DIRECT CURRENT THERMIONIC AMPLIFIERS HAVING A HIGH MUTUAL CONDUCTANCE.

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SUMMARY

FORWORD - Presentation of the Problem.

CHAPTER I- An historical outline of the development of the thermionic valve, and its subsequent application to direct current measurement problems.

CHAPTER II- The experimental evolution of amplification circuits having a high mutual conductance and a discussion of the phenomenon upon which the operation of such circuits as amplifiers is dependent.

FORWORD

Many experimenters in the last few years, spurred on by the recent rapid advancement of the importance of the photoelectric cell in commercial fields as well as in numerous branches of scientific research, have focussed their attention on the possibility of amplifying very minute direct currents such as photoelectric currents. Previous to the evolution of the thermionic valve amplifier, the quadrant electrometer afforded the only means whereby such currents could be measured. The sensitivity of this instrument, however, is not sufficient for most photoelectric problems and its manipulation requires great skill.

The introduction of the thermionic valve amplifier, however, rendered another method of measurement of these small currents. Du Bridge,(1) in his description of a bridge circuit employing special type vacuum tubes designed by Metcalf and Thomson(2) (the FP54 pliotron), gives an indication of detecting even the ultimate unit of electricity - the single electron; as by utilizing this circuit, currents as low as 5×10^{-18} ampere or 30 electrons per second can be measured.

(1) Physical Review. Feb. 15, 1931, p.392

(2) Physical Review. Nov. 1, 1930, p.1489

This circuit, however, entails very elaborate apparatus consisting of special type vacuum tubes, sensitively balanced systems and extremely careful shielding. The current sensitivity is increased at the expense of the sensitivity to voltage thus rendering a circuit with a very low voltage sensitivity. These factors, along with the necessity of operation of the circuit by a skilled technician render the circuit impractical as a laboratory instrument for ordinary low direct current measurement problems.

As a result, the attention of experimenters in this branch of scientific research was turned towards developing direct current amplifiers having a high sensitivity to voltage which would be suitable as ordinary laboratory instruments for measuring small currents.

The algebraic expression for the sensitivity to voltage of a direct current amplifier is

$$S_v = G_m S_g \qquad (1)$$

where S_v = voltage sensitivity

G_m = the mutual conductance of the tube i.e., the slope of the curve relating the grid potential to the plate current. The magnitude of the plate current places a limit on the voltage sensitivity since the amplified current must be sufficiently large to record on a meter not too delicate to register the plate current.

Considerable increase in sensitivity may be obtained by the introduction of an auxiliary battery(3) in the simple circuit in such a manner that it forces a current through the plate current meter equal to the plate current but opposite in direction. The sensitivity of the galvanometer may then be increased until irregularities in the plate current render the zero point unsteady. If the plate current from a second vacuum tube be substituted for the current due to the auxiliary battery, the fluctuations occurring in the two tubes may be made to offset each other to a considerable extent, allowing further increase in galvanometer sensitivity to be made. Using commercial thermionic tubes designed for the reception of radio broadcasting a voltage sensitivity of 10^{-5} $\frac{\text{volts}}{\text{mm}}$ has been reported for a two tube balanced circuit with a current sensitivity somewhat greater than 10^{-14} $\frac{\text{amps}}{\text{mm.}}$ (4) Metcalf and Thompson(5) have designed a special tube for direct current amplification, known as the General Electric FP54 pliotron, two of which have been used by Du Bridge(6) in

(3) Razek and Mulder, J.O.S.A. and R.S.I., June/29
(4) Razek and Mulder, J.O.S.A. and R.S.I., Dec/29
(5) Physical Review, Nov.1, 1930, p. 1489
(6) Du Bridge, Physical Review, Feb. 15, 1931.

the balanced circuit to give a voltage sensitivity of $4 \times 10^{-6}\ \frac{\text{volts}}{\text{mm.}}$.

The above two methods of balancing out the plate current enable the sensitivity of the meter, S_g, in the above equation, to be increased, the quantity G_m, the mutual conductance, however, remaining constant. P.A. Macdonald and Jean T. Macpherson(7) attacked the problem of increasing the voltage sensitivity by keeping the galvanometer sensitivity S_g constant and increasing the mutual conductance G_m with the result that a rugged two-stage amplifier employing ordinary radio tubes (UX222-UX112A) has been described with a voltage sensitivity of $3 \times 10^{-4}\ \frac{\text{volts}}{\text{mm}}$ which with an input resistance of 2×10^{9} ohms gives a current sensitivity of $1.5 \times 10^{-13}\ \frac{\text{amp.}}{\text{mm}}$ Their efforts, however, did not exhaust the possibilities in this field, rather they suggested the problem undertaken by the author to examine such a circuit in greater detail and determine the phenomenon upon which its operation is based and to obtain further increase in the mutual conductance both by the employment of a similar circuit and by modifications of such a circuit.

The results proved singularly successful. A two-stage amplifier, using ordinary radio tubes - RCA232

(7) Philosophical Magazine, Jan. 1933

and UX222 - was developed which had an extremely high mutual conductance, namely, 30,000 $\frac{\text{microamperes}}{\text{volt}}$. The phenomenon upon which the operation of two-stage amplifiers of this type is based was also ascertained. Two modifications of the circuit were developed; one employing high resistors in series with the second-stage tube and the other employing a high resistor in parallel with the second stage tube. The former circuit yielded a mutual conductance of 13,000 $\frac{\text{micro-amperes}}{\text{volt}}$ and the latter a mutual conductance of 35,000 $\frac{\text{micro-amperes}}{\text{volt}}$, with absolute stability.

Some of the desirable features of such amplification circuits are the practicability and simplicity of design and operation; the elimination to a great extent of those undesirable factors encountered so often in amplifiers, instability and tendency to drift; the cost - an extremely important factor - is reduced to a low level, the only expensive item being the sensitive meter employed in the plate circuit, an instrument necessary in any amplification circuit.

CHAPTER I

This chapter, as well as embodying a brief historical outline of the development of the thermionic valve and its subsequent application in amplification circuits, is devoted to an elementary discussion of the properties of electrons and a brief account of the electron theory of matter, this being necessitated by the fact that the problem of the thermionic valve, i.e., the study of the emission of electrons from a hot filament and their transport to the anode or "plate" entails a large number of problems, the solutions of which are based on the electron theory.

The Electron

The word "electron" was introduced by Professor G. Johnston Storey in 1891 to denote the natural unit of electricity, i.e., the quantity of electricity which was found to be invariably carried by an atom of any univalent element (such as hydrogen) in electrolysis. The term "corpuscle" was the name given by Sir J. J. Thomson to the carriers of electricity discharged from incandescent objects (such as cathodes in vacuum tubes). Thomson's research on the discharge through vacuum tubes showed this corpuscle to have a negative charge equal to one electron. Thus the two terms, electron and corpuscle, may be used indiscriminately if we understand by the term electron the natural unit of negative electricity, whereas the positive unit of electricity is designated by the term "positive electron". This latter quantity, although having the same absolute value as the (negative) electron, is found always to be associated with a mass about 1800 times that associated with the (negative) electron.

Electrons are found mostly bound by strong forces to the nuclei of atoms which carry positive charges, the atoms as a whole being electrically neutral. The fact that gases and vapours have an extremely low conductivity shows that very few free electrons are present, free electrons being defined as electrons not bound in electrically neutral systems.

The process by which these "bound" electrons are dislodged from the nuclei of the atoms, i.e., the overcoming of the forces that hold the electron in the atom, may be accomplished by three agents:

(1) Impact of electrons on the neutral atom.
(2) Electro-magnetic radiation.
(3) Heat.

These methods, in turn, give rise to three important phenomena respectively, delta rays, photo-electrons, and thermionic rays. In all cases the results are the same, i.e., the dislodgment of charged particles, but the "agent" causing the discharge is different. Since all three phenomena are connected with the study of the thermionic valve, some theoretical and experimental facts will now be noted briefly.

Ionization

The process of ionization consists in the detachment of one or more electrons from the atom, thus rendering it positively charged, i.e., producing a positive ion. Therefore, in order to ionize an atom the forces holding the electrons to the nucleus must be overcome. The energy which must be expended to accomplish this depends on the number of electrons in an atom, on their configuration, and also on the nuclear charge.

The least energy with which an electron must collide with an atom, in order to completely detach an electron, is known as the ionization energy. T is may be expressed in terms of the voltage through which the impacting electron has dropped before it collided with the atom - the ionization potential.

This ionization potential plays an important role in thermionic vacuum tubes which contain some residual gas. Ionization always occurs providing the voltage between cathode and anode exceeds this potential.

There always remains some residual gas in even the most carefully evacuated tubes, so if a thermionic tube is operated at voltages exceeding this critical value for the residual gas, ionization by collision will occur, thus producing positive ions and "secondary" electrons which increase the electron flow. In this manner the "plate current", i.e., the electron flow, is greatly augmented, and although the characteristics are distorted and unstable conditions are produced, the amplification is greatly increased.

The Photoelectric Effect

The process of the dislodgment of electrons from solid bodies by means of electromagnetic radiation is defined as the photoelectric effect. The electron in the atom is stimulated by the energy of the light wave striking the substance and may thus acquire sufficient energy to overcome the force of attraction at the surface of the substance and escape with a velocity dependent upon the energy in the light wave and the amount of work the electron must perform to overcome the surface force. This force is defined as the electron affinity. The emitted electrons will possess velocities ranging from zero to a definite maximum value due to the fact that some of the electrons are situated near the surface, whereas others further in the interior have to force their way out.

It has been shown experimentally that the only factor influencing the average velocity of emission in any particular substance is the frequency of the emitted light. For the same frequency and different substances, the emission velocity depends on the electron affinity.

It is found in dealing with thermionic valves that the grid current is increased by photoelectrons emitted by the control grid under the action of light from the filament. These effects are undesirable and care must be taken to eliminate them to as great an extent as possible for very sensitive work.

Thus as the photoelectric effect is introduced in the study of thermionic valves and as it is usually the current from a photoelectric cell that is desired to be measured, it is desirable to understand the fundamentals underlying the phenomenon of photoelectricity. However, as it is the problem of the thermionic valve that is desired to be stressed in this discussion, the mere mention of the subject of photoelectricity seems sufficient.

Thermionics

Thermionics is the study of the emission of electrons from a substance, due to increased thermal agitation of the atoms of that substance. If a substance contains electrons that are not bound to atoms to form electrically neutral systems, the substance must be conducting, because if it were placed in an electric field the free electrons would move in the direction of the electric field and thus establish a current in the substance. Thus to account for the conductivity of metallic substances the assumption has been made that metals contain a large number of free electrons. These free electrons and the atoms contained in any substance possess kinetic energy and are in a state of constant motion. A force which tends to keep the electrons and atoms in that substance - electron affinity - is assumed to exist at the surface. This assumption, made by O. W. Richardson in 1901, can be explained in a manner entirely consistent with our physical conceptions.

So that it may escape from the surface of the substance, an electron must do work in overcoming this force which tends to hold it in the substance, the work being performed at the expense of its own kinetic energy.

The kinetic energy possessed by the average electron is so small at ordinary temperatures, compared with that necessary to overcome this force, that only a few escape, the number escaping increasing rapidly as the temperature is increased. Thus, if the temperature be high enough, the value being dependent on the type of substance dealt with, a thermionic current or electron current occurs.

Thus, the electron affinity determines the number of electrons that will escape per second at any temperature from any special type of cathode, i.e., determines the thermionic current, and is characteristic of the substance employed as cathode.

Thus, it is advantageous to have the electron affinity as small as possible due to the fact that the power used in heating the cathode in order to obtain a definite thermionic current decreases as the electron affinity is decreased. This implies economy of operation as well as increased life of the tube, because of the lower temperature at which the cathode can be operated.

The electron affinity also determines the contact electromotive force of a metal. An illustration of this phenomenon is the development of a difference of potential between two different metals when placed in contact, then separated. Since an electron must do work in escaping through the surface of a metal, then two points, one outside and the other inside the surface, must be at a difference of potential.

The contact potential and electron affinity depend on the nature of the surface of the metal. Thus, a thin film of gas will alter these quantities and therefore, a change in the thermionic current obtainable from the substance will result. It has been found that the contact potential plays an important role in thermionic amplifiers designed to operate on small plate voltages.

The phenomenon of thermionics was studied as early as 1882 by Elster and Geitel who found that when a metallic filament was placed near a plate, the plate acquired a charge when the filament was heated to incandescence. This effect also came to the notice of Edison in 1883. J.A. Fleming(8) in 1896 also studied this effect, but it was J.J. Thomson(9) and O.W. Richardson who rendered a true explanation of the phenomenon when they showed that negative electricity was given off from the hot filament in the form of electrons.

Richardson(10) in 1901, showed that the electrons

(8) Philosophical Magazine, Vol.42, p.52, 1896
(9) Philosophical Magazine, Vol.48, p.547, 1899
(10) Proc.Camb.Phil.Soc. P. 286, 1901
Phil. Trans.Roy.Soc.P. 497, 1903

were emitted solely by virtue of their kinetic energy and need no chemical reaction at the surface of the filament. His theory was based on the assumption that the electrons in a metal, which are free to move under the influence of an electric field, behave like the molecules of a gas, having velocities distributed according to Maxwell's Law. These electrons are held in the substance by a force existing at the surface of the substance. At ordinary temperatures very few electrons possess sufficient kinetic energy to overcome this force. The number escaping at such temperatures is, therefore, extremely small. At any time some electrons have zero velocity, others extremely high velocity, the majority, however, possessing velocities ranging between these two extreme values. The energy W which an electron must expend in order to overcome the force of attraction at the surface is related to the number of electrons per cubic centimeter inside and outside the surface by the Boltzmann Equation(11) namely,

$$W = kT \log \frac{N}{n} \tag{2}$$

This equation expresses the fact that as the temperature increases, the number of electrons excaping from the surface of the substance will increase.

It must also be noted that contact electromotive

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(11) Van Der Bijl, Thermionic Vacuum Tube, p.25

forces must exist between the protusions and hollows of irregular surfaces. These drops in potential will be small, but if the irregularities are close to one another, the resulting electrostatic fields may be very large. Therefore, in a thermionic valve, very large plate potentials will be necessary to overcome these fields and pull all the electrons emitted to the anode. This effect also occurs if the cathode possesses impurities with different electron affinities, there being no well-defined saturation current in thermionic valves having such cathodes. This is, however, not a distinct disadvantage in thermionic tubes.

After this brief insight into the electron theory, photoelectric and thermionic effects, our attention will now be focussed on the consideration of an application of these subjects - the thermionic vacuum tube, the device that has afforded the basis of research and development work for the past decade and which has become one of the most important and useful instruments of modern physical experimenters.

THE THERMIONIC TUBE

The thermionic tube, or thermionic valve, consists in its most general form of an evacuated vessel containing a filament which is heated by passing a current through it, an anode, usually in the form of a plate or two plates, or a cylinder surrounding the filament, and a third electrode in the form of a wire grating situated between the filament and the anode. The heated filament emits electrons which are drawn to the anode under the influence of a potential difference between the filament and anode, in such a manner as to maintain the anode positive with respect to the filament. The third electrode, known as the control grid, functions as the controlling element, and is employed to control the flow of electrons from the filament to the anode. The electron current flowing from filament to anode can be varied by applying potential variations to the grid.

At the time of its introduction in 1901, Richardson's explanation of the mechanism of the emission of electrons from hot bodies was not regarded as possessing any great practical value. However, in 1905 Fleming applied Richardson's principle when he conceived the idea of utilizing a thermionic tube as a rectifier for the detection electromagnetic waves. De Forest in 1907 introduced the control grid. It was the insertion of this third electrode which has made the thermionic tube a device of tremendous potentialities - one that can justly be placed in the same category with such fundamental devices as the steam engine and the telephone. The introduction of the grid at once rendered the possibility of amplification and it was immediately utilized as an amplifier and oscillator generator. As early as 1914, the three-electrode valve was used as a repeater in the commercial system of telephone communication, and by 1915, transmission of speech by radio was successfully accomplished.

A brief account of the simplest types of thermionic tubes, namely, the two-electrode vacuum tube and the three electrode vacuum tube will now be rendered. However, in this discussion, no attempt will be made to treat the subject in detail to any extent, this being deemed unnecessary in view of the fact that a very complete discussion of thermionic valves and the factors limiting the flow of current through such valves has been dealt with in preceding communication by Gertrude L. Bradley(12).

The Simple Two-Electrode Vacuum Tube

The simplest form of a thermionic tube contains two electrodes, a cathode which may be heated to any desired temperature, and an anode or plate, placed in an evacuated vessel. (Figure I) This form of vacuum tube is often called a "diode", the family name for two-electrode vacuum tubes. For any definite temperature of

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(12) A low Voltage Direct Current Amplifier,-G.L.Bradley
A thesis presented to the Department of Physics in the University of Manitoba, April, 1933.

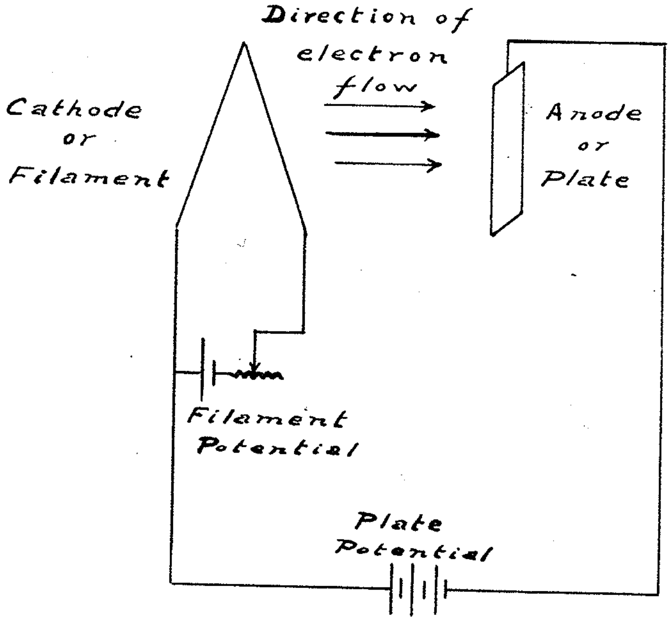

FIGURE 1.

The Two-Electrode Tube Circuit.

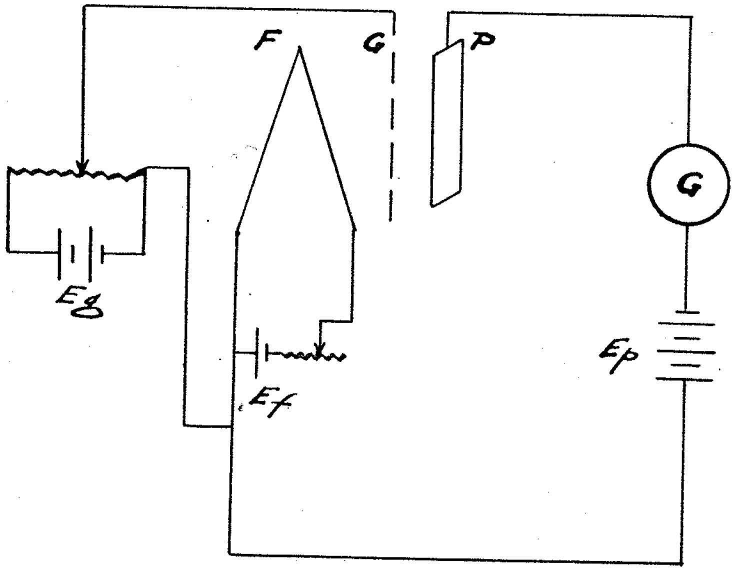

FIGURE 4.

The Three-Electrode Tube Circuit.

the cathode, obtained by applying a certain potential to the cathode E_{f_1}, the electron current to the anode, for various potentials applied between the cathode and anode, the anode being made positive with respect to the cathode as in Figure I below, renders a curve of the general form $A_1B_1C_1$ shown in Figure 2. Any application of additional anode voltage above that at point B_1 of the curve results in practically no further increase in the current. Thus, this upper section, B_1C_1 of the curve is termed the "saturation current." However, should a different potential, E_{f_2}, be applied to the cathode, a different curve $A_2B_2C_2$ is obtained, having a different saturation point B_2. In actual practice, the saturation current sections, B_1C_1 and B_2C_2 are not truly horizontal but slope slightly upward.

One of the factors placing this limitation on the electron current is the repelling effect on the electrons emitted from the cathode by the electrons in the space between the cathode and anode, due to the space charge of the electrons in the space. Lenard, Stoletow and Von Schweidler, in their early experiments on the photoelectric effect noticed this limitation of current by space charge when the current is caused only

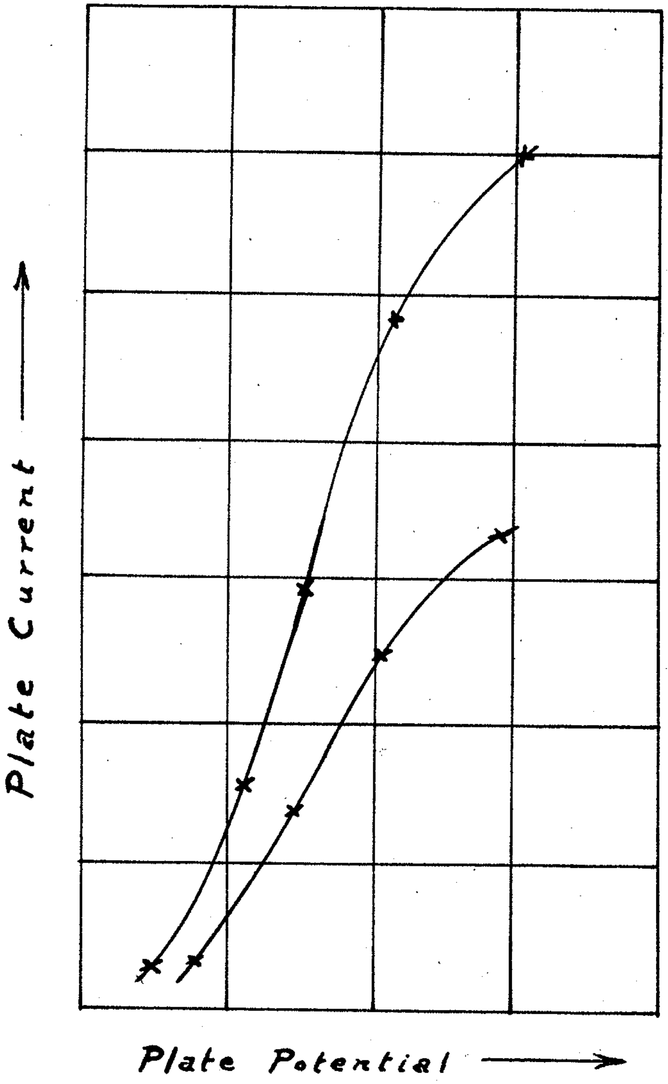

FIGURE 2

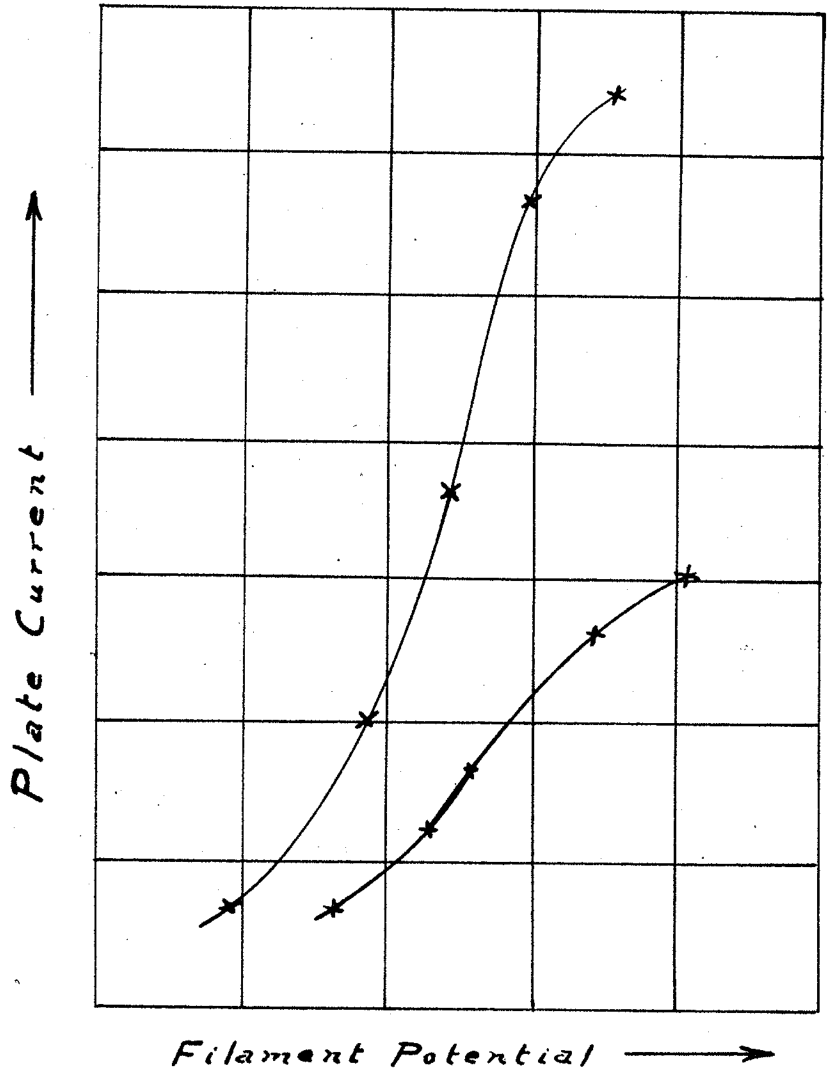

FIGURE 3

by electrons. This effect also came to the attention of Soddy(13) during the course of his experimentation with metallic oxides in 1907. The true explanation of the decreased current, however, was not rendered until 1908 when O.W.Richardson(14) and J.E. Lilienfield(15) gave an explanation of the negative space charge.

