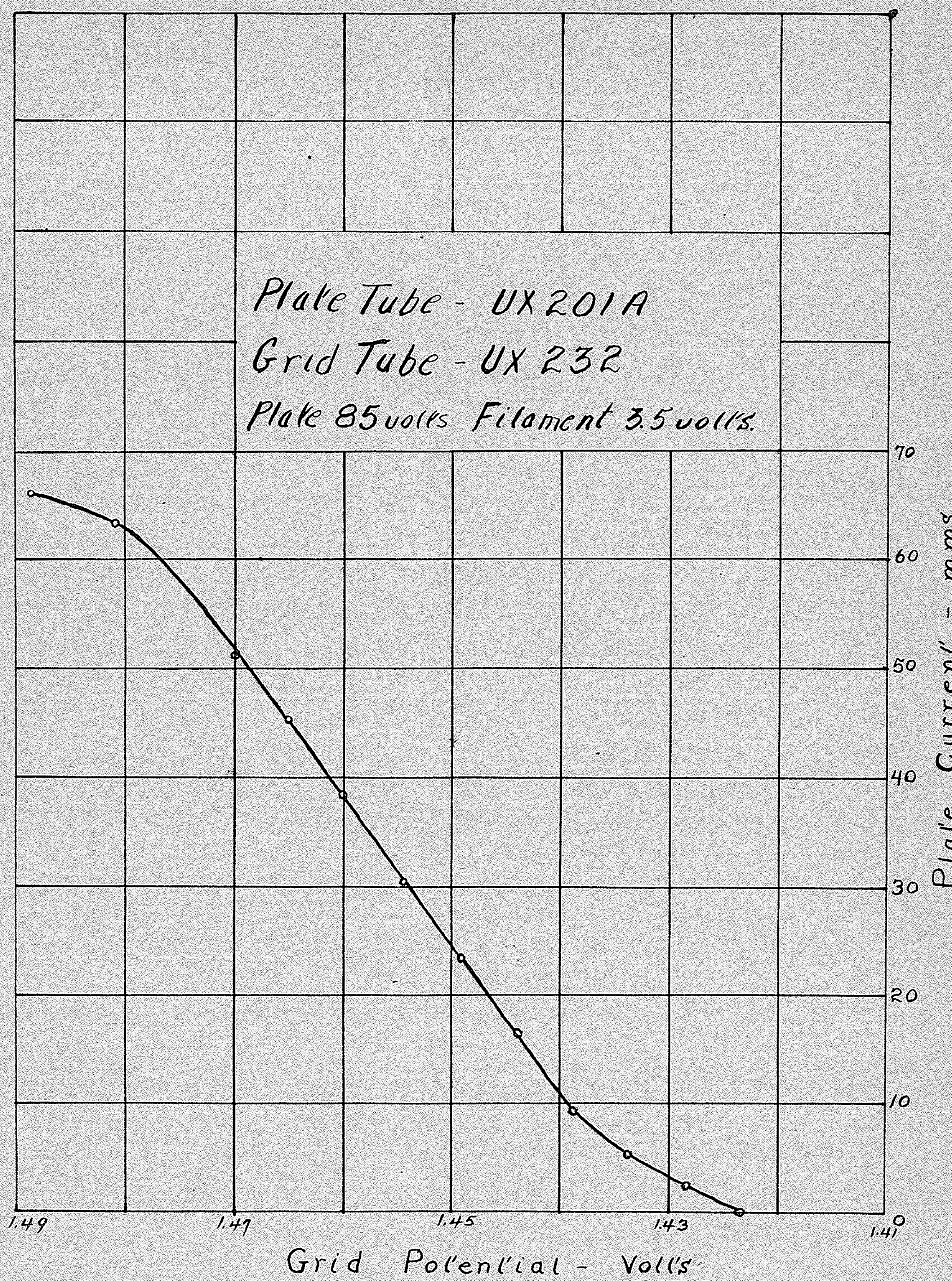


Plate Tube - UX 201 A
Grid Tube - UX 232
Plate 85 volts Filament 3.5 volts.
70
60
50
40
30
20
10
0
Plate Current - mms.
1.49
1.47
1.45
1.43
1.41
Grid Potential - Volts

Figure 43.

observed deflections for four trials using the same change of potential each time were 78, 78, 79, 79 mms. with a variation of 1. From these observations the voltage sensitivity is $5.4 \times 10^{-3}/78.5$ or 6.9×10^{-5} volt/mm.

The sensitivity of the galvanometer was increased further to 7×10^{-8} amp/mm. and the plate current balanced out. For a change in the grid potential of 5×10^{-4} volt the resulting deflection of the galvanometer was observed to be between 40 and 50 mms. for several trials. The voltage sensitivity in this case, taking the average deflection to be 45 mms., equals $.0005/45$ or 1.1×10^{-5} volt/mm.

Part (4)

The data obtained in this part is shown in Figure 45.

Sensitivity of the galvanometer.... 8.6×10^{-6} amp/mm.

Slope of the curve................. 5/170

Voltage sensitivity................ 3×10^{-2} volt/mm.

<u>Summary</u>.

Method	Voltage sensitivity
Single tube circuit	3×10^{-2} volt/mm.
Two tube circuit	7.5×10^{-4} "
Battery compensation	3.5×10^{-5} "
Bridge compensation	1.1×10^{-5} "

In part (2) in which the plate current was balanced out with an auxiliary battery the galvanometer showed a fluctuation of the needle amounting to approximately 5 mms. amplitude. In part (3) using a galvanometer sensitivity of 2.6×10^{-7} amp/mm.

the needle of the galvanometer oscillated with an amplitude of 1 mm. but otherwise the stability was excellent. When the grid potential was changed back after making an observation of the deflection, the galvanometer in every case returned to zero. With a sensitivity of 7×10^{-8} amp/mm. the oscillation of the galvanometer increased to an amplitude of 5 mms. the oscillation however being quite regular in nature.

(4) <u>233 as Plate Tube and a 234 as Grid Tube.</u>

Operating Potentials (constants)

E-battery .... 6.1 volts

Screen grid potential of 234... 6.3 "

Filament potential of 234...... 1.3 "

Part (1)

The best working potentials for the plate tube (233) were found to be; Plate 130 volts, Filament 1.9 volts. The plate current-grid potential curve for the unit operated at these potentials is shown in Figure 46 (a).

Sensitivity of the galvanometer.... 1.07×10^{-7} amp/mm.

Slope of the curve............. .013/60

Voltage sensitivity............ 2×10^{-4} volt/mm.