The limitation of current by space charge can be briefly demonstrated in a qualitative manner as follows: Let a definite voltage E_{p_1} be applied between the cathode and anode. Now if the current to the anode be observed as a function of the cathode potential (i.e. the cathode temperature), the current will at first increase until it reaches a value F_1 (Figure 3). Any further increase in the cathode potential will not cause a further increase in the current, and the section F_1G_1 of the curve is obtained. This current is referred to as the "temperature saturation current." Beyond the point F_1 no further current increase is noted because so many electrons are emitted that the resulting volume density of their charge causes all other emitted electrons to be repelled, and these return to the cathode.

(13) Nature Nov. 1907, P. 53
(14) Nature Jan. 1908, P.197
(15) Phy. Zeitchr. 1908,P.193, Vol.9

Should the anode potential be increased to E_{p_2} the current will be found to increase, since more electrons are drawn away from the cathode. Thus the temperature must be raised to F_2 before full space charge can manifest itself. Thus, the higher the applied voltage, the higher the cathode temperature must be to obtain full space charge effect.

The Three Electrode Vacuum Tube - The action of the Control Grid - Control of Space Current

A schematic diagram of the three-electrode vacuum tube circuit embodying the voltages applied to the filament, plate and control grid is shown in Figure 4 and the description is given below. The meanings of the various symbols employed in the diagram are:

P = Plate or anode

G = Control Grid

F = Filament or cathode.

E_p = Battery rendering P positive with respect to F.

E_g = Battery rendering G negative with respect to F.

E_f = Battery to heat filament or cathode.

The quantitative effect of this third electrode - the grid - was first given by Van der Bijl in 1913. A short account of this effect will now be given.

The positive potential of P results in the drawing of electrons from F, through G, to P. The negative potential on G has the tendency to drive them back to F, so that by increasing E_g, a value may be reached for which all emitted electrons are driven back to the cathode.

If $E_g = 0$ and the contact potential between F and GP is supposed zero, then the electric field between F and G has a definite value, dependent upon the construction of the tube and the difference of potential between F and G (F and G are now supposed to be metallically connected). This is due to the fact that the potential of P causes a stray field to act through the openings of the grid. If the potential difference between P and FG be equal to E_p the field at a point near F is equivalent to the field that would be sustained at that point if a potential difference equal to $\frac{E_p}{\mu}$ be applied between the cathode and the grid. In the usual circuit P is positive and the direction of the field is to draw the electrons away from F, but it does not draw electrons to the grid, as would happen if a potential difference were applied directly to F and G, but tends to draw electrons to P, through the openings of G.

As well as this stray field there is the contact potential difference K between F and GP. Hence, if K be reckoned positive when it tends to draw electrons away from the cathode and if the maximum velocity of emission, expressed in volts, of the electrons liberated from the cathode be V, then in order to drive all the emitted electrons back to the cathode, a potential difference must be applied between F and G given by the expression:

$$E_g = \frac{E_p}{\mu} + \epsilon \qquad (3)$$

where E_g = the potential difference to be applied between F and G.

μ = amplification constant (definition to be rendered later),

and $\epsilon = K + V =$ constant.

This expression can be regarded as the effective voltage when the potential difference between the grid and filament is zero.

This expression really implies that if the grid and filament are at the same potential, a potential difference E_p between filament and plate causes a stray field to act through the openings of the grid, which is equivalent to the field that would be produced if a potential difference equal to E_p were applied directly between filament and grid.$\overline{\mu}$

The small quantity ϵ represents an intrinsic potential difference between the filament and the system constituted by the grid and plate. The constant μ depends on the operating voltages. If now a potential difference of magnitude E_g be applied directly between filament and grid, the effective voltage in the tube is obtained simply by adding E_s and E_g.

Thus, the effective voltage may be expressed as:

$$\frac{E_p}{\mu} + E_g + \epsilon \qquad (4)$$

The current to the plate can obviously be expressed as a function of this quantity(16)

$$I_p = f\left(\frac{E_p}{\mu} + E_g + \epsilon\right) \qquad (5)$$

where f = a constant, and

I_p = plate current.

A similar expression for the plate current is given by Nottingham(17), this expression only holding over a narrow range of the plate current - grid potential characteristic curve.

$$I_p = \frac{1}{Z_p}\left(E_p + E_g + E_o\right) \qquad (6)$$

where Z_p = plate impedance, to be defined later,

E_o = constant.

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(16) Van Der Bijl, Thermionic Vacuum Tube, p. 146

(17) Nottingham; Jour. Franklin Institute 209, 287, 1930.

Equation (6) is true only when E_o, μ, and Z_p can be treated as constants which are independent of E_p and E_g, for a limited range under consideration. This is quite legitimate as the equation may be experimentally verified. Equations (5) and (6) are of the same form, Ohm's Law being assumed to hold over a small portion of the curve.

CHARACTERISTIC CURVES OF THE THERMIONIC TUBE

Considering equation (5) namely,

$$I_p = f\left(\frac{E_p}{\mu} + E_g + \epsilon\right) \qquad (5)$$

we see that this expression contains two independent variables, E_p and E_g. Therefore, a three-electrode tube circuit possesses at least two families of characteristics - the current as a function of filament - plate voltage E_p, for various negative values of filament - grid voltage E_g, and the current as a function of filament-grid voltage E_g, for various values of the plate potential E_p.

However, due to the fact that the control grid takes some current irrespective of how negative a grid bias is employed, the problem is not so simple. A discussion of the various factors causing this will be rendered at a later stage in this communication. This grid current causes distortions in the grid potential-plate current curve.

However, to predict the action of a thermionic tube functioning as an amplifier, there are two fundamental families of curves to be taken into consideration, namely, the grid potential-grid current family, and the grid potential-plate current family. These families will now be considered in turn.

1. Grid Potential-Grid Current

Figure 5(b) shows a typical grid potential-grid current curve, obtained from a UX 201A tube. Figure 5(a) shows the circuit employed in obtaining this curve. The meaning of the various symbols employed in the diagram are:-

E_g = Grid bias battery
E_f = Filament battery
E_p = Plate battery
v = Voltmeter
G = Galvanometer to measure the grid current

The grid current may be considered as being composed of four various components:

1. Grid to filament leakage current.
2. Plate to grid leakage current.
3. Positive ion current, due to the ionization of the residual gas and due to the emission of positive ions by the filament.

4. Electron current to the grid. When the grid is slightly negative with respect to the negative terminal of the filament, a certain number of electrons are able to overcome the adverse negative potential between the filament and grid because of their initial kinetic energy, which is due to the high temperature of the filament.

Arising from a grid current curve, such as Figure 5(b) are two important quantities - Grid Impedance and Grid Conductance - which will now be defined.

(a) Grid Impedance

This quantity is defined as the reciprocal of the slope of the grid current curve. It is evident from Figure 5(b) that this quantity is positive for small negative values of the grid potential and negative for larger negative values of the grid potential. Thus,

$$Z_g = \frac{d\ E_g}{d\ I_g} \qquad (7)$$

where Z_g = grid impedance

dE_g = small change in grid potential

dI_g = small change in grid current

(b) Grid Conductance

The slope of the curve relating the grid potential to the grid current is defined as the grid conductance.

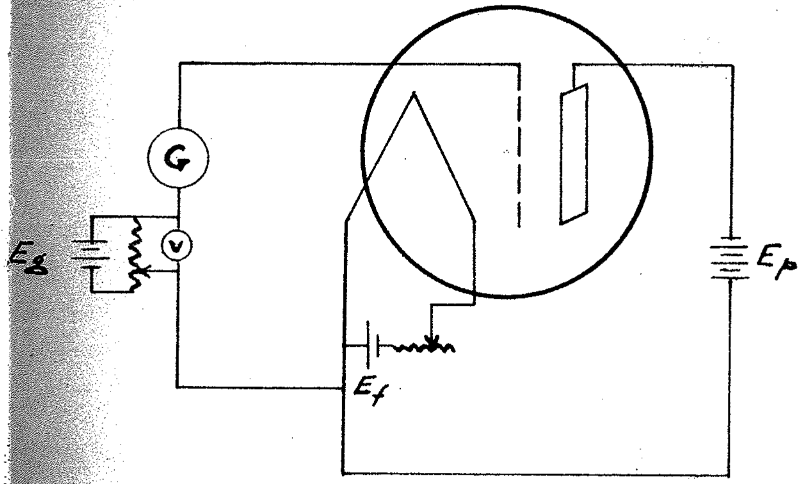

FIGURE 5a.

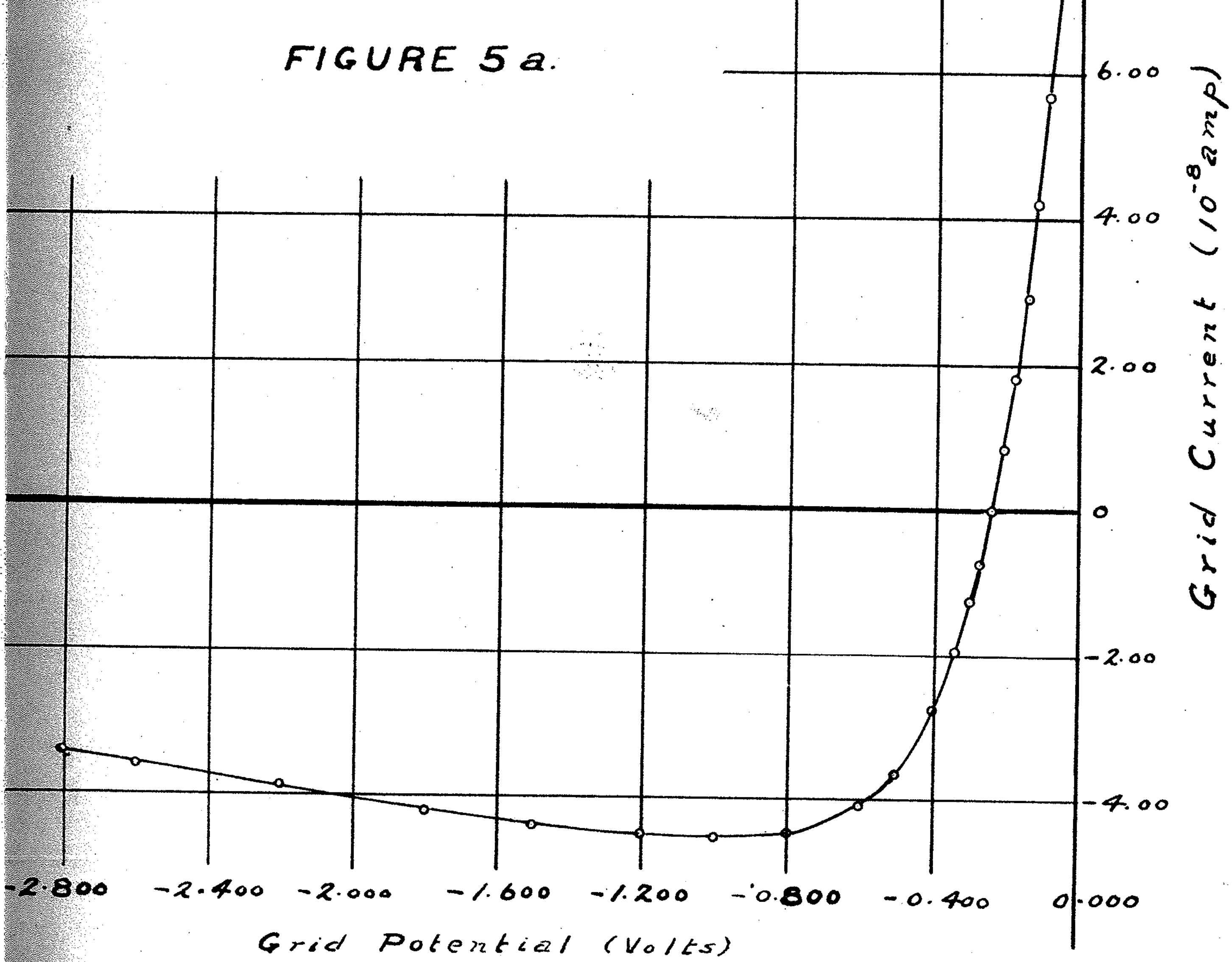

FIGURE 5b.

Thus,

$$G_g = \frac{d\ I_g}{d\ E_g} \qquad (8)$$

where G_g = grid conductance .

II.Grid Potential-Plate Current

A diagram of the circuit for the measurement of the plate current characteristic and a typical curve obtained is given in Figures 6(a) and 6(b) respectively. The meanings of the symbols employed in Figure 6(a) are:

E_g = Grid bias battery

E_f = Filament battery

E_p = Plate battery

V = Voltmeter

G = Galvanometer to measure the plate current.

The magnitude and form of such a curve as that shown in Figure 6(b) are influenced by many factors; thus, in order to predict the sensitivity of the amplifier under any given conditions, the plate current form, for these conditions, must be known.

It is now considered timely to insert several definitions related to the plate current that will be used subsequently in this communication.

Mutual Conductance (G_m).

The mutual conductance is given by the slope

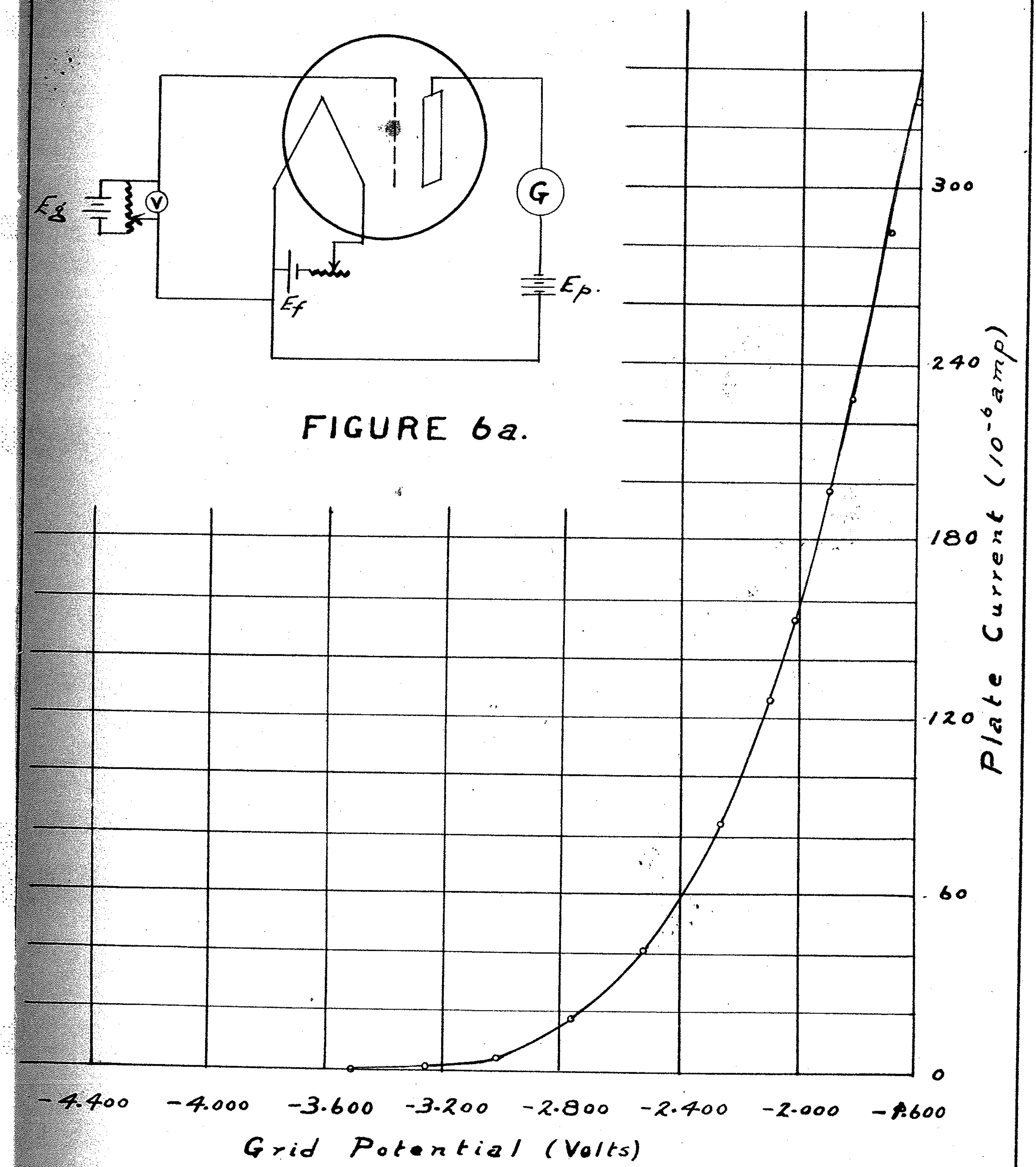

FIGURE 6a.

FIGURE 6b.

of the grid potential-plate current curve at a constant plate potential. An algebraic expression for the mutual conductance is therefore:

$$G_m = \left(\frac{dI_p}{dE_g}\right), E_p = \text{constant} \qquad (9)$$

where G_m = mutual conductance,

dE_g = small change in grid potential,

dI_p = change in plate current.

The mutual conductance renders a measure of the effect of the grid potential on the plate current and, therefore, it is desirous to have as large a mutual conductance as possible, whereas the grid conductance should be a minimum to attain sensitivity in an amplifier. That is, the input current must raise the potential of the grid as much as possible, and this must alter the plate current a maximum extent.

<u>Plate Impedance</u>

The reciprocal of the slope of the grid potential-plate current curve is defined as the plate impedance Z_p, at the corresponding plate and grid potential. This may be expressed algebraically in the form

$$\frac{1}{Z_p} = \frac{dI_p}{dE_g} \qquad (10)$$

A derivation of a simple relation between mutual conductance and plate impedance follows:

By equation (6) we have

$$I_p = \frac{1}{Z_p} (E_p + \mu E_g + E_o) .$$

And by equation (9) we have

$$G_m = \frac{(d\ I_p)}{(d\ E_g)}, E_p = \text{constant} .$$

Thus, differentiating I_p with respect to E_g, E_p constant, in equation (6) we have,

$$G_m = \frac{\mu}{Z_p} . \qquad (11)$$

Amplification Constant μ.

The maximum voltage amplification obtainable from any tube is represented by the amplification constant. It is a function only of the geometry of the tube, being dependent on the mesh of the grid, the diameter of the grid wire, and the distance between the grid and the plate. The grid potential-plate current curves afford a method of determination of this quantity. It is found in practice that this quantity, μ, is not quite constant, its value decreasing with the operating voltages. Expressed algebraically, the amplification constant

$$\mu = \frac{d\ E_p}{d\ E_g} . \qquad (12)$$

Plate Resistance

The resistance of a tube is due to the work which the electrons emitted from the filament must perform in their transport from the filament to the plate. An electron, in moving through the filament must perform an amount of work equal to the electron affinity. In its motion from the filament to the plate, it has to do work in overcoming the contact potential difference between the cathode and anode as well as in overcoming the space charge effect.

The direct current resistance of a tube is given by the ratio of the plate potential E_p to the plate current I_p.

i.e., $$R_p = \frac{E_p}{I_p} \qquad (13)$$

where R_p = plate resistance .

In this discussion thus far an attempt has been made to render some account of the theory, functions, and characteristics of the modern thermionic valve. We will now enter into a discussion of direct current amplification circuits - both simple and complex.

THE SIMPLE AMPLIFIER

As has been indicated previously, the detection and measurement of direct currents in high resistance circuits depend on the observation of a change produced in the plate current of a thermionic tube, resulting from a change in the grid potential. This is usually brought about by the drop of potential produced in the grid resistance by the current being measured.

By studying the grid potential-grid current and grid potential-plate current curves, with operating resistance in the plate circuit, a prediction of the manner in which the plate current of the tube is dependent upon the grid potential may be obtained. That is, the sensitivity of the circuit, defined as the change in the plate current corresponding to a small change in the grid potential, may be thus determined.

$$S_v = \frac{d\ I_p}{d\ E_g} \qquad (14)$$

where S_v = sensitivity to voltage,

$d\ I_p$ = change in plate current,

$d\ E_g$ = change in grid potential.

The Computation of Sensitivity to Voltage

The expression for the plate current in a thermionic tube was given in equation (6) as

$$I_p = \frac{1}{Z_p}(\ E_p + \mu E_g + E_o)$$

Now, the Kirkhoff Law equation for the plate current is:

$$E_p = V_p - R_pI_p \qquad (15)$$

where E_p = plate potential,

I_p = plate current,

V_p = "b" battery potential, and

R_p = plate circuit resistance.