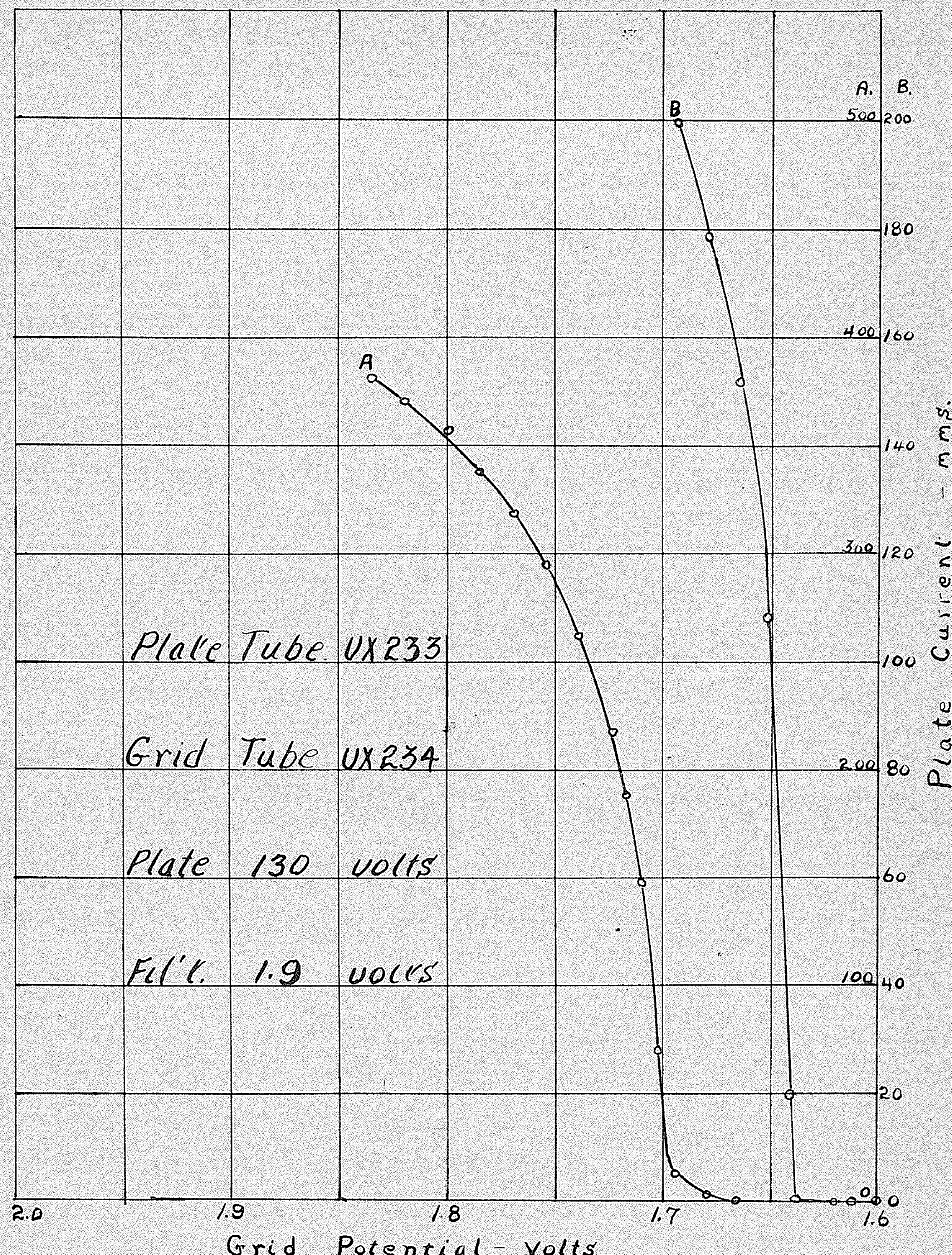
Part (2)

The data for this part is shown in Figure 46 (b).

Sensitivity of the galvanometer.... 3.26×10^{-8} amp/mm.

Measured slope of the curve........ .013/275

Voltage sensitivity................ 5×10^{-5} volt/mm.



A. B.
500 200
180
400 160
140
300 120
100
200 80
60
100 40
20
0
A
B
Plate Tube UX233
Grid Tube UX234
Plate 130 volts
Fil't. 1.9 volts
Plate Current - mms.
2.0
1.9
1.8
1.7
1.6
Grid Potential - Volts

Figure 46

Part (3)

A second 232 was not available for the purpose of compensating the plate current of the plate tube, therefore no data is available for this part.

Summary.

Method	Voltage sensitivity
Two tube circuit uncompensated	2×10^{-4} volt/mm.
Battery compensation	5×10^{-5} "

In part (1) the galvanometer was perfectly stable and the plate current very small, thus allowing a high sensitivity with the galvanometer. In part (2) there was a slight regular fluctuation of the galvanometer with an amplitude of 2.5 mms.

(5) UX222 as Plate Tube and 232 as Grid Tube.

Operating Potentials (constant).

E-battery .... 6.1 volts

Screen grid potential of 232... 6.3 "

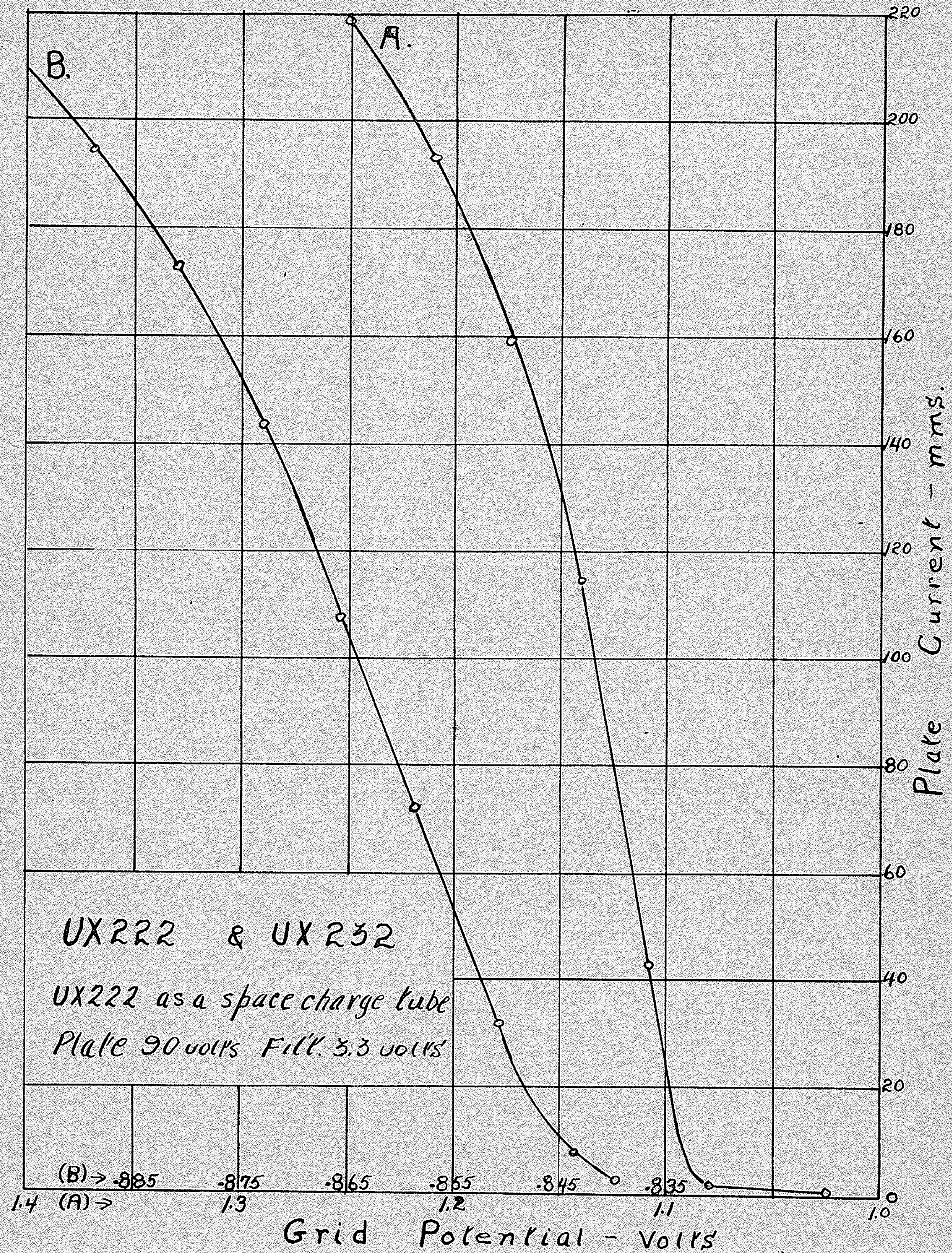
Filament potential of 232...... 1.2 "

Space Charge potential of 222.. 22.5 "

The 222 was used as the plate tube using the control grid as a space charge grid operated at 22.5 volts and the screen grid used as the control grid.