By equation (6) we have

$$E_p = I_pZ_p - \mu E_g - E_o\,.$$

Upon substitution of this value of E_p in equation (15) we have :

$$I_pZ_p - \mu E_g - E_o = V_p - R_pI_p$$

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

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

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

Differentation of I_p with respect to E_g renders the following expression for the sensitivity to voltage of the circuit.

$$S_v = \frac{d\,I_p}{d\,E_g} = \frac{\frac{}{Z_p}}{1 + \frac{R_p}{Z_p}} = \frac{G_m}{1 + \frac{R_p}{Z_p}}\,. \qquad (16)$$

It must be borne in mind that here μ , E_o, and Z_p are considered constants. This assumption is quite legitimate in view of the fact that the final equation (16) above lends itself to experimental verification[18].

We must now consider the relative magnitudes of the factors of this equation.

Should R_p be very small as compared with Z_p the sensitivity would be directly proportional to the mutual conductance. However, if R_p is not small, then the sensitivity is less than the mutual conductance, because Z_p is always positive.

Considering R_p small (the general case) should, in any manner, a drop in potential be impressed on the grid of a vacuum tube, then the resulting change in the plate current would cause a deflection "d" of the galvanometer, which has a sensitivity, say, of $S_g \frac{\text{mms.}}{\text{amp.}}$.

Then

$$\frac{d}{S_g} = \Delta i_p = G_m \cdot \Delta e_g \qquad (17)$$

where Δi_p and Δe_g are the respective changes in plate current and grid potential.

The sensitivity to voltage in $\frac{\text{volts}}{\text{mm.}}$ of such an amplifier is, therefore,

$$S_v = \frac{d}{\Delta e_g} = G_m \cdot S_g . \qquad (18)$$

From this equation it is evident that the only factors to be considered in voltage amplification are

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(18) Nottingham: Journal Franklin Institute 209, 287. 1930

the mutual conductance and the sensitivity of the galvanometer employed in the plate circuit. Thus in any amplification circuit, if a high sensitivity to voltage is to be attained, a tube of high mutual conductance together with a sensitive galvanometer should be used.

The Computation of Sensitivity to Current

In this instance the change in the plate current with a change in any other current in the input circuit is observed.

The Kirkhoff Law for the grid current is

$$E_g = V_g - R_g(I_g - i) \qquad (19)$$

where E_g = grid potential ,

I_g = grid current ,

R_g = input resistance ,

V_g = grid battery, i.e., "c" battery potential ,

i = current being measured, e.g. photoelectric current.

Differentiation of this equation with respect to i gives

$$\frac{d\,E_g}{d\,i} = R_g - R_g \cdot \frac{d\,I_g}{d\,E_g} \times \frac{d\,E_g}{d\,i}$$

i.e., $$\frac{d\,E_g}{d\,i} = R_g - \frac{R_g}{Z_g} \times \frac{d\,E_g}{d\,i} \qquad \text{since} \quad \frac{d\,I_g}{d\,E_g} = \frac{1}{Z_g}$$

$$\frac{d\,E_g}{di}\left\{1 + \frac{R_g}{Z_g}\right\} = R_g$$

$$\frac{d\ E_g}{di} = \frac{R_g}{1 + \frac{R_g}{Z_g}} . \qquad (20)$$

If R_g be small in comparison to Z_g, then

$$\frac{d\ E_g}{di} \doteq R_g \qquad (21)$$

or, that is, the change in grid potential is equal to the drop in potential produced by the photoelectric current over the grid resistance.

However, Z_g may be either positive or negative, depending upon which part of the grid current characteristic the amplifier is operated. Thus, the change in grid potential may be either greater or less than the drop across the grid resistance.

If Z_g be negative and R_g be adjusted to approach the value Z_g then $\frac{d\ E_g}{di}$ becomes very great, since in this case, the denominator approaches zero.

Now, equation (16) expressed the voltage sensitivity as

$$S_v = \frac{dI_p}{dE_g} = \frac{G_m}{1 + \frac{R_p}{Z_p}} , \qquad (16)$$

and equation (20) gave (20)

$$\frac{d\ E_g}{di} = \frac{R_g}{1 + \frac{R_g}{Z_g}} .$$

Thus, on combining these equations the resulting expression is of the form

$$\frac{d\ I_p}{di} = \frac{G_m}{1 + \frac{R_p}{Z_p}} \cdot \frac{R_g}{1 + \frac{R_g}{Z_g}} . \qquad (22)$$

This renders an expression for the sensitivity to current of an amplification circuit.

$$S_c = \frac{d\ I_p}{di} = \frac{R_g}{1 + \frac{R_g}{Z_g}} \cdot S_v . \qquad (23)$$

However, on the other hand, if Z_g be positive, and all other quantities constant with the exception of R_g the sensitivity will increase with R_g reaching an upper limit when $R_g = \infty$.

$$\left(\frac{d\ I_p}{di}\right)_{R_g = \infty} = \frac{G_m}{1 + \frac{R_p}{Z_p}} \cdot Z_g . \qquad (24)$$

This equation expresses the floating grid condition. Thus, in the comparison of two tubes, the one with the higher input impedance at the floating grid potential will have the higher sensitivity, if the mutual conductances are identical.

A much higher sensitivity to currents is obtained, however, when Z_g is negative, and this state may be accomplished by the application of sufficient negative bias to the control grid.

The sensitivity of any amplification circuit, however, is limited by its freedom from irregular disturbances which arise in general from three sources:

1. External apparatus.
2. Batteries
3. Thermionic emission of valve filament.

A brief account of these irregularities and how they may be offset to a considerable extent will now be undertaken.

1. External Apparatus

In general any amplifying circuit is very sensitive to high frequency disturbances. These disturbances may be avoided by completely enclosing the apparatus in a conducting earthed shield.

2. Batteries

Any changes in the potential between grid and filament will be amplified irrespective of whether they are caused by the current from the photocell or by changes in the voltage of the batteries. Absolute constancy of the filament battery and the grid bias battery especially is imperative. Variations in the plate voltage must also be minimized to as great an extent as possible although this is of less importance since these variations are reduced effectively by the magnification factor of the valve.

It is impossible to completely avoid the slow regular voltage variations encountered as the batteries run down but these are, in general, of little importance. Trouble arises only from rapid and irregular battery variations.

3. Thermionic Emission of Valve Filament.

This effect is caused by minute changes in the surface residual gas. Alterations of the electric field or the filament temperature may cause this gas to be shifted to or from the filament surface and so change the characteristics, both grid potential-plate current and grid potential-grid current families. For this reason it is advisable not to operate the amplifier for some little time after the filament potential has been applied in order that a steady state of filament temperature may be attained.

As has been implied in the foreword of this communication, the amplified current must approximate the same order of magnitude as the plate current in order to record the amplified current on the galvanometer scale. Thus, the smaller the plate current, the more sensitive the amplifier, all other factors being constant.

Figure 8 shows a circuit exhibiting the principle of the usual method of reducing the plate current flowing through the galvanometer namely, the application of a reverse electromotive force to the galvanometer from an auxiliary source.

A current I_c, whose magnitude is controlled by the resistance R_c, is caused by the auxiliary battery K. This current flows through the galvanometer G in the opposite direction to the plate current I_p, thus balancing I_p out of the circuit and allowing only the amplified current to be recorded on the galvanometer. In this manner the instrument may be increased in sensitivity limited only by the degree of exactitude and constancy of the balance.

Greater sensitivity may yet be obtained by balancing out the plate current by a second vacuum tube, whose characteristics have been adjusted to match those of the amplifying tube so that fluctuations in the operating potentials are compensated in the plate circuit.

THE BRIDGE AMPLIFIER

In the bridge circuit, the plate current from the valve amplifying the current to be measured is

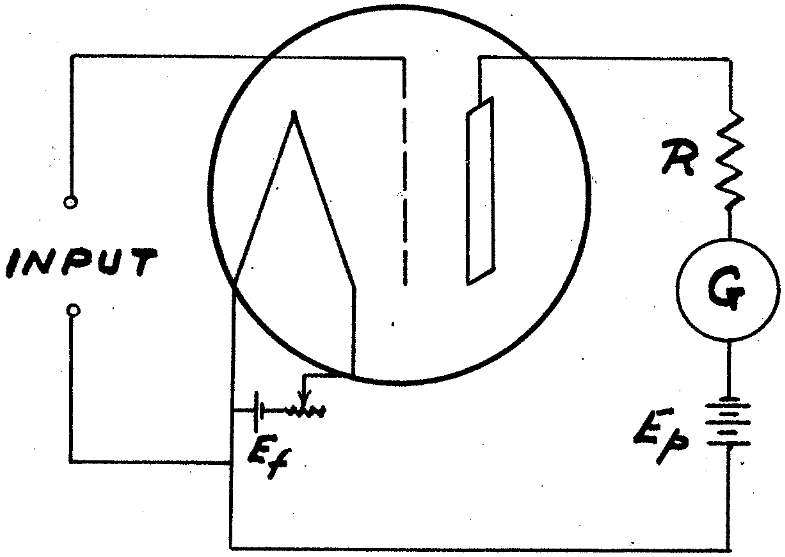

FIGURE 7.

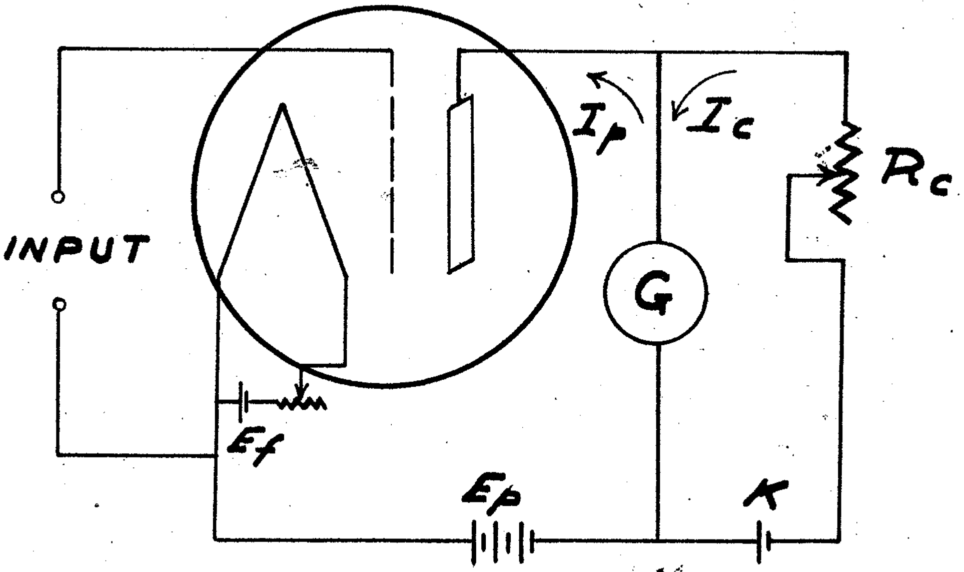

FIGURE 8.

compensated by the plate current from a similar valve whose grid is maintained at a fixed potential. The gain of regularity in this circuit more than makes up for the loss in ideal sensitivity.

This principle was first recognized by Wold(19) in 1916 when he described an amplifier consisting of a Wheatstone bridge arrangement, the amplifying tube in one arm and the balancing tube in the other. This was followed in 1921 by J. Brentano's(20) method of measuring ionization currents by three-electrode tubes in a bridge circuit. Brentano's current measurements were made by the steady deflection galvanometer method. He claimed a sensitivity to voltage and current of 1.2×10^{-4} $\frac{\text{volts}}{\text{mm}}$ and 3×10^{-13} $\frac{\text{amps}}{\text{mm.}}$ respectively employing this circuit.

A schematic diagram of Brentano's circuit is shown in Figure 9. Valves V_1 and V_2 are connected through equal resistances T_1 and T_2. One terminal of each of these resistances is connected to the positive pole of the plate battery V_p, the other being connected to the galvanometer G. The heating currents through the filaments are regulated by the resistances R_1 and R_2. Each of the grids may be connected to the positive plate of an ionization chamber through C_1 and C_2.

(19) U. S. Patent No. 1232879 - 1916-17
(20) Nature, Dec. 22, 1921.

The heating currents are set so as to give equal plate currents through both valves, when the grids are insulated. However, when one grid becomes charged due to the ionization current, the plate current through the valve is altered, and the galvanometer current is altered a corresponding amount. By insertion of an electromotive force in one valve circuit by means of battery and resistances, the two tubes may be matched. Fluctuations in the heating currents and in the plate potentials are thus reduced since the heating currents for the filaments and plate voltages are supplied from the same sources for both valves.

The next publication was not forthcoming until 1927 when a description of a valve amplifier to replace the electrometer for the measurement of ionization currents of the order of 10^{-12} ampere was rendered by C.E. Wynn-Williams(21). This circuit was not applicable to measurements of the nature of X-ray ionization currents. Wynn-Williams, however, in 1928 published a modification of this circuit(22), wherein certain precautions were taken as to shielding, etc., so that any direct currents, of the magnitude of 10^{-12} - 10^{-13} ampere, might be measured, irrespective of their source. This method was

(21) Proc. Camb.Phil.Soc., 1927, XXIII, Page 811.
(22) Phil. Mag. August 1928, page 324.

identical to that of Brentano with a few minor alterations. The current sensitivity was not increased, obtaining only 10^{-12} - 10^{-13} ampere, and the scale was found to be not strictly linear. Fluctuations of the potentials of batteries thus producing continuous or slightly different changes in the two plate currents, rendered an unsteady zero.

Artificial matching was then resorted to so that a steady zero might be attained. This was accomplished by the adjustment of the two series filament resistances, which were composed of two portions of a slide wire, until small changes in the battery voltages produced no change in the galvanometer deflection. This was an improvement over the method of Brentano, which had two independent variable resistances, R_1 and R_2 (Figure 9).

A criticism of Wynn-Williams' publication of August 1928 was given by Brentano(23) in 1929 when he described a vacuum tube circuit using hard vacuum tubes which were not available at the time of his first publication in 1921. With this set-up a sensitivity of 4 x 10^{-14} amperes and 2 x 10^{-5} volts was obtained. Brentano pointed out that his method published in 1921 did not differ from that of Wynn-Williams except in one

(23)- Phi. Mag. 1929

unimportant detail - the introduction of the slide wire described above. He also claimed that the sensitivity of Wynn-Williams' circuit was limited due to irregularities causing unsteadiness of the zero. The increase of the capacity of the one grid when connected to the ionisation electrode was neglected by Wynn-Williams. These capacities should be of the same order of magnitude, the exact values being dependent upon the characteristics and the insulation of the grids.

In the previous circuit, employing soft valves, it was impossible to get a sufficiently dense space charge near the filament. Hence the plate current would vary greatly with the change in temperature of the filament. Thus the control of the heating current became important. However, using the highly evacuated tubes now available, the fluctuations of the heating current had very little effect under suitable conditions.

The important developments noted in this circuit in comparison with earlier circuits are: the employment of screen grid type valves to obtain greater stability; the inner grid of the compensating valve 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.

J. M. Eglin[24] in 1929 published some further improvements on this type of direct current amplifier. The improvements were the result of the following modifications:

1. A resistance was inserted in series with the tube in one arm of the bridge to render compensation for variations in plate and grid battery voltage.

2. The tubes were suspended to offer protection from mechanical vibrations.

3. Tubes with pure tungsten filaments were employed so as to avoid changes in contact potentials. The plates enclosed the filaments completely to lower the effect of wall charges.

Figure 10 shows a schematic diagram of Eglin's circuit.

Wynn-Williams connected one terminal of the input circuit to the grid of one tube, and the other terminal to the filament. This rendered the leakage of the grid-filament a portion of the input circuit.

The tube T_1, in Figure 10, takes a voltage obtained from a small current passing through the high resistance R_{g_1} in the grid circuit, and effectively transfers this voltage (amplified by the action of the tube) to the plate circuit.

(24) J.O.S.A. and R.S.I Vols. 18-19, 1929.

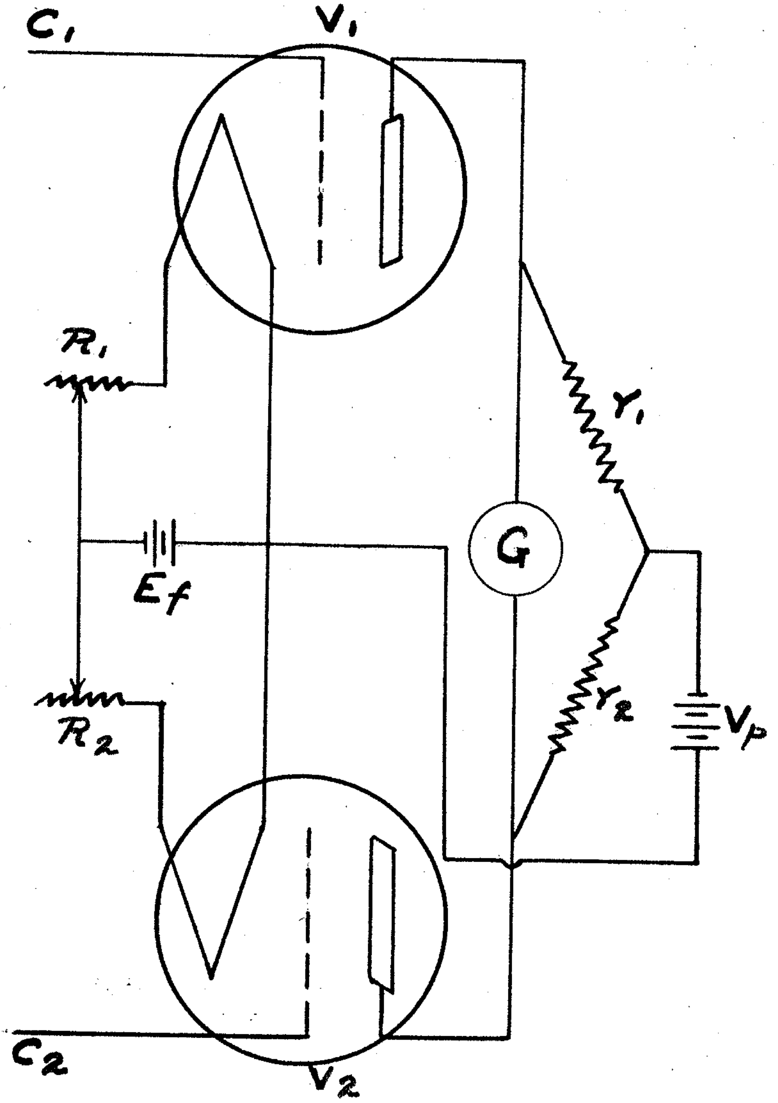

FIGURE 9.

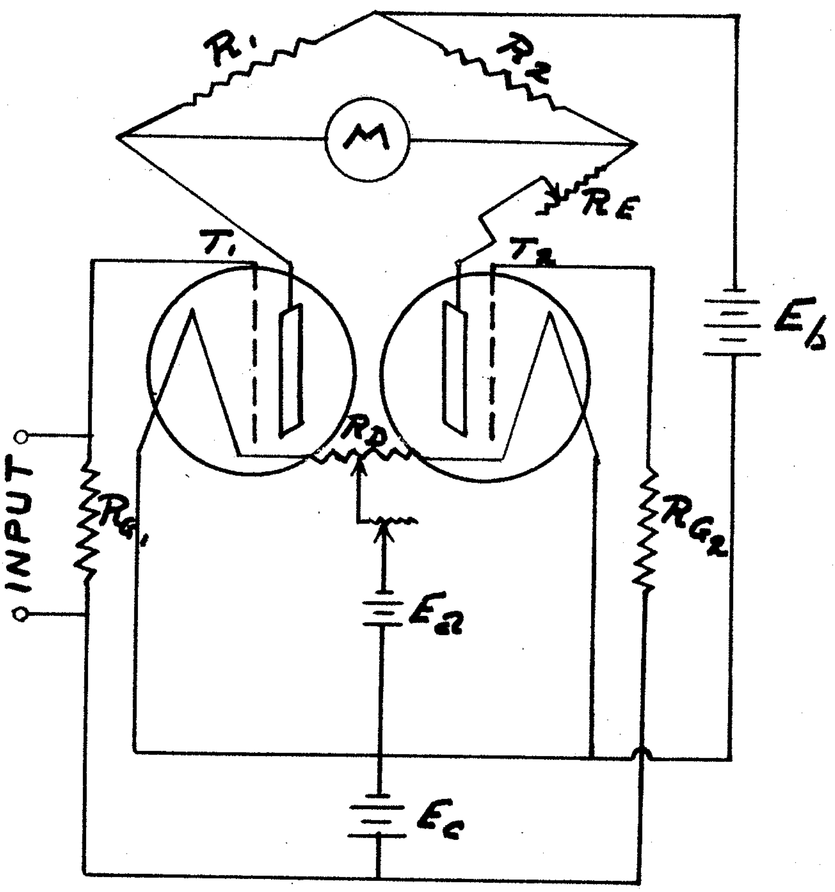

FIGURE 10.

The grid battery E_c is made sufficiently large so that the electron current to the grid is almost negligible. This grid current was considered by Eglin to be too minute 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 factors upon a grid voltage-grid current characteristic. Then the variation of the plate currents would be due only to the departure from linearity of the plate current-grid voltage characteristics of the tube, and the fluctuations of the potential supplies.

The changes in the filament voltage may alter 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. Fluctuations in plate voltage are compensated for by a resistance R_z in series with the second tube.

P. J. Mulder and J. Razek(25) in 1929 described a simple circuit employing high resistors in the grid circuit. They have shown the alterations in the grid potential-plate current characteristics of a CX-312A tube, caused by introducing resistances into the grid

(25) J.O.S.A. and R.S.I., Vols. 18-19 , June 1929.

circuit (see Figure 11). The curve with the circles is the normal grid potential-plate current characteristic whereas the others represent the characteristic after introducing various grid resistors into the circuit.

The 2710 megohm curve had a very steep portion. This curve was found to be irreversible. For the tube used, grid resistors up to 1800 megohms could be introduced with the assurance that the curves obtained would be reproducible.

The explanation of the curves in Figure 11 was found to lie in the grid currents. Flat portions to the right of the normal characteristic, where the grid is only slightly negative, are due to the current of electrons picked up by the grid. The portions on the other side of the normal characteristic are caused by current in the reverse direction. Here the grid is more negative and the current is predominantly or entirely due to the positive ions collected by the grid. From these curves it may be seen that the introduction of resistance into the grid circuit makes the slope of the characteristic greater so long as positive ion grid current flows.