Part (1)

The best working potentials for the plate tube (222) were found to be; Plate 90 volts, Filament 3.3 volts. The plate current-grid potential curve for the unit operated at these potentials is shown in Figure 47 (a).



B.
A.
UX222 & UX232
UX222 as a space charge tube
Plate 90 volts Fil. 3.3 volts
220
200
180
160
140
120
100
80
60
40
20
0
Plate Current - mms.
(B) → -885
-875
-865
-855
-845
-835
1.4 (A) →
1.3
1.2
1.1
1.0
Grid Potential - Volts

Figure 47.

Sensitivity of the galvanometer.... 2.42×10^{-7} amp/mm.

Measured slope of the curve........ 105/110

Voltage sensitivity................ 5×10^{-4} volt/mm.

A second set of working potentials were found to be Plate 135 volts and Filament 3.3 volts. The curve for these potentials is shown in Figure 47 (b).

Sensitivity of the galvanometer.... 1.25×10^{-6} amp/mm.

Slope of the curve................. .025/128

Voltage sensitivity................ 2×10^{-4} volt/mm.

Part (3)

The plate current of the plate tube was balanced out by means of the current from a second 222. The potential of the grid was changed by .018 volt and the resulting deflection of the galvanometer was 250 mms. for several trials.

Sensitivity of the galvanometer.... 3.36×10^{-8} amp/mm.

Voltage sensitivity................ 7.2×10^{-5} volt/mm.

The working potentials for this part were Plate 135 volts and Filament 3.3 volts.

Part (4)

The data for this part using a plate potential of 90 volts and a filament potential of 3.3 volts is shown in Figure 48.

Sensitivity of the galvanometer.... 2.3×10^{-6} amp/mm.

Measured slope of the curve........ .57/138

Voltage sensitivity................ 4×10^{-3} volt/mm.

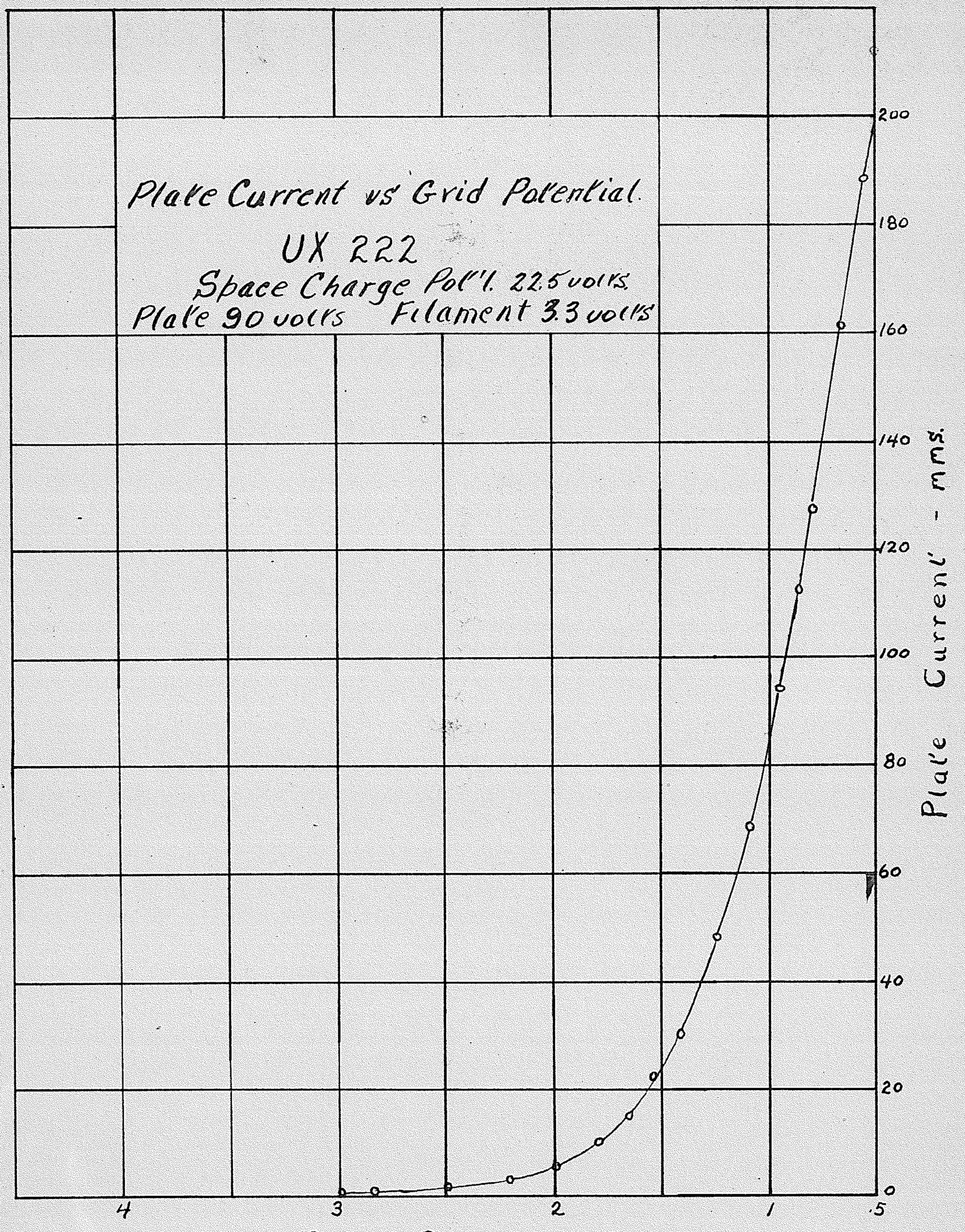


Plate Current vs Grid Potential
UX 222
Space Charge Pot'l. 22.5 volts
Plate 90 volts Filament 3.3 volts
200
180
160
140
120
100
80
60
40
20
0
Plate Current - mms.
4
3
2
1
.5
Grid Potential - Volts

Figure 48

<u>Summary</u>.

Method	Voltage sensitivity
Single tube circuit	4×10^{-3} volt/mm.
Two tube circuit (plate 90)	5×10^{-4} "
Two tube circuit (plate 135)	2×10^{-4} "
Bridge compensation (plate 90)	7.2×10^{-5} "

3. <u>Final Summary of the Results</u>.

UX112A as Plate Tube and UX222 as Grid Tube.

E-battery............ 6.1 volts Filament (222)..... 1.2 volts

Plate potential (112A) 86 " Screen grid........ 6.3 "

Filament " " 3.0 "

Uncompensated.................. 1.75×10^{-3} volt/mm.

Battery compensation........... 3.5×10^{-5} "

Bridge compensation .... 1.5×10^{-4} "

201A as Plate Tube and UX222 as Grid Tube.

E-battery............ 6.1 volts Filament (222)..... 1.2 volts

Plate (201).......... 86 " Screen grid (222).. 6.3 "

Filament (201)....... 4.5 "

Uncompensated................. 2.4×10^{-3} volt/mm.

Battery compensation........... 1.3×10^{-4} "

Bridge compensation............ 10^{-4} "

201A as Plate Tube and UX232 as Grid Tube.

E-battery............ 6.1 volts. Filament (232).... 1.2 volts

Plate (201).......... 85 " Screen grid (232). 6.3 "

Filament (201)....... 3.5 "

Uncompensated.................. 7.5×10^{-4} volt/mm.

Battery compensation........... 3.5×10^{-5} "

Bridge compensation............ 1.1×10^{-5} "

233 as Plate Tube and 234 as Grid Tube.

E-battery.......... 6.1 volts. Filament (234)..... 1.3 volts

Filament (233)..... 1.9 " Screen grid (234)... 6.3 "

Plate(233)......... 130 "

Uncompensated.................. 2×10^{-4} volt/mm.