The tube has been successfully used in this manner by Mulder and Razek for the amplification of

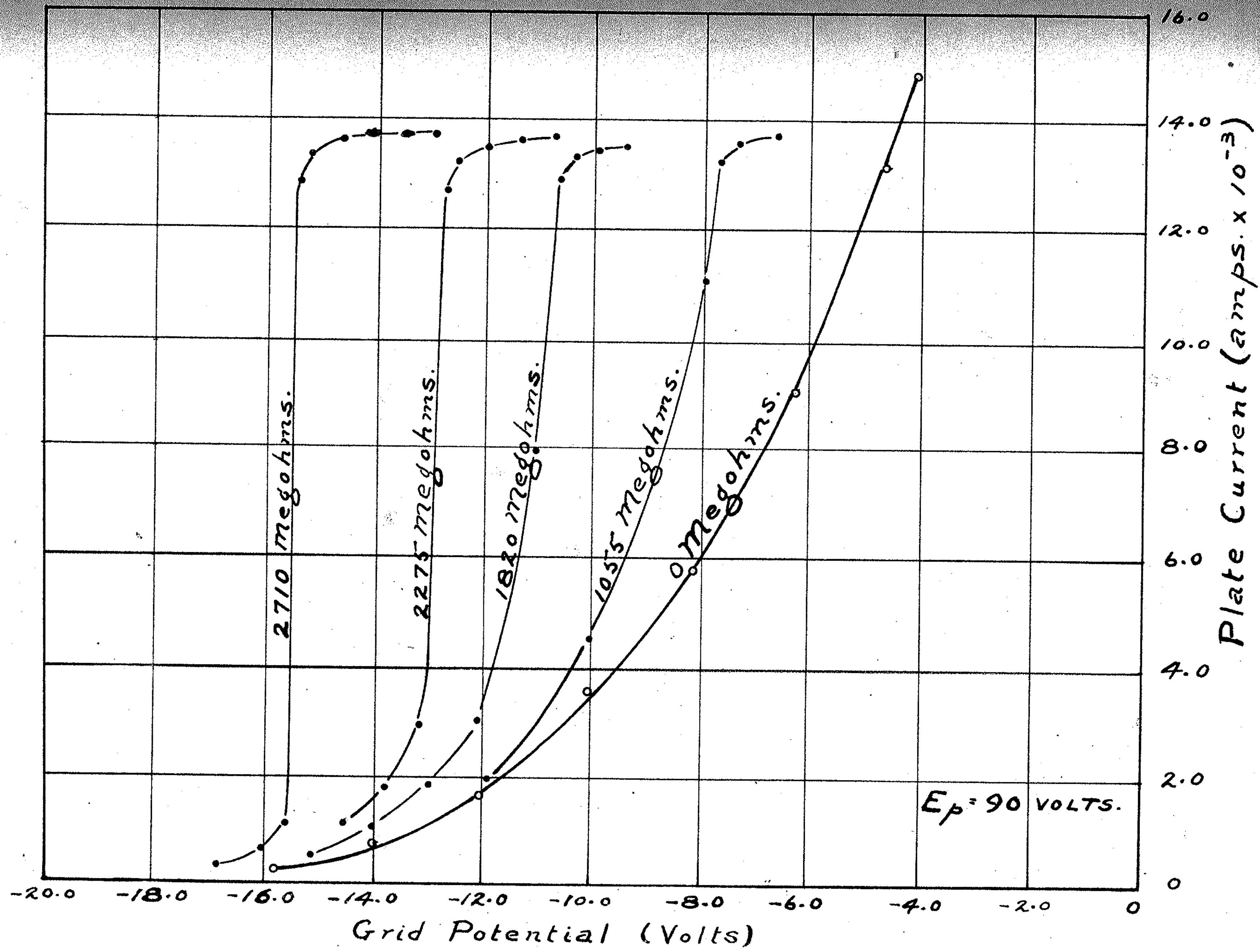
2710 megohms.
2275 megohms.
1820 megohms.
1055 megohms.
0 Megohms.
Ep = 90 VOLTS.
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
Plate Current (amps. x 10^-3)
-20.0
-18.0
-16.0
-14.0
-12.0
-10.0
-8.0
-6.0
-4.0
-2.0
0
Grid Potential (Volts)

FIGURE 11.

photoelectric currents.

Great difficulty was encountered inobtaining resistors of high values that possessed constancy of value over any lengthy interval of time. Razek and Mulder found that xylol and alcohol sealed in glass tubes with sealed in contacts proved satisfactory for periods not exceeding a few months.

The above authors(26) have also dovoloped a bridge circuit using high resistors in the grid circuits. In this circuit:

1. The mutual conductance was to be as large as possible; consequently, power tubes were employed.

2. Common filament, common plate, and common grid batteries were used so as to reduce fluctuations due to batteries.

3. The use of a single battery for the filament, the plate, and the grid bias voltage was found to simplify the process of reducing fluctuations considerably.

It was found possible to supply both filaments from the common battery by making them part of a potential divider from which the plate and grid bias voltages are taken.

A more detailed description of the circuit and the method of balance used need not be dealt with in

(26) Mulder and Razek, J.O.S.A and R.S.I, Vols 18-19 Dec, 1929.

this communication as balanced circuits are not employed by the writer in his work.

Razek and Mulder claimed a sensitivity to voltage of 1×10^{-5} $\frac{\text{volts}}{\text{mm}}$ and a sensitivity to current of 7×10^{-15} $\frac{\text{amps}}{\text{mm}}$ with this circuit. Their amplifier possessed certain definite advantages over others that had previously been proposed.

1. Ordinary commercial tubes, selected only for high internal insulation, were employed.

2. These tubes could be operated at any points whatsoever on their characteristics.

3. Complete and readily attainable compensation for battery fluctuations was afforded.

4. It made use of the ionization currents to obtain high sensitivity.

Obviously, a bridge amplifier of this sort may be used to replace the quadrant electrometer in many experiments.

From the discussion already given it is evident that considerable success has been obtained employing ordinary type radio tubes, both three-electrode and screen grid types, in amplification circuits. The difficulties encountered were mainly due to the fact that all the thermionic tubes had been designed for amplification of rapidly varying currents, and thus, do not possess characteristics desirable for direct current work.

Up to the time of the introduction of a special type vacuum tube, the FP54 pliotron, for the purpose of direct current amplification, the maximum current sensitivity, obtained using ordinary radio tubes in the bridge circuit, was in the neighborhood of 10^{-14} amperes. Metcalf and Thompson(27) by the use of this special valve, detected currents of the order 10^{-17} amperes, which is a greater sensitivity than that obtained from the best Compton electrometers. Another feature of this circuit was its great ruggedness and dependability as compared to the electrometer circuit.

<u>Low Grid Current Vacuum Tube - FP54 Pliotron</u>

In ordinary tube circuits the internal resistance R_g is shunted by the grid resistance Z_g of the tube itself and hence the total resistance cannot exceed Z_g. At ordinary operating voltages Z_g is not greater than a few hundred megohms, due to insulation leakages in the tube, the collection of positive ions by the grid, and other causes. Thus, it is evident that the premier requirement for direct current amplification is that the input resistance must be high or that the grid currents

(27) Physical Review, Nov. 1930, Vol. 36, page 1489.

in the tube must be very small, under operating conditions. Metcalf and Thompson were able to satisfy this condition.

The grid current in a tube with the grid sufficiently negative to repel all electrons is due to:

1. Leakage over glass or insulation. This is small in comparison with the other currents and may be reduced to a minimum by the usual methods.

2. Ions formed by the presence of gas in the tube. With the highest vacuum obtainable the positive ion current was found to be greater than 10^{-13} amperes, if operating above the ionization potential. With the voltage below 8 volts, no ionization current was produced.

3. Thermionic grid emission due to heating of the grid by filament power. Employment of low filament power will eliminate the heating of the grid.

4. Ions emitted by the filament. Wahlen(28) and Smith(29) showed that positive ions are emitted in large numbers by a hot filament. These are drawn to the negative grid and may even amount to 10^{-12} amperes from a small tungsten filament. To overcome the negative space charge, a grid is inserted between the filament and the grid to repel the ions. This grid is known as a space charge grid. The mutual conductance of the tube is also

(28) Physical Review, 1929,34 - 164
(29) Physical Review, 1930,35 - 381

increased by the presence of this special grid.

5. Photoelectrons emitted by the control grid under the action of light from the filament. The employment of thoriated filaments, operated at low temperatures effectively reduces the emission of photoelectrons from the grid.

6. Photoelectrons emitted by the control grid under the action of soft X-rays, produced by the normal plate current. Low plate voltages reduce the currents produced by the effect of soft X-rays from the plate.

With these facts in view, a special tube, the F254 pliotron, was constructed with the following operating characteristics:

Filament voltage	2.5 volts
Plate voltage	6.0 volts
Control grid voltage	-4.0 volts
Space charge grid voltage	4.2 volts
Mutual conductance	25 $\frac{\text{microamperes}}{\text{volt}}$
Amplification	1
Plate resistance	40,000 ohms
Grid current	10^{-15} amperes
Input resistance	10^{-16} ohms
Current Sensitivity	10^{-17} $\frac{\text{amperes}}{\text{mm}}$
Voltage Sensitivity	2.5×10^{-6} $\frac{\text{volts}}{\text{mm}}$

Lee du Bridge(30) developed three types of circuits employing this special FP54 tube:

1. Simple single tube circuit. Currents as small as 10^{-14} amperes were measured using this set-up. An auxiliary battery and a rheostat were employed to balance out the plate current. The voltage sensitivity obtained was slightly greater than 5×10^{-4} $\frac{\text{volts}}{\text{mm}}$. Accurate measurements of currents of the order 10^{-13} amperes, the same magnitude as can be measured by any standard electrometer, were obtained.

2. A two tube bridge circuit similar to those of Wold, Wynn-Williams, and Eglin. Greater stability was rendered with this circuit than with the simple circuit. The voltage sensitivity was found to be 2.5×10^{-6} $\frac{\text{volts}}{\text{mm}}$ and, using an input resistance of 10^{10} ohms, the sensitivity to currents was found to be 4×10^{-16} $\frac{\text{amps}}{\text{mm}}$. Currents in the neighborhood of 5×10^{-18} amps were detected, but not accurately measured by this circuit. The maximum sensitivity was found to be five times greater than that of the best Compton electrometer and twenty-five times greater than that of the ordinary electrometer. Great precautions must be taken in the matter of shielding such a circuit; the container employed

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(30) Physical Review, Feb. 15th, 1931.Vol. 37, P. 392.

must be almost air-tight, the connections must be good, the condition of the storage batteries employed must be good, the tubes must be kept dry to prevent insulation leaks. Du Bridge even went so far as to enclose the control grid leads in quartz tubes painted on the outside with "aqudag" to eliminate effects due to residual ionisation of the air.

3. A two-stage circuit employing FP54 tubes and UX112A tubes (Figure 12). The first stage consists of a bridge circuit similar to #2 except that the "dummy" tube in #2 is replaced by a variable resistance R_3. The circuit may be balanced by adjusting r_1 and r_2 so as to be independent of battery fluctuations. A bridge circuit may also be used in the second stage but there is less drain on batteries with the simple compensating circuit shown. The meanings of the various symbols employed in diagram 12 are as follows:

R_1, R_2 = fixed resistance 10,000 ohms (bridge arms)
R_3 = variable resistance 20,000 ohms
r_1, r_2 = 400 ohm potentiometers
r_3 = rheostat 20 ohms
r_4 = rheostat 6 ohms
r_5 = fine adjustment rheostat 1,000 ohms in compensating circuit.
μA = microammeter.

With this circuit, currents of 10^{-14} amperes were amplified to such a value that they could be read on a microammeter. A second stage of amplification could of course be used with either (1) or (2) above. Greater simplicity and convenience is attained by using in the first stage a balanced circuit in which the "dummy" tube is replaced by a variable resistance. In place of the galvanometer, the second stage of amplification is substituted.

In the first stage the chief requirement is a high grid resistance, a factor not at all necessary in the second stage where the employment of a tube of high mutual conductance is imperative.

If a voltage e is applied to the grid of the tube T_1, then the change in voltage of the grid of the tube T_2, will be ke where k stands for the expression

$$\frac{\mu R_p}{R_p + r_p} \quad . \qquad (25)$$

Here μ = voltage amplification factor of Tube T_1 ,

R_p = external resistance in the circuit.

r_p = internal impedance of tube T_1.

The change in plate current of the second tube will then be $\Delta i_p = G_{m_2} \cdot ke$ where G_{m_2} is the mutual conductance of the second tube. This change in plate current will be read on the microammeter. Now, the voltage amplification obtained by the FP54 in the circuit shown is actually less than 1, so that if another FP54 were used in the second stage, the overall sensitivity would be less than for a single tube. However, as a tube of large mutual conductance (UX112A) was used in the second stage, an increase in sensitivity was obtained.

The overall sensitivity obtained in the above circuit was approximately 375 $\frac{\text{microamperes}}{\text{volt}}$. Using an input resistance of 10^{11} ohms, an output current of 1 microampere was obtained for an input current of 2.7 x 10^{-14} amperes. This was a current amplification of 3.75×10^{7}.

The advantages afforded by such a circuit are ruggedness, portability, and economy (an inexpensive microammeter serving as an indicating instrument).

The precautions to be taken in the operation of such an amplifier are extreme shielding, the employment of an almost air-tight container being necessary; and the amplifier must be operated from thirty minutes to two hours before readings may be accurately recorded so that temperature equilibrium and a steady state of

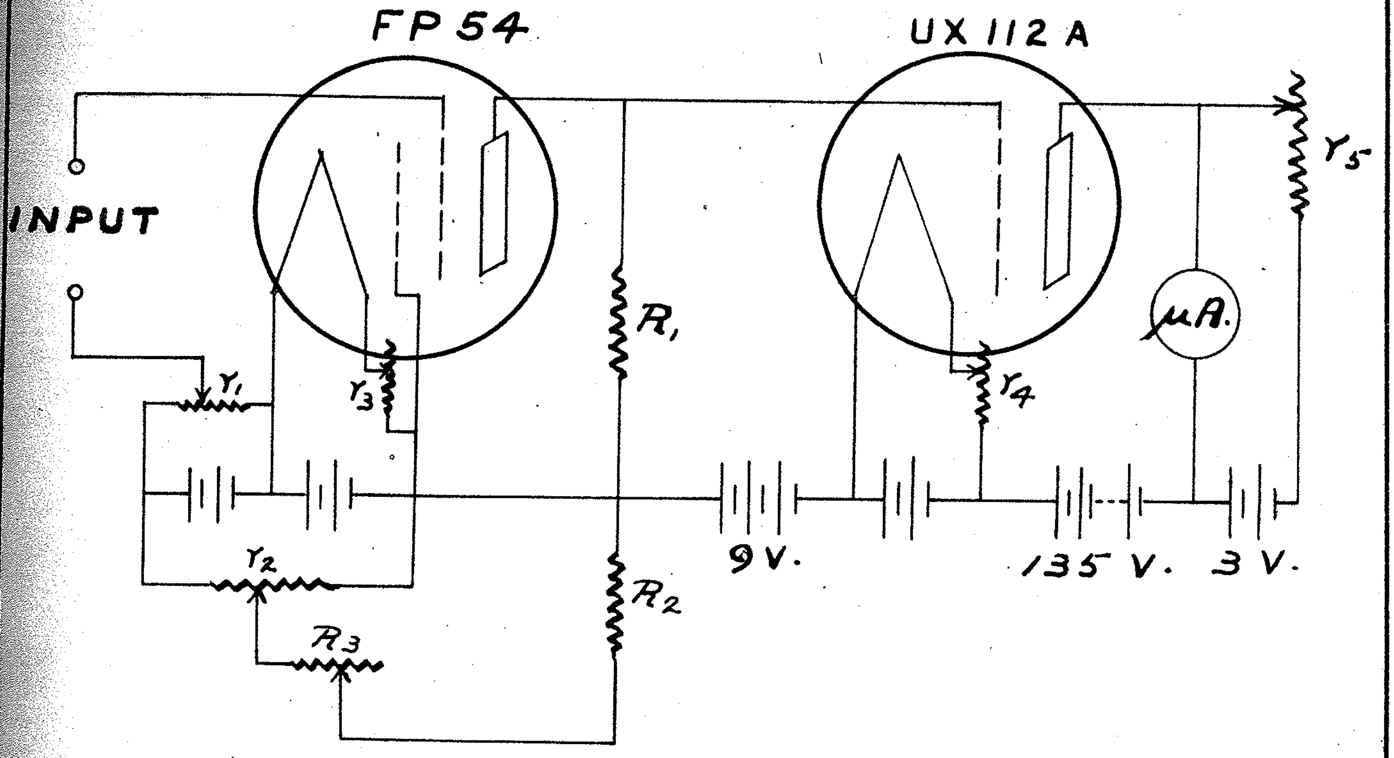


FIGURE 12.

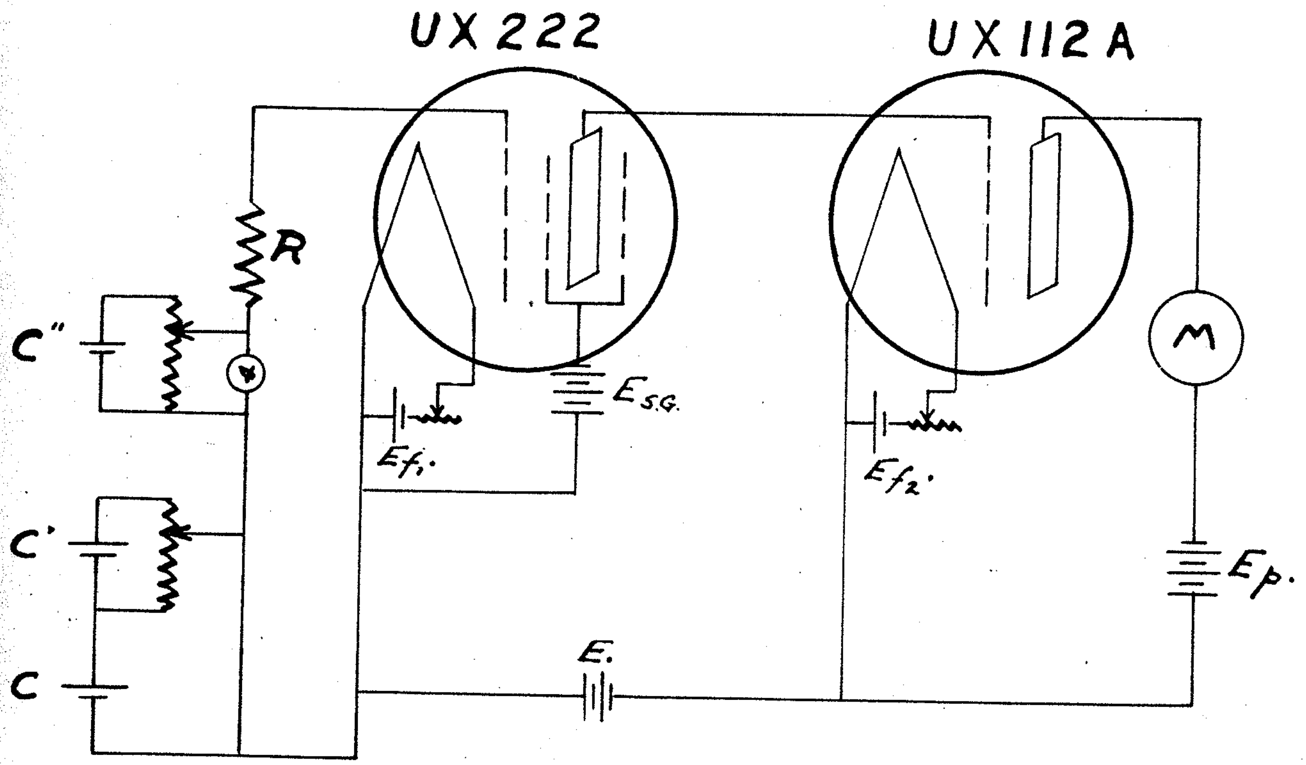


FIGURE 13.

static charges on the walls of the tubes, etc., may be attained.

P. A. Macdonald and J. T. Macpherson(31) have recently described a two-stage circuit employing an ordinary radio valve, type UX222, in the first stage in place of the special FP54 pliotron used by Du Bridge. Figure 13 shows the circuit employed by Macdonald and MacPherson. Here; C, C' and C" are the grid bias batteries; R is the high input resistor; E_f and E_{f_2} are the filament batteries; M, the plate current meter (a microammeter or even a voltmeter); and E, E_{sG} and E_p the E, screen grid and plate batteries respectively.

The phenomenon upon which these authors based what they believed to be a new circuit was that the direction of flow of the grid current altered at a definite value of the grid potential, Figure 14 shows graphically the grid current of a UX112A General Electric tube as a function of the grid potential. It is seen that at a potential of the grid of -0.33 volts, 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

(31) Philosophical Magazine, Jan.1933.

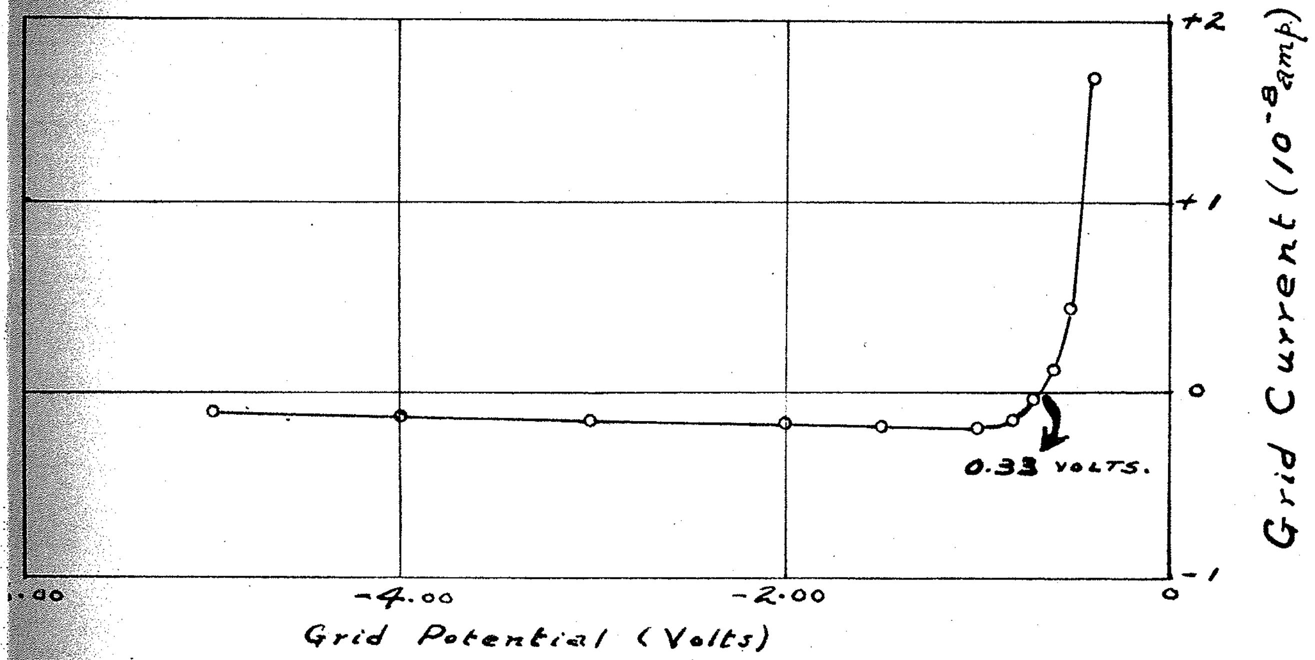


FIGURE 14.

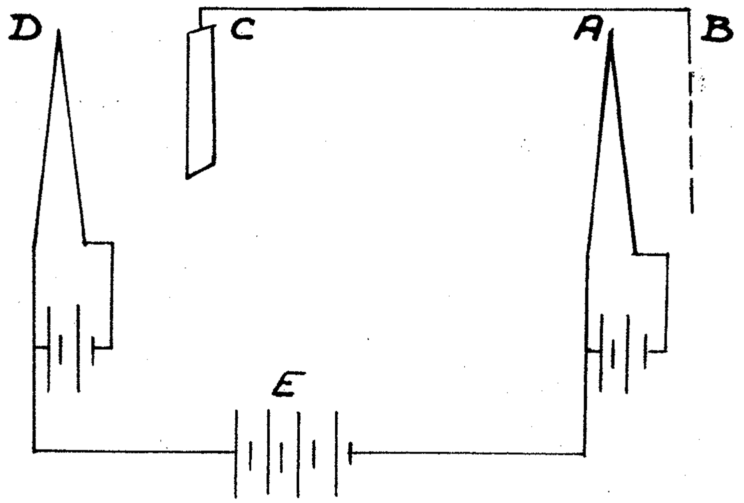


FIGURE 15 a.

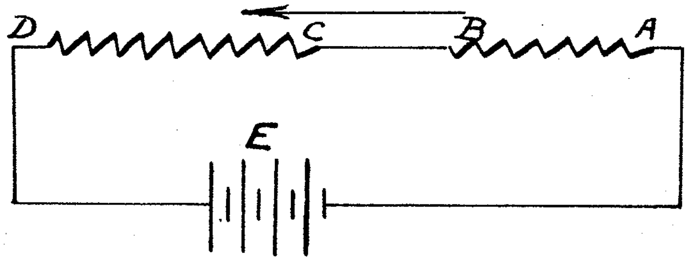


FIGURE 15 b.

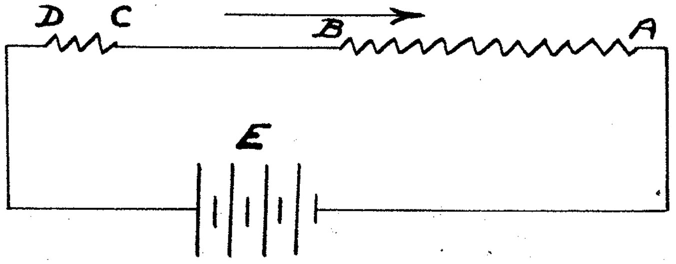


FIGURE 15c.

ions to the grid and the repulsion by it of the negative electrons.

Suppose now that a circuit be set up as in Figure 15(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 electrons to flow from D to C but not in the reverse direction. If the potential of B is greater than -0.33 volts the direction of current flow will be that of Figure 15(b), since the electrons flow from the filament A to the grid B and encounter the maximum resistance between the plate C and the filament D. However, if B is given a potential less than -0.33 volts, the current is reversed in direction, the positive ions flowing to the grid being equivalent to a flow of electrons from the grid B to the filament A. The resistance of DC to electrons moving in this direction is relatively low, while that of BA is increased. Thus in Figure 15(b) the major drop in potential of the battery E is across DC, while in Figure 15(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 by Macdonald and Macpherson with the result that a stable amplifier of high voltage sensitivity was obtained.

Their results indicate a sensitivity to voltage of $3 \times 10^{-4} \frac{\text{volts}}{\text{mm}}$ which with the input resistance employed namely, 2×10^{9} ohms, renders a sensitivity to current of $1.5 \times 10^{-13} \frac{\text{amperes}}{\text{mm}}$ for the system. The instrument is extremely stable at this sensitivity having a drift of only 34 mms. in five hours, after equilibrium has first been established. The overall amplification is with this set up 10^{3}, and an ordinary voltmeter may be used as the plate current meter, thus giving a rugged instrument that may be readily transported. No particular shielding is necessary, except of course with the grid system, which is readily obtained by placing the two tubes in a grounded metal box. The instrument is sensitive to sunlight, probably due to the liberation of photoelectrons from the grid system, and care must be taken to see that no light falls on the tubes.

Following this P. A. Macdonald and T. W. Tweed(32) investigated a simple circuit using low plate potentials in contrast to the general mode of research adopted by investigators in direct currents up to this time who employed the operating constants recommended for

(32) Physics. Vol. 4, No.5, May, 1933.

alternating current work by the manufacturers of the valves. In this field, since the relative magnitudes of the plate and amplified currents are of no particular importance, one would use as large operating potentials as possible in order to obtain the maximum output.

The sensitivity to voltage measured in volts per mm. scale deflection, of a direct current thermionic amplifier (simple circuit) was taken as inversely proportional to the mutual conductance divided by the plate current of the valve employed. The mutual conductance was found to decrease less rapidly than the plate current, as the filament and plate potentials were lowered, the most sensitive operating value of the plate potential of a UX222 tube was found to be 1.5 volts giving a voltage sensitivity of $8 \times 10^{-4} \frac{\text{volts}}{\text{mm}}$ in the simple circuit with no plate current compensation.

The sensitivity to current is given by

$$S_c = \left\{ \frac{R}{1 + \frac{R}{R_g}} \right\} \cdot S_v \qquad (26)$$

where R_g is the grid filament resistance and R is the magnitude of the input resistor.

It is apparent from this expression that the sensitivity to current will increase directly with R provided this quantity is small relative to R_g. Moreover under this condition it is independent of the sign of R_g, that is, it does not matter whether an electron or positive ion grid current is employed. The upper limit to the value of R that may be used is, at present, placed by the magnitude of the resistances available. These may be obtained commercially having values as great as 10^{11} ohms, so that in order to obtain the maximum effect the grid-filament resistance of the tube should not be much less than 10^{13} ohms.

Lowering filament and plate potentials to increase the grid-filament resistance was not new having been carried out with signal success by Metcalf and Thompson(33) in producing a vacuum tube suitable for use as an electrometer. These investigators employing low potentials and aided with a positive space charge grid secured grid filament resistances as high as 10^{16} ohms, with a specially constructed tube.

General experience with amplifiers leads one to conclude that better results are obtained by using as low an input resistance as possible. For this reason, Macdonald and Tweed chose to set the operating constants of the valve to give maximum voltage sensi-

(33) Physical Review, 36, 1489 (1930).

tivity and utilize the existing grid-filament resistance, rather than attempt to improve this quantity at the expense of the voltage sensitivity.

The above mentioned authors also examined the manner in which the screen grid affected the grid current curve. This curve was found to be moved toward the origin as the screen potential was increased, not, however, to the same extent that the plate current curve was moved away. The above two findings showed the value of employing a screen grid. Since grid currents decrease with increasing negative bias, the larger the screen grid potential the greater the grid-filament resistance, an upper limit being placed by the tendency of the region of linear mutual conductance to disappear with higher screen voltages.

By suitable use of the screen grid, a grid-filament resistance of 10^{14} ohms was obtained thus giving a current sensitivity of $8 \times 10^{-15} \frac{\text{amperes}}{\text{mm.}}$ with an input resistor of 10^{11} ohms.

Macdonald and Tweed concluded from their work that ordinary radio valves are quite satisfactory for many types of direct current amplification, provided suitable operating constants are used. The following table gives the operating values recommended by these authors for high sensitivity direct current amplifiers.

Constants

Filament potential	1.25 volts
Plate potential	1.50 volts
Galvanometer sensitivity	$2.8 \times 10^{-10} \frac{\text{amps}}{\text{mm}}$
Voltage sensitivity	$8 \times 10^{-4} \frac{\text{volts}}{\text{mm.}}$
Plate current	0.07×10^{-6} amp.
Mutual conductance	$0.35 \times 10^{-6} \frac{\text{amp}}{\text{volt.}}$

Variables

Screen Grid Potential	Grid-filament Resistance	Maximum Input Resistor
12.0 volts	1×10^{14} ohms(positive ion)	10^{12} ohms
10.0 volts	6×10^{13} ohms(positive ion)	6×10^{11} ohms
8.0 volts	1.2×10^{13} ohms(electron)	10^{11} ohms
6.0 volts	9.8×10^{12} ohms(electron)	10^{11} ohms

The advantage of the use of the simple circuit as here employed, over balanced circuits is its simplicity, freedom from drift and irregularities of balance. The instrument has been used for over six months for the daily measurement of radon seeds in the Radium Laboratory of the Manitoba Cancer Relief and Research Institute, established in the Department of Physics, University of Manitoba.

Thus far in this communication an attempt has been made to show the developments that lead up to the introduction of the thermionic valve and its subsequent application to the measurement of direct currents. As obviously a complete discussion of the theoretical and mathematical developments could not be presented, difficulty was encountered in the discrimination of the abundant material available. However, the author trusts that enough has been said to make the subject under consideration in the following chapter understandable to any reader, irrespective of his previous acquaintance with the subject.

CHAPTER II

THE EXPERIMENTAL DEVELOPMENT OF A DIRECT CURRENT THERMIONIC AMPLIFIER HAVING A HIGH MUTUAL CONDUCTANCE

Impressing a potential difference between the control grid and filament of a thermionic tube causes a change in the plate current of the tube. The algebraic expression for the sensitivity to voltage is

$$S_v = G_m S_g \qquad (27)$$

where S_v = voltage sensitivity ,

S_g = galvanometer sensitivity,

and G_m = the mutual conductance of the tube; that is, the slope of the curve relating the grid potential E_g to the plate current I_p.

It has been noted(34) that considerable increase in sensitivity may be obtained:

(1) By introducing into the simple circuit an auxiliary battery in such a manner that it forces a current through the plate current meter equal to the plate current but in the opposite direction; or:

(2) By substitution of the plate current from a second vacuum tube for the current due to the auxiliary battery. These two methods of balancing out the plate current enable S_g, the sensitivity of the meter employed

(34) Chapter I, page 39

to measure the plate current, to be increased, the quantity G_m, the mutual conductance, however, remaining constant.

As may be seen from the latter section of Chapter I, many experimenters with thermionic tubes have employed the above-mentioned methods of increasing the meter sensitivity or modifications of them to attain highly sensitive direct current amplification circuits using ordinary type radio valves as well as valves specially constructed for direct current amplification purposes.

P. A. Macdonald and J. T. Macpherson(35) have attacked the problem of increasing the sensitivity to voltage from a different angle in their description of a two-stage circuit in which the meter sensitivity S_g has been kept constant and the mutual conductance G_m increased.

The problem undertaken by the author to be presented in this communication consists of a detailed examination of this type of amplification circuit and an attempt to show how the voltage sensitivity may be readily controlled.

(35) Phil. Mag. January, 1933
(Chapter I, page 56)

I. THE DETERMINATION OF THE PROPERTIES POSSESSED BY SUCH A TWO-STAGE AMPLIFICATION CIRCUIT

The first circuit examined contained a UX201A three-element tube with the grid connected through a RCA232 four-element screen grid tube in the manner of Figure 16. The 201A tube will be referred to hereinafter as the "plate or output tube," the 232 being called the "grid or input tube."

An examination of the roles played in the operation of the circuit by the various potentials embodied in the circuit was first undertaken.

(1) Variation of the Potential Applied to the Control Grid of the Input tube

It was found that the plate current of the output tube may be controlled by the potential of the control grid of the input tube. Data substantiating this fact is given in Table I below, which when plotted, renders the curve given in Figure 17.

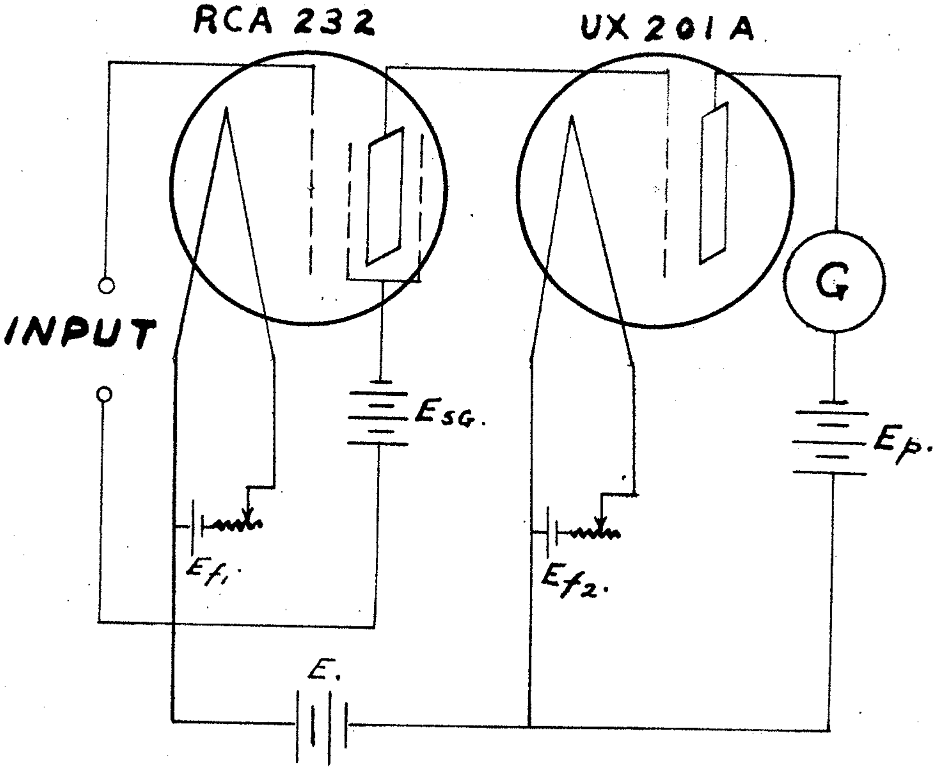


FIGURE 16.

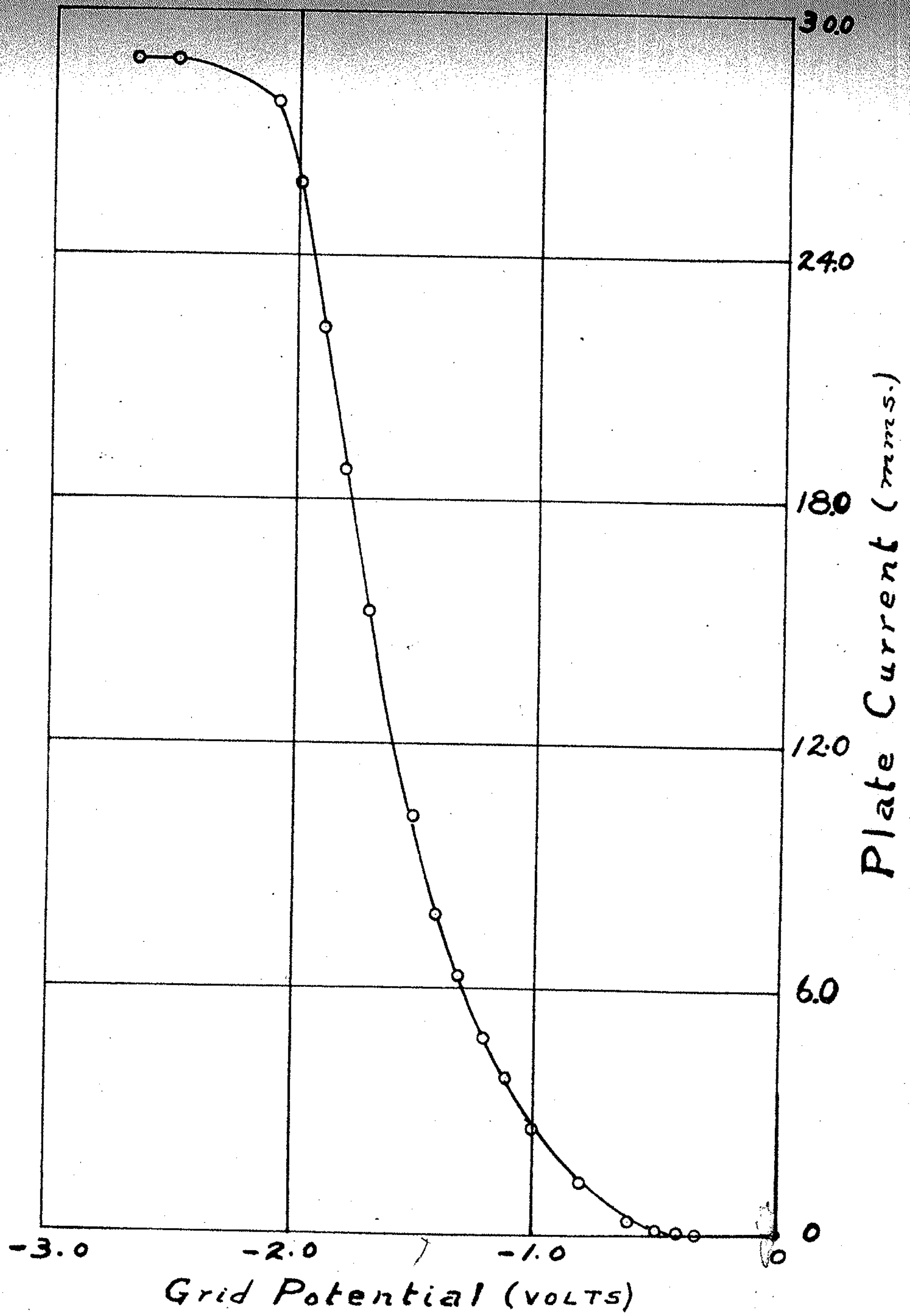


FIGURE 17.

TABLE I

Input Tube RCA232 / Filament Volts 2.0 / E or Plate Volts 7.30

Output Tube UX201A / Filament Volts 5.0 / Plate Volts 90.0

Input tube used as a triode, the screen grid being tied to the plate.

Grid Potential (volts)	Plate Current (mms.)
-3.00	28.80
-2.50	28.80
-2.10	27.80
-2.00	25.80
-1.90	22.30
-1.80	18.80
-1.70	15.30
-1.50	10.30
-1.40	7.80
-1.30	6.30
-1.20	4.80
-1.10	3.80
-1.00	2.60
-0.80	1.30
-0.60	.60
-0.40	.30
-0.20	.10
-0.00	.00

(2) Variation of the E Potential

Table II gives the data showing the alterations in the plate current of the output tube caused by slight changes in the negative potential applied to the control grid of the input tube for various values of the plate potential of the input tube, that is, for various E potentials, i.e., the grid potential-plate current characteristics of the unit for various E potentials are obtained, and are plotted in Figure 18. Here, again the input tube was employed as a triode, the screen grid being tied to the plate.

TABLE II

Input Tube RCA232 (Triode)
Filament Volts 2.0

Output Tube UX201A
Filament Volts 5.0
Plate Volts 90.0

(a) E Potential 7.30 volts

Grid Potential (volts)	Plate Current (mms)
-3.00	28.80
-2.50	28.80
-2.10	27.80
-2.00	25.80
-1.90	22.30
-1.80	18.80
-1.70	15.30
-1.50	10.30
-1.40	7.80
-1.30	6.30
-1.20	4.80
-1.10	3.30
-1.00	2.60
-0.80	1.30
-0.60	.60
-0.40	.30
-0.20	.10
-0.00	.20

(b) E Potential 5.70 volts

Grid Potential (volts)	Plate Current (mms)
-2.50	27.50
-2.10	27.50
-2.00	26.30
-1.90	24.50
-1.80	22.50
-1.70	19.00
-1.50	12.50
-1.40	10.50
-1.30	8.00
-1.20	6.00
-1.10	4.50

(b) continued

Grid Potential (volts)	Plate Current (mms)
-1.00	3.00
-0.80	1.50
-0.60	.50
-0.40	.30
-0.20	.10
-0.00	.00

(c) E Potential 2.90 volts

Grid Potential (volts)	Plate Current (mms)
-2.00	15.10
-1.60	15.10
-1.50	14.10
-1.40	12.60
-1.30	10.10
-1.20	7.10
-1.10	5.10
-1.00	3.40
-0.90	2.40
-0.80	1.70
-0.70	1.00
-0.60	.30
-0.50	.10
-0.30	.00

(d) E Potential 0.00 volts

Grid Potential (volts)	Plate Current (mms)
-1.00	1.80
-0.80	1.60
-0.60	.60
-0.40	.00

The sensitivity to voltage of the system as indicated by the curves of Figure 18 is 2.6 x 10^{-2} $\frac{\text{volts}}{\text{mm}}$ and is seen to be independent of the potential applied at E except for very low values.

(3) Variation of the Screen Grid Potential of the Input Tube.

The input tube was next employed as a four element tube, the screen grid being maintained at a positive potential with respect to the negative side of the filament. In Table III is given the data showing the relation between the grid potential of the input tube and the plate current of the output tube for various values of the potential applied to the screen grid.

TABLE III

Input Tube RCA232	Output Tube UX201A
Filament Volts 2.0	Filament Volts 5.0
Plate or E Volts 7.3	Plate volts 90.0

Various screen grid potentials are employed in turn.