Battery compensation........... 5×10^{-5} "

UX222 as Plate Tube and 232 as Grid Tube.

Plate.............. 90 volts. Filament 232........ 1.2 volts

Filament........... 3.3 " Screen grid 232..... 6.3 "

Space charge grid.. 22.5 " E-battery........... 6.1 "

Uncompensated.................. 2×10^{-4} volt/mm.

Bridge compensation............ 7×10^{-5} "

The results of this investigation show definitely that the voltage sensitivity of the amplifier can be increased by 10 to 100 times that of the uncompensated circuit by applying the two methods of plate current compensation, namely, by means of an auxiliary battery and by means of the plate current from a second similar tube. The stability, in all cases, was found to be very good and whenever fluctuations did occur they were found to be quite regular about the zero, the amplitude being constant. The greatest amplitude was encountered when a 201A was used as plate tube and a UX232 as the grid tube, and even then amounted to only 5 mms. With a 233 as plate tube and a 234 as grid tube the fluctuations were observed to have an amplitude of 2.5 mms. while in all the other cases the galvanometer showed no fluctuation whatever, coming to perfect rest at each position with no appreciable drift.

From an examination of the final results obtained with each combination of tubes, it can be concluded that it is possible to obtain a voltage sensitivity in the neighbourhood of 10^{-5} volt/mm. with this type of amplifier using a 201A as the plate tube and a 233 as the grid tube, compensated by either method. The operating potentials of the circuit in this case being;

Plate (201)........	85 volts.	Filament 232........	1.2 volts
Filament (201).....	3.5 "	Screen grid 232.....	6.3 "
E-battery..........	6.1 "		

However voltage sensitivities ranging from 10^{-4} volt/mm. to 5×10^{-5} volt/mm. are obtainable, combined with good stability, when other types of ordinary commercial vacuum tubes are employed, but it has been found in this investigation that the combination of a 201A and a 232 gave the greatest sensitivity combined with a degree of stability which permitted accurate measurement.

The sensitivity of this circuit is limited by the sensitivity of the measuring instrument in the plate circuit,i.e. the galvanometer, and by the fluctuations of the zero point. No matter how carefully and exactly the balancing out of the plate current was performed, small regular fluctuations appeared in the zero as the sensitivity of the galvanometer was increased, thus rendering the readings unreliable.

In the construction and operation of an amplifier of this type, certain precautions are necessary, precautions which are familiar to every investigator in this field of research.

The shielding of the apparatus should be complete in every detail; every piece of apparatus in cluding batteries and galvanometer should be, if possible, included in the same shielded box and the shielding grounded to overcome any electrostatic pick-up, which would cause erratic movements of the plate meter. The valves should be enclosed in an air-tight copper container to guard against the moisture of the air, which will cause the grid-filament leakage resistance to vary, and also to protect against the action of light falling upon the valves, causing photo-electrons to be emitted. Both of these effects would cause irregularities to be present in the galvanometer thus rendering the readings unreliable. All connections should be soldered and the leads well-insulated to prevent poor contacts and insulation leaks.

The instrument must be allowed to reach a state of equilibrium before any attempt is made to use it. It is adviseable to allow the circuit to run at the required potentials for a period of an hour or more before taking measurements, in order to ensure no irregularities are present in the electron current of the valves. These irregularities would in turn be transmitted to the galvanometer causing erratic movements of the zero.

Fluctuations in the plate and filament batteries are provided for by the method of compensation with a second vacuum tube, and can be further overcome by using large storage cells for the filaments and heavy duty "B" batteries for the plate supply.

In conclusion, I wish to express my sincere thanks to Professor Frank Allen, Director of the Department of Physics of the University of Manitoba, for the facilities of the Research Laboratory which were placed at my disposal; and to Dr. P.A.Macdonald, Assistant Professor and Radium Physicist, for the suggestion of this problem and for his generous advice and assistance.