(a) Screen Grid Potential 0.0 volts

Grid Potential (volts)	Plate Current (mas)
-1.20	26.50
-1.10	26.50
-1.00	26.00
-0.90	25.50
-0.85	24.50
-0.80	10.00
-0.70	1.20
-0.60	0.00
-0.50	0.00

(b) Screen grid Potential 3.00 volts

Grid Potential (volts)	Plate Current (mas)
-1.80	26.50
-1.70	26.50
-1.60	26.00
-1.50	25.20

(b) continued

-1.45	24.50
-1.40	8.80
-1.30	.20
-1.20	.00

(c) Screen Grid Potential 6.00 volts

Grid Potential (volts)	Plate Current (mms)
-2.50	26.50
-2.40	26.50
-2.30	26.40
-2.20	26.30
-2.10	26.20
-2.00	26.00
-1.90	25.00
-1.85	17.50
-1.80	7.00
-1.75	1.70
-1.70	0.20
-1.60	0.10
-1.50	0.00

(d) Screen Grid Potential 8.00 volts

Grid Potential (volts)	Plate Current (mms)
-2.70	26.50
-2.60	26.50
-2.50	26.00
-2.40	25.50
-2.35	25.00
-2.20	13.50
-2.10	1.00
-2.00	0.10

Figure 19 shows the graphs obtained from the above data. The sensitivity to voltage is 1.67 x 10^{-3} volts and is seen to exceed that attained when the in-
mm
put tube is employed as a triode. It is also evident from the curves of Figure 19 that the sensitivity to

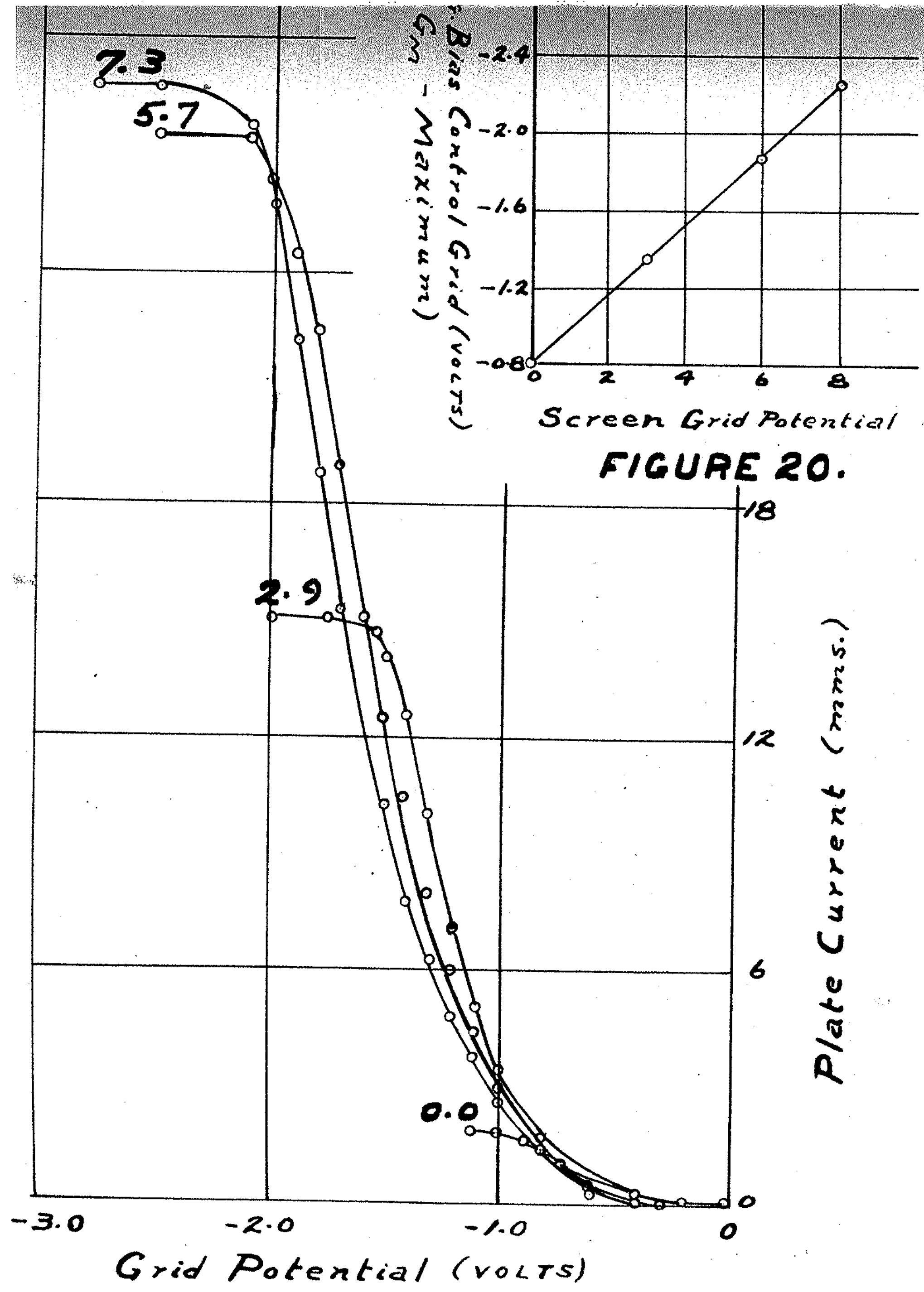


FIGURE 20.

FIGURE 18.

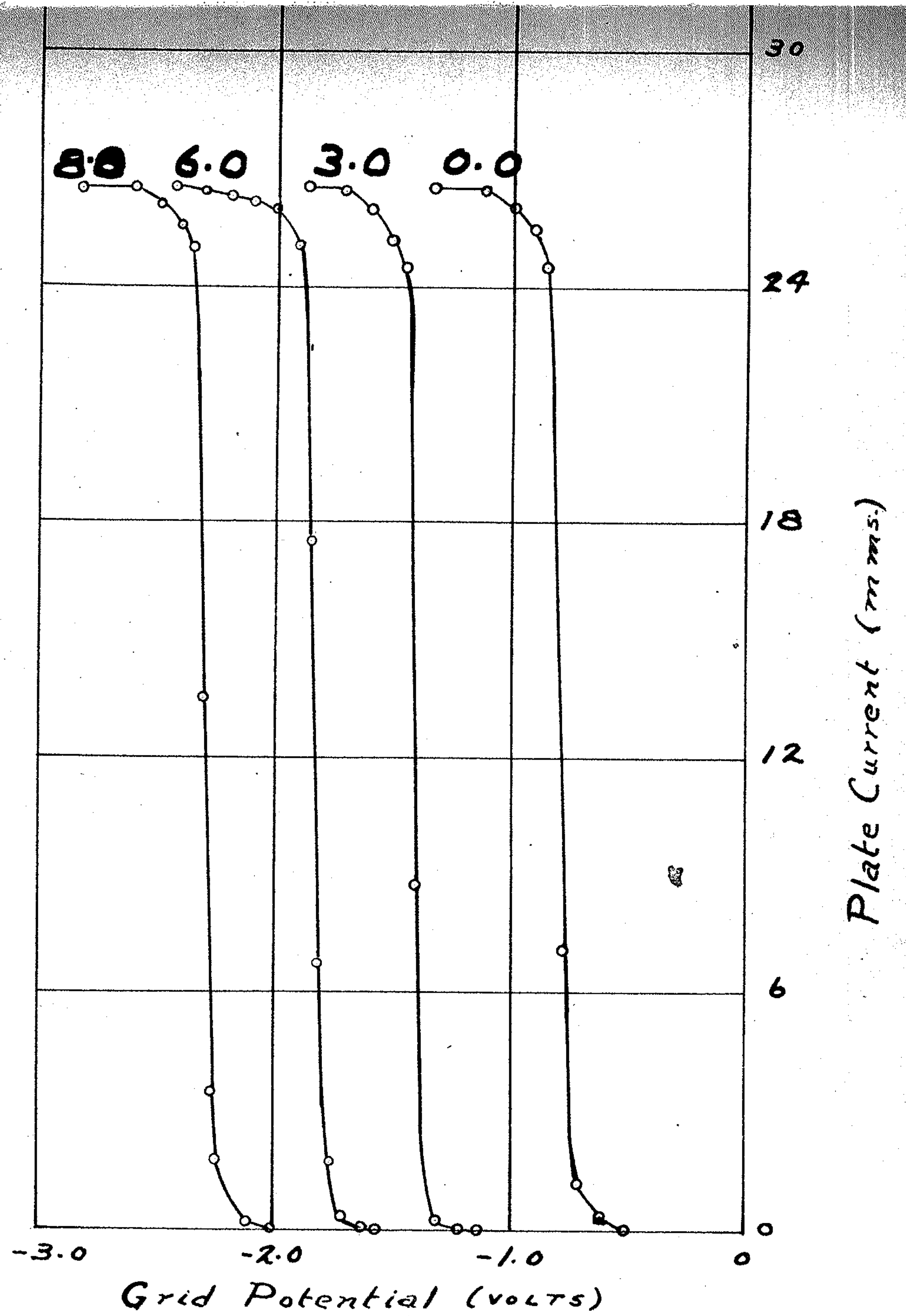


FIGURE 19.

voltage is independent of the value of the screen grid potential employed, the curves being parallel and shifting to regions of greater negative grid bias for increasing values of screen grid potential.

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 as may be seen from the linear curve given in Figure 20, plotted from data obtained from the curves of Figure 19, given in Table IV below.

TABLE IV

Input Tube RCA232
Filament Volts 2.0
Plate or B volts 7.3

Output Tube UX201A
Filament Volts 5.0
Plate Volts 90.0

Screen Grid Potential of Input Tube	Negative Grid Bias of the Control Grid of Input Tube at which G_m is a Maximum
0.00 (volts)	-0.800 (volts)
3.00 "	-1.366 "
6.00 "	-1.866 "
8.00 "	-2.266 "

(4) Variation of the Plate Potential of the Output Tube

The potential applied to the plate of the output tube was then varied over a considerable range, 16.8 to 135.0 volts, the grid potential-plate current characteristics of the system being observed for each value of plate potential employed.

It may be seen from the curves of Figure 21,

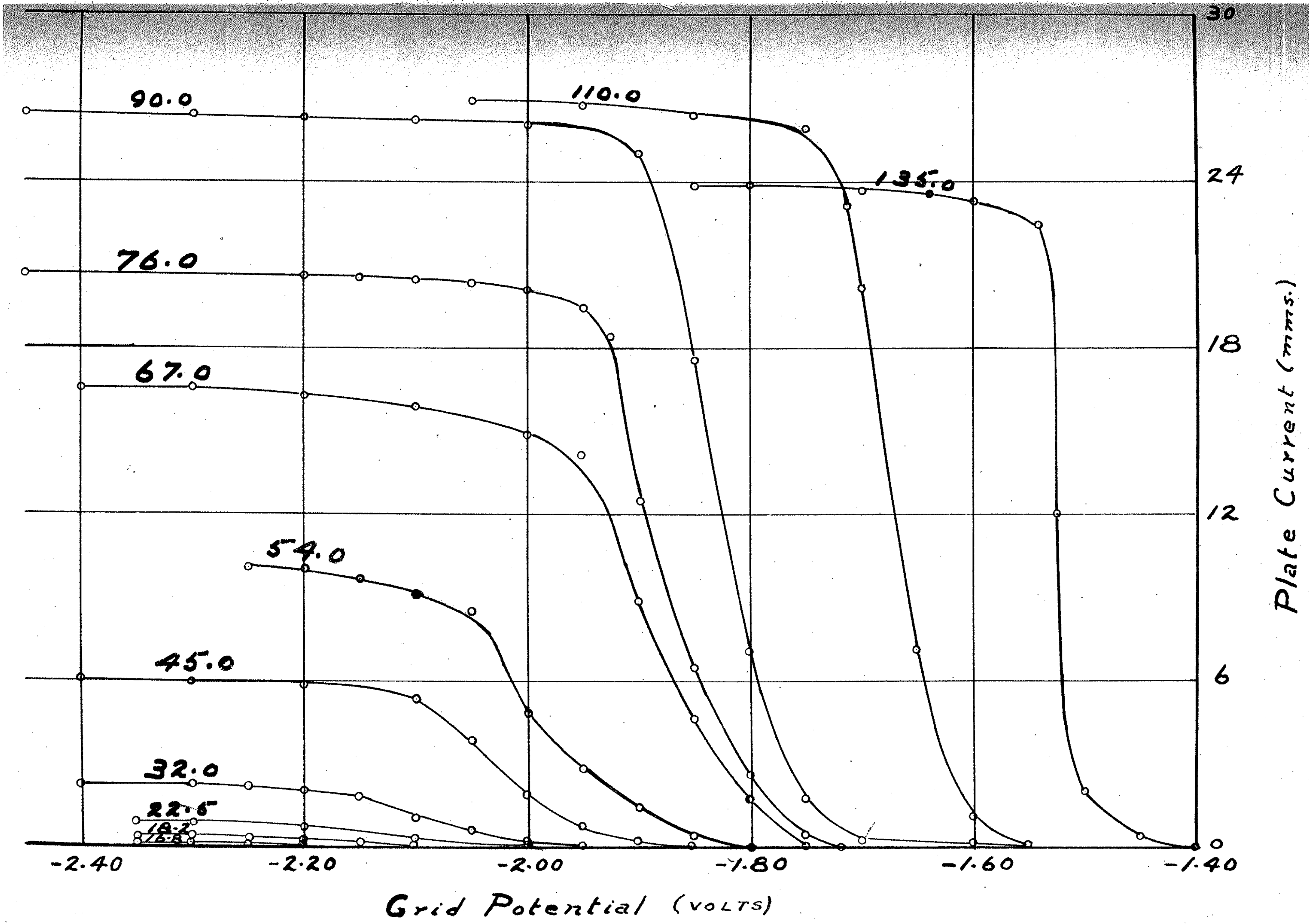

90.0
110.0
135.0
76.0
67.0
54.0
45.0
32.0
22.5
18.2
16.8
30
24
18
12
6
0
Plate Current (mms.)
-2.40
-2.20
-2.00
-1.80
-1.60
-1.40
Grid Potential (volts)

FIGURE 21.

plotted from the data given in Table V, the the sensitivity to voltage of the unit varies with the plate potential of the output tube, increasing with increasing values of this plate potential.

TABLE V

Input Tube RCA232	Output Tube UX201A
Filament Volts 2.0	Filament Volts 5.0
Plate or B volts 7.3	Various plate Voltages
Screen Grid Volts 6.0	

(a) Plate Potential 135.0 Volts

Grid Potential (volts)	Plate Current (mms)
-1.900	23.80
-1.800	23.80
-1.700	23.60
-1.640	23.50
-1.600	23.30
-1.540	22.50
-1.525	12.00
-1.500	2.00
-1.450	0.40
-1.400	0.00

(b) Plate Potential 110.0 volts

Grid Potential (volts)	Plate Current (mms)
-2.100	26.90
-2.000	26.90
-1.950	26.70
-1.900	26.60
-1.850	26.30
-1.800	26.10
-1.750	25.90
-1.700	20.10
-1.650	7.10
-1.600	1.10
-1.550	0.10
-1.500	0.00

(c) Plate Potential 90.0 volts

Grid Potential (volts)	Plate Current (mms)
-2.500	26.50
-2.400	26.50
-2.300	25.40
-2.200	25.30
-2.100	26.20
-2.000	26.00
-1.900	25.00
-1.850	17.50
-1.800	7.00
-1.750	1.70
-1.700	0.20
-1.600	0.10
-1.500	0.00

(d) Plate Potential 76.0 volts

Grid Potential (volts)	Plate Current (mms)
-2.600	20.80
-2.500	20.80
-2.200	20.60
-2.150	20.50
-2.100	20.40
-2.050	20.30
-2.000	20.00
-1.950	19.40
-1.925	18.40
-1.900	12.40
-1.850	6.40
-1.800	2.60
-1.750	0.40
-1.700	0.00
-1.650	0.00

(e) Plate Potential 67.0 volts

Grid Potential (volts)	Plate Current (mms)
-2.400	16.60
-2.300	16.60
-2.200	16.20
-2.100	15.80
-2.000	14.80
-1.950	14.30

(e) continued

-1.900	8.80
-1.850	4.60
-1.800	1.70
-1.750	0.00

(f) Plate Potential 54.0 volts

Grid Potential (volts)	Plate Current (mms)
-2.300	10.00
-2.200	10.00
-2.150	9.50
-2.100	9.10
-2.050	8.50
-2.000	4.30
-1.950	2.80
-1.900	1.40
-1.850	0.40
-1.800	0.00

(g) Plate Potential 45.0 volts

Grid Potential (volts)	Plate Current (mms)
-2.500	6.10
-2.400	6.10
-2.300	5.90
-2.200	5.80
-2.100	5.20
-2.050	3.80
-2.000	1.80
-1.950	0.70
-1.900	0.30
-1.850	0.00

(h) Plate Potential 32.0 volts

Grid Potential (volts)	Plate Current (mms)
-2.400	2.30
-2.300	2.30
-2.250	2.20
-2.200	2.00
-2.150	1.80
-2.100	1.00

(h) continued

-2.050	0.60
-2.000	0.20
-1.950	0.00
-1.900	0.00

(i) Plate Potential 22.5 volts

Grid Potential (volts)	Plate Current (mms)
-2.400	.90
-2.300	.90
-2.200	.70
-2.100	.30
-2.000	.10
-1.900	.00

(j) Plate Potential 18.2 volts

Grid Potential (volts)	Plate Current (mms)
-2.400	.40
-2.300	.40
-2.250	.30
-2.200	.20
-2.150	.10
-2.100	.00
-2.050	.00

(k) Plate Potential 16.8 volts

Grid Potential (volts)	Plate Current (mms)
-2.400	.20
-2.300	.20
-2.250	.10
-2.200	.00

Table VI gives the voltage sensitivities of the unit for the various potentials applied to the plate of the output tube obtained from the curves of Figure 21.

TABLE VI

Input Tube RCA232
Filament Volts 2.0
Plate or B volts 7.3
Screen Grid Volts 6.0

Output Tube UX201A
Filament Volts 5.0

Plate Potential of Output Tube		Sensitivity to Voltage of the Unit	
135.0	Volts	68.0×10^2	mms/volt
110.0	"	31.0×10^2	"
90.0	"	20.8×10^2	"
76.0	"	15.0×10^2	"
67.0	"	10.6×10^2	"
54.0	"	7.2×10^2	"
45.0	"	4.2×10^2	"
32.0	"	1.5×10^2	"
22.5	"	$.5 \times 10^2$	"
18.2	"	$.2 \times 10^2$	"
16.8	"	$.1 \times 10^2$	"

Figure 22, plotted from the above data, shows the relation between the sensitivity to voltage of the unit and the potential applied to the plate of the output tube. This graph seems to indicate some regular relation between these two quantities although this relation was not ascertained.

(5) Variation of the Filament Potential of the Output Tube

The effect of varying the potential applied to the filament of the output tube was then observed. The data obtained for various filament potentials ranging from 2.50 to 5.00 volts is recorded in Table VII.

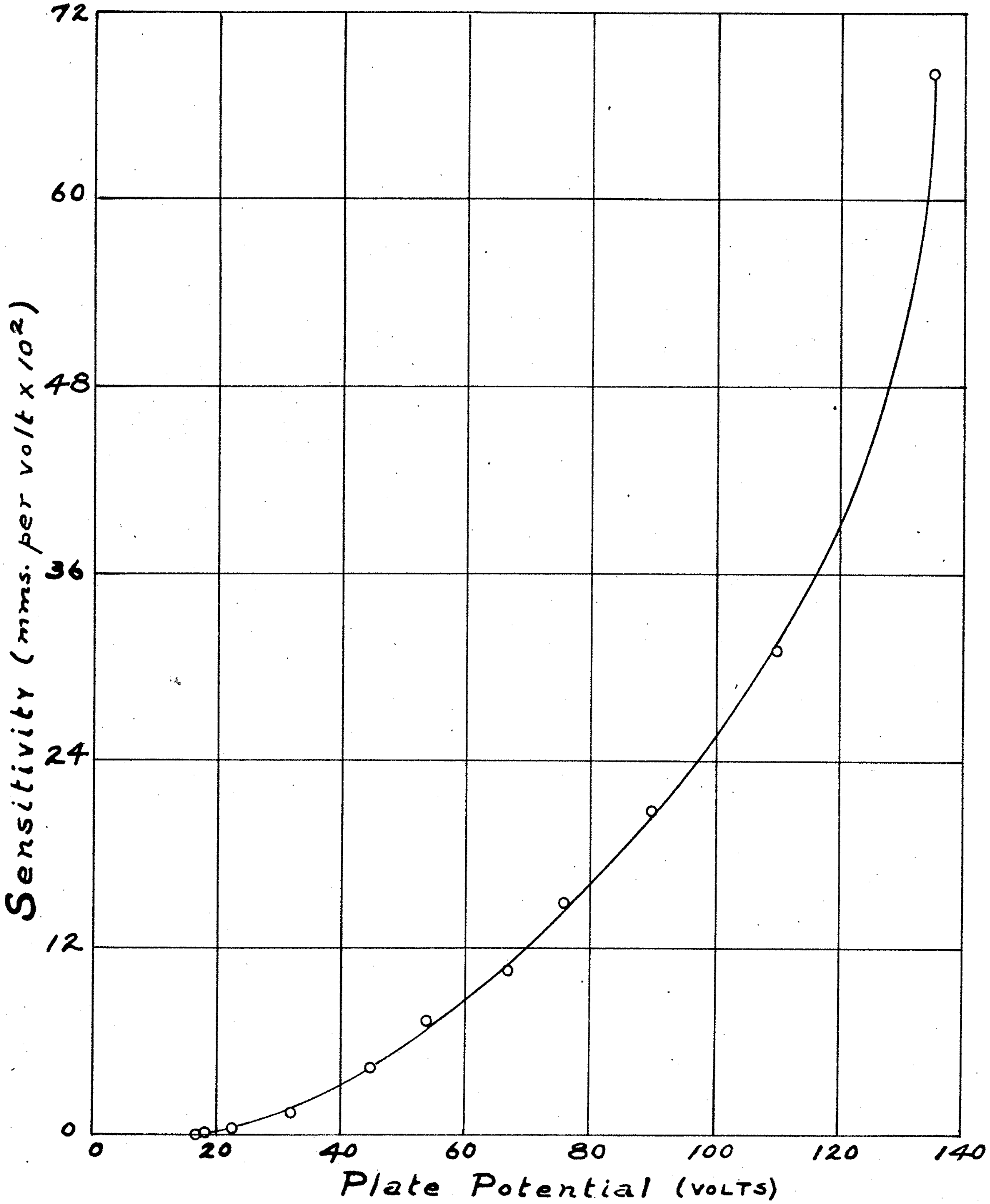

Sensitivity (mms. per volt x 10²)
72
60
48
36
24
12
0
0
20
40
60
80
100
120
140
Plate Potential (VOLTS)

FIGURE 22

TABLE VII

Input Tube RCA232	**Output Tube UX201A**
Filament Volts 2.0	Various Filament Voltages
Plate or E Volts 7.3	
Screen Grid Volts 6.0	Plate Volts 90.0

(a) Filament Potential 5.0 Volts

Grid Potential (volts)	Plate Current (mms)
-2.400	27.50
-2.300	27.50
-2.200	27.40
-2.100	27.20
-2.000	27.00
-1.940	26.90
-1.880	25.70
-1.862	22.00
-1.856	19.00
-1.848	15.00
-1.839	12.20
-1.818	8.40
-1.800	5.50
-1.793	2.00
-1.783	1.10
-1.700	0.50
-1.600	0.10
-1.500	0.00

(b) Filament Potential 4.5 Volts

Grid Potential (volts)	Plate Current (mms)
-2.300	26.00
-2.250	26.00
-2.200	25.80
-2.150	25.60
-2.100	25.40
-2.050	25.20
-2.000	25.00
-1.915	24.20
-1.901	23.50
-1.889	20.00
-1.875	15.00
-1.856	11.00
-1.824	8.00
-1.800	5.00
-1.750	0.50
-1.700	0.00

(c) Filament Potential 4.0 volts

Grid Potential (volts)	Plate Current (mas)
-2.200	24.00
-2.100	24.00
-2.000	23.80
-1.911	21.80
-1.895	19.50
-1.886	15.50
-1.877	11.90
-1.856	8.00
-1.846	3.00
-1.837	1.00
-1.800	0.50
-1.750	0.00

(d) Filament Potential 3.5 volts

Grid Potential (volts)	Plate Current (mas)
-2.300	20.30
-2.200	20.30
-2.100	20.20
-2.000	20.10
-1.950	19.50
-1.925	15.10
-1.900	9.10
-1.875	4.00
-1.850	1.30
-1.800	0.10
-1.750	0.00

(e) Filament Potential 3.0 Volts

Grid Potential (volts)	Plate Current (mas)
-2.000	9.80
-1.960	9.50
-1.900	8.50
-1.850	4.30
-1.800	0.60
-1.700	0.00

(f) Filament Potential 3.5 volts

Grid Potential (volts)	Plate Current (mms)
-2.100	1.90
-2.000	1.10
-1.900	1.50
-1.850	0.50
-1.800	0.00

It is seen from the graphs plotted from this data (Figure 23) that the sensitivity of the unit is dependent upon the filament potential employed on the output tube, increasing with increasing filament potentials, but not to the same extent as was the case when the plate potential of the output tube was altered (Figure 21).

(6) Variation of the Filament Potential of the Input Tube

The potential applied to the filament of the input tube was then varied over a considerable range, 1.2 to 2.0 volts, and the effect on the sensitivity of the unit noted. The data is given in Table VIII below.

TABLE VIII

Input Tube RCA232	Output Tube UX201A
Various Filament Voltages	Filament Volts 5.0
Plate or B Volts 7.3	Plate Volts 90.0
Screen Grid Volts 6.0	

(a) Filament Potential 2.00 volts

Grid Potential (volts)	Plate Current (mms)
-2.400	27.50
-2.300	27.50
-2.200	27.40

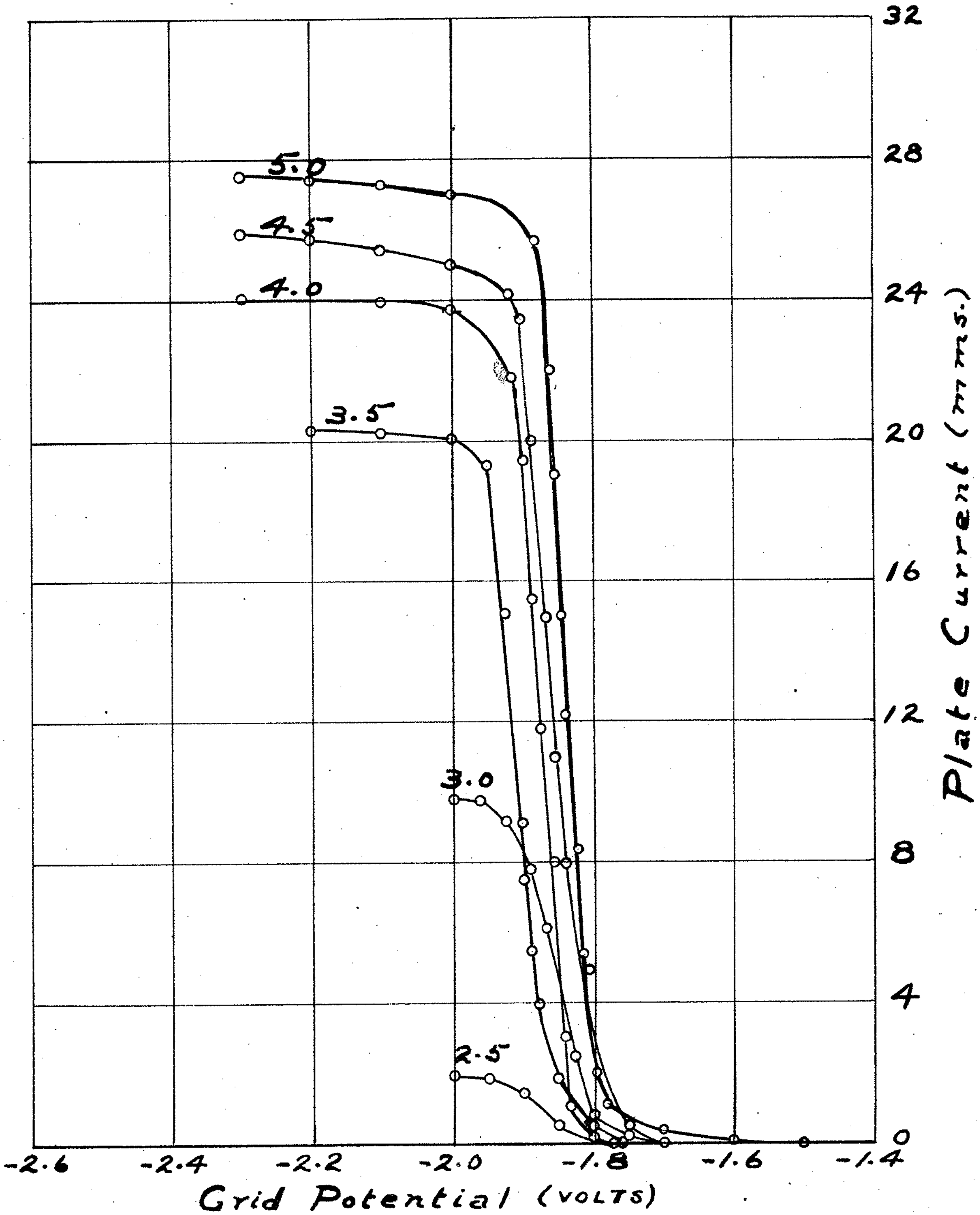

5.0
4.5
4.0
3.5
3.0
2.5
32
28
24
20
16
12
8
4
0
Plate Current (mms.)
-2.6
-2.4
-2.2
-2.0
-1.8
-1.6
-1.4
Grid Potential (VOLTS)

FIGURE 23.

(a) continued

-2.100	27.20
-2.000	27.00
-1.940	26.90
-1.880	25.70
-1.862	22.00
-1.856	19.00
-1.849	15.00
-1.839	12.20
-1.818	8.40
-1.800	5.50
-1.793	2.00
-1.783	1.10
-1.700	0.50
-1.600	0.10
-1.500	0.00

(b) Filament Potential 1.20 volts

Grid Potential (volts)	Plate Current (mms)
-2.100	26.10
-2.000	26.10
-1.900	26.00
-1.800	25.80
-1.724	24.80
-1.697	23.80
-1.670	17.00
-1.653	12.00
-1.636	8.00
-1.628	4.00
-1.604	0.80
-1.500	0.00

(c) Filament Potential 1.60 volts

Grid Potential (volts)	Plate Current (mms)
-1.350	26.20
-1.300	26.20
-1.200	26.00
-1.100	25.70
-1.000	25.30
-0.938	24.30
-0.917	22.70
-0.909	19.20
-0.900	15.70
-0.891	13.20

(d) continued

-0.883	10.20
-0.874	8.20
-0.866	6.70
-0.857	5.20
-0.849	2.70

(e) Filament Potential 1.20 volts

Grid Potential (volts)	Plate Current (mms)
-1.100	25.90
-1.000	25.90
-0.900	25.80
-0.800	25.40
-0.750	25.10
-0.700	24.20
-0.678	22.10
-0.671	19.10
-9.663	16.10
-0.656	13.60
-0.650	12.10
-0.642	10.40
-0.637	9.00
-0.630	7.70
-0.612	4.10
-0.600	1.40
-0.573	0.30
-0.550	0.20
-0.500	0.10
-0.400	0.00

The curves plotted (Figure 24) from this data show that the sensitivity to voltage of the system is independent of the filament potential of the input tube, the curves shifting to regions of greater negative bias of the control grid of the input tube for increasing values of the potential applied to the filament of the input tube.

Having thus ascertained the effects produced

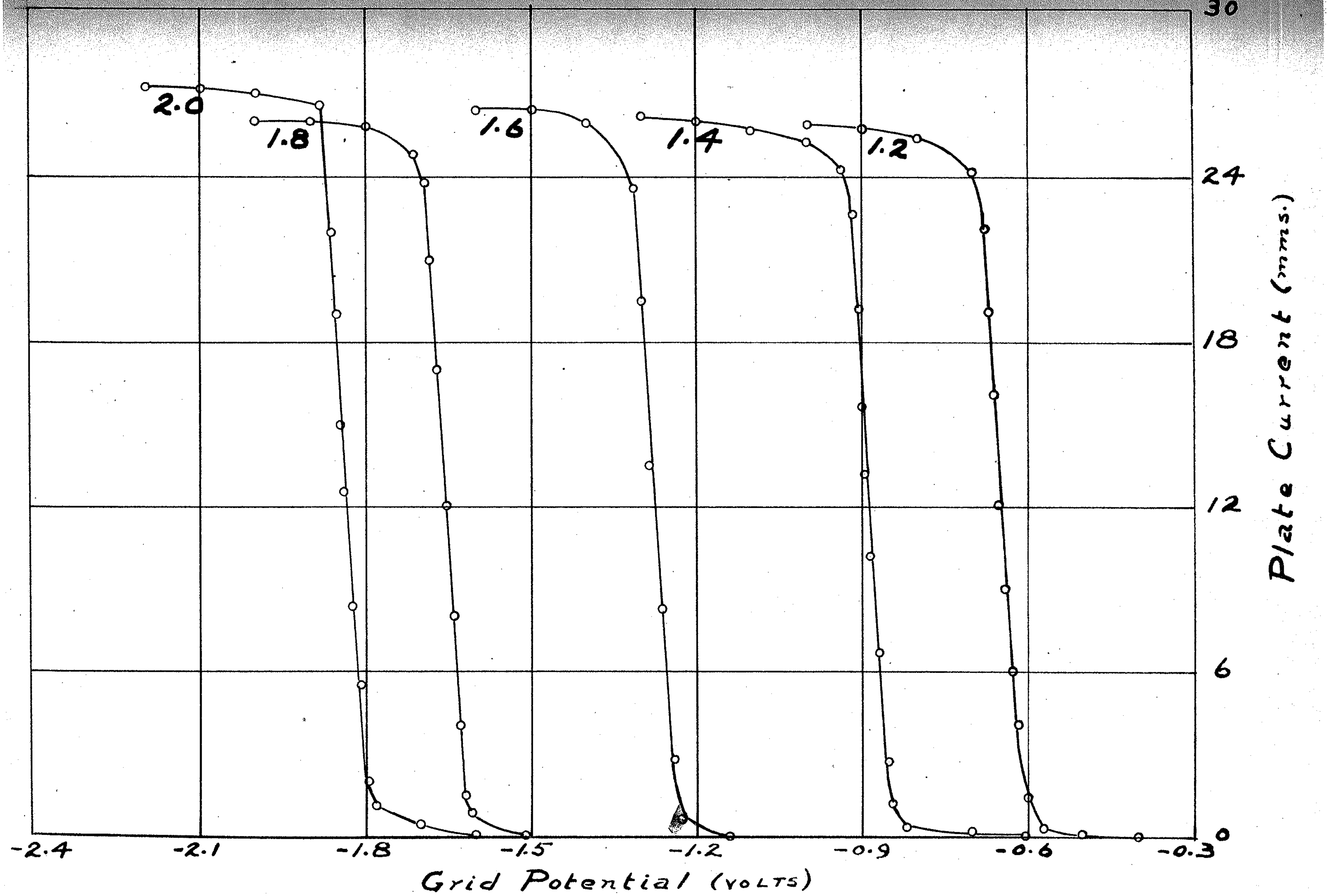

2.0
1.8
1.6
1.4
1.2
30
24
18
12
6
0
Plate Current (mms.)
-2.4
-2.1
-1.8
-1.5
-1.2
-0.9
-0.6
-0.3
Grid Potential (VOLTS)

FIGURE 24.

by altering the various potentials applied to the circuit, an attempt was then made to determine the factors to which the high amplification obtained from such a circuit is attributed.

Macdonald and Macpherson in their communication attributed the amplification to the change in the potential distribution of the circuit brought about by substituting the positive ion for the electron grid current of the output tube.

This suggested an examination of the grid current of the output tube to see whether it consists of a positive ion or an electron current when the high amplification of the system is experienced.

II. THE EXAMINATION OF THE GRID CURRENT OF THE OUTPUT TUBE USED AS A SPACE CHARGE TUBE

In order that the magnitude of the grid current of the output tube might, if need be, be readily controlled, a slight modification of the previous circuit was necessitated. A UX222 four-element tube, using the screen grid as control grid and charging the regular control grid positively with respect to the negative side of the filament to act as a space charge grid, was employed as output tube replacing the UX201A triode used in the preceding circuit. Figure 26 shows a

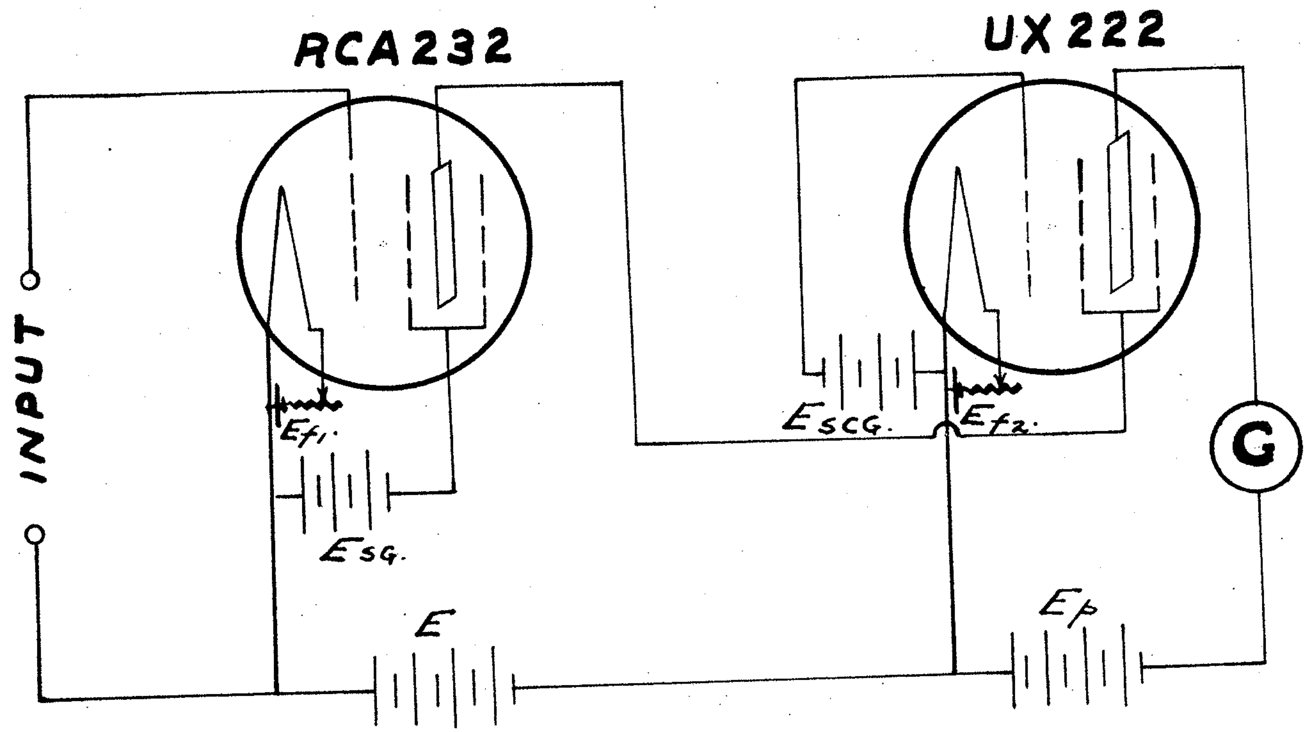


FIGURE 25.

schematic diagram of the modified circuit wherein a UX222 is used as a space charge tube in the output stage.

(1) The Similarity of the Properties Possessed by the Two Circuits

The effects produced by varying the E potential, the input tube being employed as a triode (screen grid tied to plate) and by varying the potential applied to the screen grid of the input tube when employed as a four-element tube were observed, the data being given in Tables IX and X respectively.

TABLE IX

Input Tube RCA232
Filament Volts 2.0
Triode(screen grid tied to plate)
Various plate or E Voltages

Output Tube UX222 as
a Space Charge Tube.
Plate Volts 90.0
Space charge grid
volts 45.0

(a) E Potential 7.30 volts

Grid Potential (volts)	Plate Current (mas)
-1.700	36.10
-1.650	36.10
-1.600	36.00
-1.550	35.90
-1.500	35.70
-1.440	35.50
-1.400	35.10
-1.350	34.70
-1.300	33.60
-1.250	32.50
-1.200	30.60
-1.150	27.60
-1.125	25.50
-1.100	23.20
-1.075	20.00
-1.050	16.30

(a) continued

-1.025	12.80
-1.000	9.00
-0.975	5.20
-0.950	3.10
-0.925	1.90
-0.900	0.80
-0.875	0.30
-0.850	0.10
-0.825	0.00

(b) E Potential 5.80 volts

Grid Potential(volts)	Plate Current (mms)
-1.800	36.10
-1.750	36.10
-1.700	36.00
-1.650	35.90
-1.600	35.80
-1.550	35.70
-1.500	35.60
-1.440	35.50
-1.400	35.40
-1.350	35.30
-1.300	35.10
-1.240	34.90
-1.200	34.60
-1.150	33.90
-1.100	33.10
-1.050	31.60
-1.000	30.10
-0.950	26.70
-0.900	22.10
-0.875	18.90
-0.850	15.10
-0.825	11.00
-0.800	7.90
-0.775	4.60
-0.750	2.90
-0.725	1.50
-0.700	0.80
-0.675	0.20
-0.650	0.10
-0.625	0.00
-0.600	0.00

(c) E Potential 2.90 volts

Grid Potential (volts)	Plate Current (mas)
-1.100	33.80
-1.000	33.80
-0.950	33.60
-0.900	33.40
-0.850	33.20
-0.800	33.00
-0.750	32.50
-0.700	31.90
-0.650	31.10
-0.600	29.60
-0.550	27.90
-0.500	25.20
-0.450	21.20
-0.400	16.30
-0.350	11.30
-0.250	7.20
-0.200	4.20
-0.150	2.20
-0.100	1.30
-0.050	0.50
-0.020	0.00

TABLE X

Input Tube RCA232
Filament Volts 2.0
Plate or E volts 7.3
Various Screen Grid Voltages

Output Tube UX222 employed as a space charge tube.
Filament Volts 3.3
Plate Volts 90.0
Space charge grid volts 45.0

(a) Screen Grid Potential 8.80 volts

Grid Potential (volts)	Plate Current (mas)
-2.050	33.30
-1.980	33.25
-1.940	33.10
-1.900	33.00
-1.850	32.80
-1.800	32.50
-1.750	32.20
-1.700	31.90
-1.650	31.20

(a) continued

-1.600	30.60
-1.550	29.10
-1.500	27.00
-1.456	25.80
-1.429	20.00
-1.415	17.00
-1.412	14.00
-1.410	12.00
-1.406	8.30
-1.403	3.20
-1.401	1.00
-1.4009	0.20
-1.4001	0.10
-1.3960	0.00
-1.3900	0.00

(b) Screen Grid Potential 6.00 volts

-1.650	32.90
-1.600	32.90
-1.550	32.80
-1.500	32.70
-1.450	32.60
-1.400	32.50
-1.350	32.40
-1.300	32.30
-1.250	32.10
-1.200	31.90
-1.150	31.60
-1.100	31.10
-1.050	30.30
-1.000	29.30
-0.950	27.30
-0.900	25.70
-0.875	20.10
-0.858	16.30
-0.850	13.10
-0.846	10.60
-0.843	6.50
-0.841	2.60
-0.840	1.10
-0.839	0.40
-0.837	0.20
-0.836	0.10
-0.833	0.00

(c) Screen Grid Potential 3.00 volts

Grid Potential (volts)	Plate Current (mas)
-1.300	32.10
-1.200	32.10
-1.150	31.90
-1.100	31.60
-1.050	31.30
-1.000	31.00
-0.950	30.70
-0.900	30.10
-0.850	28.90
-0.800	27.00
-0.750	25.90
-0.700	20.30
-0.675	12.10
-0.650	4.20
-0.6436	0.50
-0.6423	0.20
-0.6404	0.00
-0.6379	0.00

Figures 26 and 27 show this data when plotted. These graphs render results similar to those obtained from the aforementioned circuit, the sensitivity to voltage of the unit being independent of the E potential and screen grid potential employed, the curves shifting to regions of greater negative grid bias of the control grid of the input tube for increasing values of the E and screen grid potentials.

Thus we see that these properties of the two circuits are identical. It was deemed unnecessary to repeat the preceding operations to determine the remaining properties of the circuit, it being concluded from the similarity of operation shown above that the two

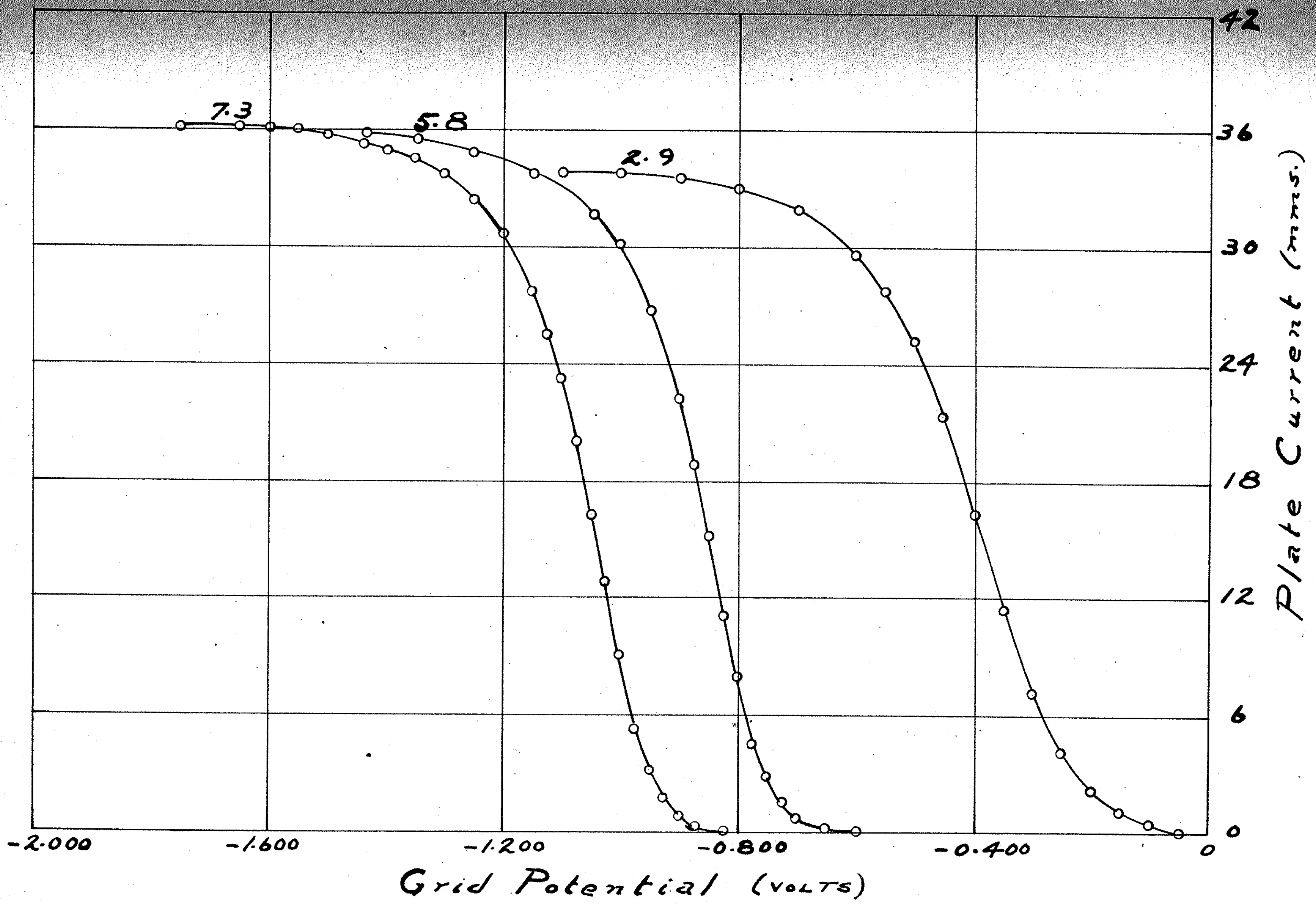
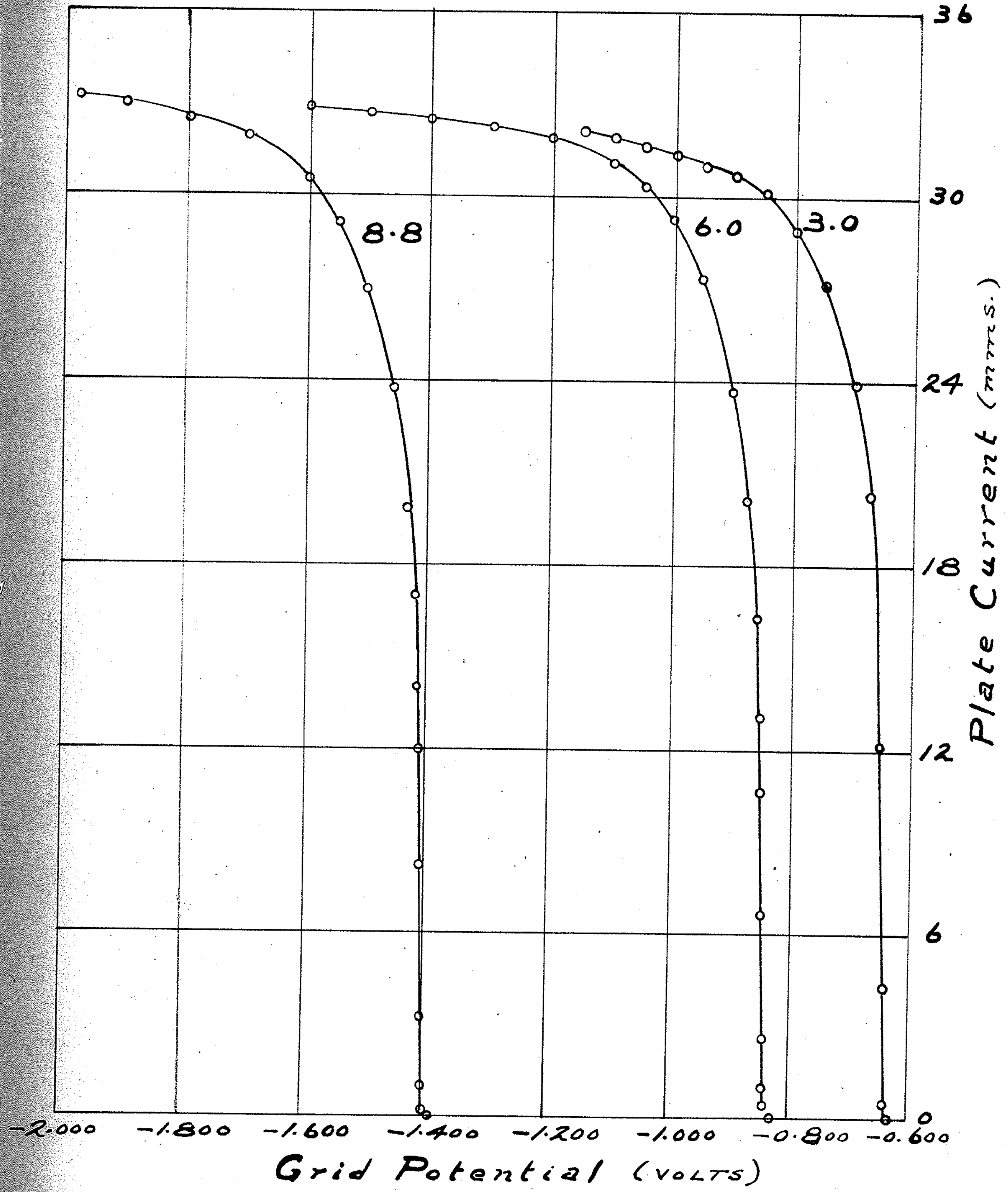

7.3
5.8
2.9
42
36
30
24
18
12
6
0
-2.000
-1.600
-1.200
-0.800
-0.400
0
Plate Current (mms.)
Grid Potential (volts)

FIGURE 26.



36
30
24
18
12
6
0
8·8
6.0
3.0
-2.000
-1.800
-1.600
-1.400
-1.200
-1.000
-0.800
-0.600
Grid Potential (VOLTS)
Plate Current (mms.)

FIGURE 27.

circuits have similar properties.

The voltage sensitivity, however, is found to be increased with this modified circuit, being $6.94 \times 10^{-3} \frac{\text{volts}}{\text{mm}}$ when the input tube is used as a triode, and $1.00 \times 10^{-3} \frac{\text{volts}}{\text{mm}}$ when it is used as a four-element tube.

It now remains to see what additional properties this modified circuit possesses due to the presence of the positively charged space charge grid tube in the output stage.

(2) Variation of the Positive Potential Applied to the Space Charge Grid in the Output Tube

Table XI gives the data showing the relation between the grid potential of the control grid of the input tube and the plate current of the output tube for various positive potentials applied to the space charge grid of the output tube.

TABLE XI

Input Tube RCA232
Filament Volts 1.95
Plate or E Volts 7.25
Screen Grid Volts 5.90

Output Tube UX222 employed as a Space Charge Tube
Filament Volts 3.3
Plate Volts 90.0
Various space charge grid voltages.

(a) Space Charge Grid Potential 45.2 volts

Grid Potential (volts)	Plate Current (microamps)
-1.7000	497.0
-1.6000	497.0

(a) continued

-1.5000	487.0
-1.4500	476.0
-1.4000	461.0
-1.3450	440.0
-1.3000	418.0
-1.2500	370.0
-1.2150	290.0
-1.2040	241.0
-1.1990	214.0
-1.1960	175.0
-1.1940	132.5
-1.1926	93.0
-1.1905	38.0
-1.1894	20.6
-1.1889	10.8
-1.1884	5.4
-1.1883	3.6
-1.1872	0.0

(b) Space Charge Grid Potential 43.4 volts

Grid Potential (volts)	Plate Current(microamps)
-1.7500	456.0
-1.7000	456.0
-1.6500	451.0
-1.6000	446.0
-1.5500	439.0
-1.5000	435.0
-1.4500	426.0
-1.4000	414.0
-1.3500	387.0
-1.3000	366.0
-1.2800	336.0
-1.2500	296.0
-1.2400	239.0
-1.2325	197.0
-1.2301	163.0
-1.2277	152.5
-1.2265	103.0
-1.2250	65.7
-1.2240	39.1
-1.2236	25.8
-1.2223	19.5
-1.2216	2.2
-1.2205	0.0

(c) Space Charge Grid Potential 41.8 volts

Grid Potential (volts)	Plate Current(microamps)
-1.8000	414.0
-1.7000	414.0
-1.6500	412.0
-1.6000	406.0
-1.5500	400.0
-1.5000	394.0
-1.4500	388.0
-1.4000	369.0
-1.3450	338.0
-1.3000	306.0
-1.2800	271.0
-1.2500	191.0
-1.2450	143.5
-1.2425	124.0
-1.2413	102.0
-1.2401	72.7
-1.2386	45.6
-1.2376	25.0
-1.2361	6.5
-1.2359	1.1
-1.2353	0.0

(d) Space Charge Grid Potential 40.2 volts

Grid Potential(volts)	Plate Current(microamps)
-1.8000	374.0
-1.7500	374.0
-1.7000	372.0
-1.6500	370.0
-1.6000	366.0
-1.5500	359.0
-1.5000	352.0
-1.4500	345.0
-1.4000	326.0
-1.3500	298.0
-1.3000	239.0
-1.2943	223.0
-1.2909	216.0
-1.2884	210.0
-1.2858	197.5
-1.2821	194.0
-1.2795	173.0
-1.2745	150.0

(d) continued

-1.2683	89.0
-1.2670	70.5
-1.2658	47.6
-1.2646	29.2
-1.2633	16.2
-1.2621	5.4
-1.2609	0.0

(e) Space Charge Grid Potential 33.5 Volts

Grid Potential(volts)	Plate Current(microamps)
-1.9000	345.0
-1.8100	345.0
-1.7500	342.0
-1.7000	337.0
-1.6500	332.0
-1.6000	325.0
-1.5500	320.0
-1.5000	315.0
-1.4550	305.0
-1.4000	292.0
-1.3700	262.0
-1.3300	215.0
-1.3150	173.0
-1.3000	113.0
-1.2974	86.3
-1.2961	70.5
-1.2948	54.2
-1.2935	38.0
-1.2922	22.8
-1.2909	10.9
-1.2896	2.2
-1.2884	0.0

(f) Space Charge Grid Potential 36.0 volts

Grid Potential (volts)	Plate Current(microamps)
-2.0000	287.5
-1.9000	287.5
-1.8500	286.5
-1.8000	285.0
-1.7500	283.5
-1.7000	282.0

(f) continued

-1.6500	280.5
-1.6000	275.0
-1.5500	266.0
-1.5000	256.0
-1.4500	236.0
-1.4000	200.5
-1.3850	188.5
-1.3632	152.0
-1.3591	138.0
-1.3564	130.0
-1.3524	113.0
-1.3484	101.0
-1.3431	66.5
-1.3418	54.1
-1.3392	30.5
-1.3378	20.6
-1.3366	9.8
-1.3353	3.25
-1.3339	1.09
-1.3327	0.00

(g) Space Charge Grid Potential 34.3 volts

Grid Potential (volts)	Plate Current(microamps)
-1.9000	245.0
-1.8500	245.0
-1.8000	243.0
-1.7500	241.0
-1.7000	239.0
-1.6500	236.0
-1.6000	228.0
-1.5500	216.0
-1.5000	202.0
-1.4550	185.0
-1.4100	141.0
-1.4000	114.0
-1.3902	87.7
-1.3861	63.5
-1.3806	36.8
-1.3779	16.3
-1.3766	5.4
-1.3759	3.3
-1.3752	0.0

(h) Space Charge Grid Potential 31.8 volts

Grid Potential (volts)	Plate Current(microamps)
-2.0000	198.00
-1.9650	198.00
-1.9000	196.50
-1.8500	195.00
-1.8000	193.00
-1.7500	189.70
-1.7000	184.50
-1.6500	179.00
-1.6000	172.50
-1.5500	155.00
-1.5000	133.50
-1.4800	109.50
-1.4700	93.00
-1.4500	68.30
-1.4443	52.10
-1.4399	38.00
-1.4356	19.70
-1.4326	4.35
-1.4314	2.17
-1.4299	0.00

(i) Space Charge Grid Potential 23.3 volts

Grid Potential (volts)	Plate Current(microamps)
-2.0200	124.00
-1.9500	122.50
-1.9000	121.70
-1.8500	119.80
-1.8000	115.60
-1.7500	112.00
-1.7000	105.50
-1.6500	93.20
-1.6000	76.00
-1.5841	66.10
-1.5686	56.30
-1.5634	41.30
-1.5474	28.20
-1.5429	21.70
-1.5399	16.30
-1.5384	10.87
-1.5355	2.17
-1.5311	1.09
-1.5325	0.00

(j) Space Charge Grid Potential 25.6 volts

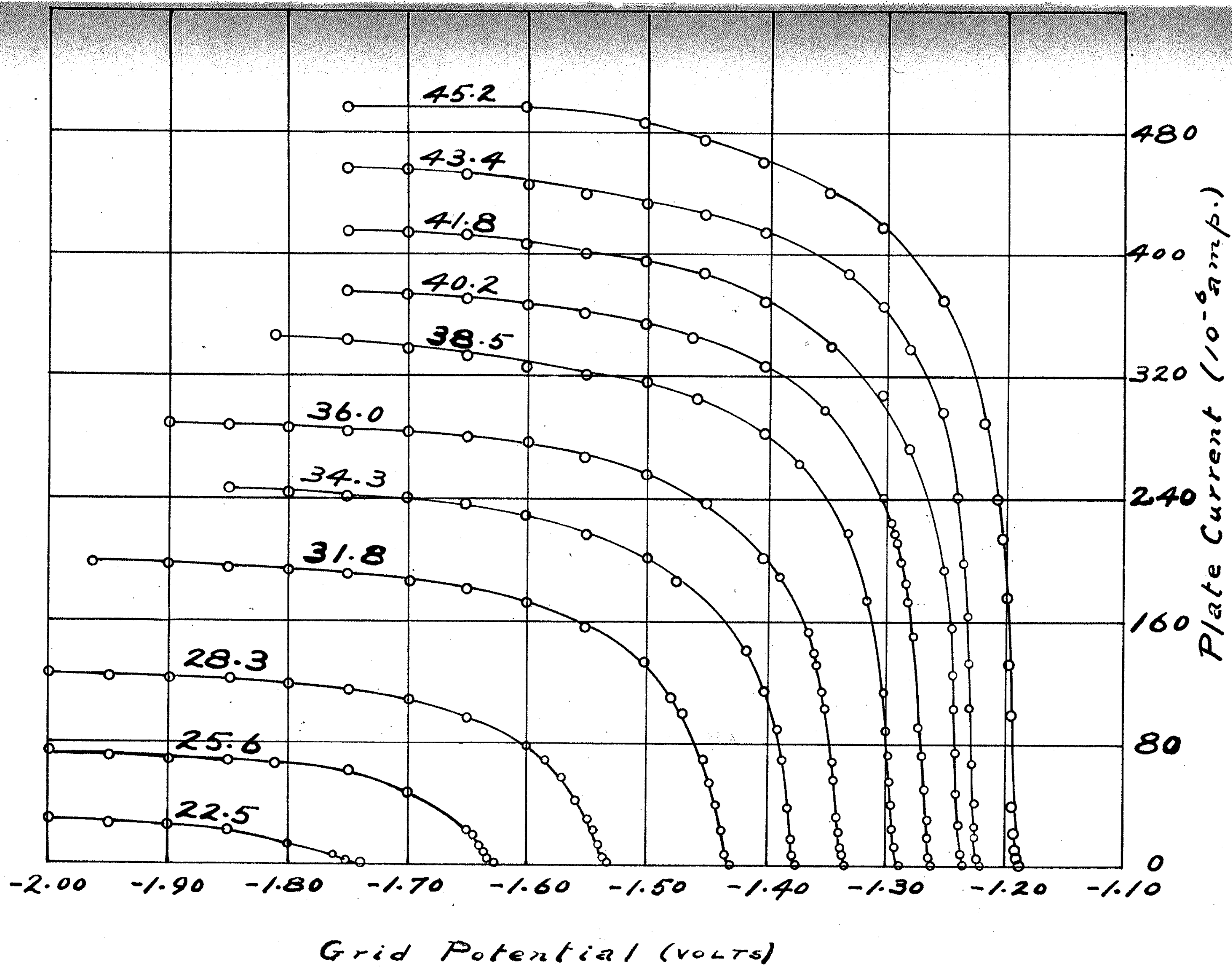
Grid Potential(volts)	Plate Current(microamps)
-2.0200	74.00
-1.9500	70.50
-1.9000	68.30
-1.8500	66.10
-1.8100	65.10
-1.7500	59.70
-1.7000	44.50
-1.6500	21.70
-1.6432	18.40
-1.6385	10.85
-1.6353	6.51
-1.6336	4.34
-1.6304	2.17
-1.6256	0.00

(k) Space Charge Grid Potential 22.5 volts

Grid Potential(volts)	Plate Current(microamps)
-2.2000	32.60
-2.1000	32.60
-2.0500	30.45
-2.0000	28.20
-1.9500	26.10
-1.9000	22.80
-1.8500	19.50
-1.8000	10.85
-1.7600	3.25
-1.7500	1.09
-1.7400	0.00

Figure 28 shows this data when plotted. It is seen that the mutual conductance of the unit increases with increasing positive space charge grid potential, increasing from 200 $\frac{\text{microamperes}}{\text{volt}}$ at 22.5 volts space charge grid potential to 30,000 $\frac{\text{microamperes}}{\text{volt}}$ at 45.2 volts.

The data showing the relation between the mutual conductance of the unit and the potential applied to the



45·2
43·4
41·8
40·2
38·5
36·0
34·3
31·8
28·3
25·6
22·5
480
400
320
240
160
80
0
Plate Current (10⁻⁶ amp.)
-2.00
-1.90
-1.80
-1.70
-1.60
-1.50
-1.40
-1.30
-1.20
-1.10
Grid Potential (VOLTS)

FIGURE 28.

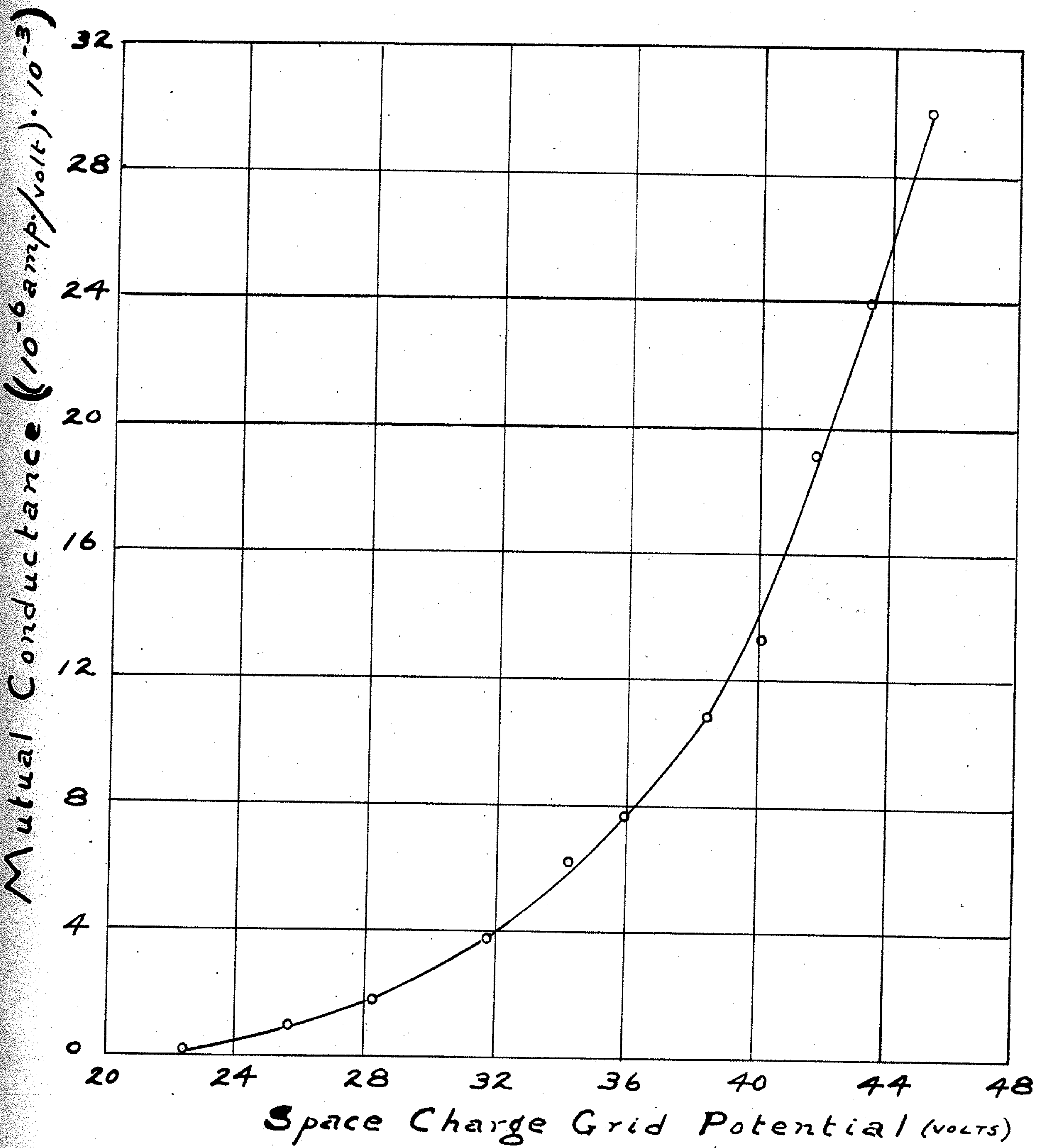

Mutual Conductance ((10⁻⁶ amp./volt)·10⁻³)
32
28
24
20
16
12
8
4
0
20
24
28
32
36
40
44
48
Space Charge Grid Potential (VOLTS)

FIGURE 29.

space charge grid of the output tube is give in Table XII and Figure 29 shows the curve obtained from this data.

TABLE XII

Input Tube RCA232
Filament Volts 1.95
Plate or B volts 7.25
Screen Grid Volts 5.90

Output Tube UX222 employed as a space charge tube.
Filament Volts 3.3
Plate Volts 90.0

Space Charge Grid Potential		Mutual Conductance of the Amplifying Unit	
22.50	volts	207	$\frac{\text{microamperes}}{\text{volt}}$
25.60	"	1039	
28.30	"	1852	"
31.80	"	3902	"
34.30	"	6333	"
36.00	"	7692	"
38.50	"	10909	"
40.20	"	13333	"
41.80	"	19200	"
43.40	"	24000	"
45.20	"	30000	"

(3) An Examination of the Grid Current of the Output Tube

A simple one-tube circuit (Figure 30) was employed to determine the grid potential-grid current and grid potential-plate current characteristics of the tube used in the output stage of the amplification unit for the various positive potentials applied to the space charge grid of this output tube as in Table XI. The data is given in Table XIII and the curves obtained from this data are shown in Figures 31 to 41.

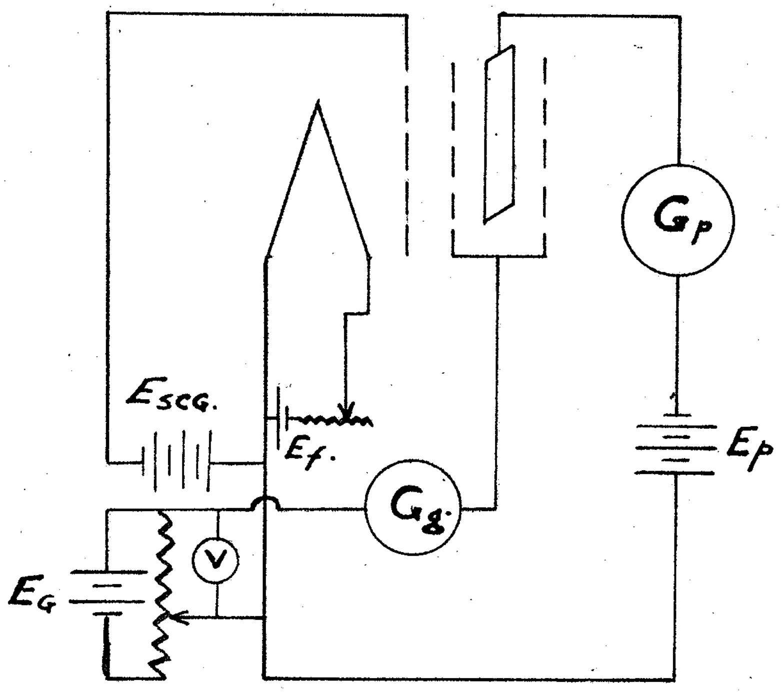


FIGURE 30.

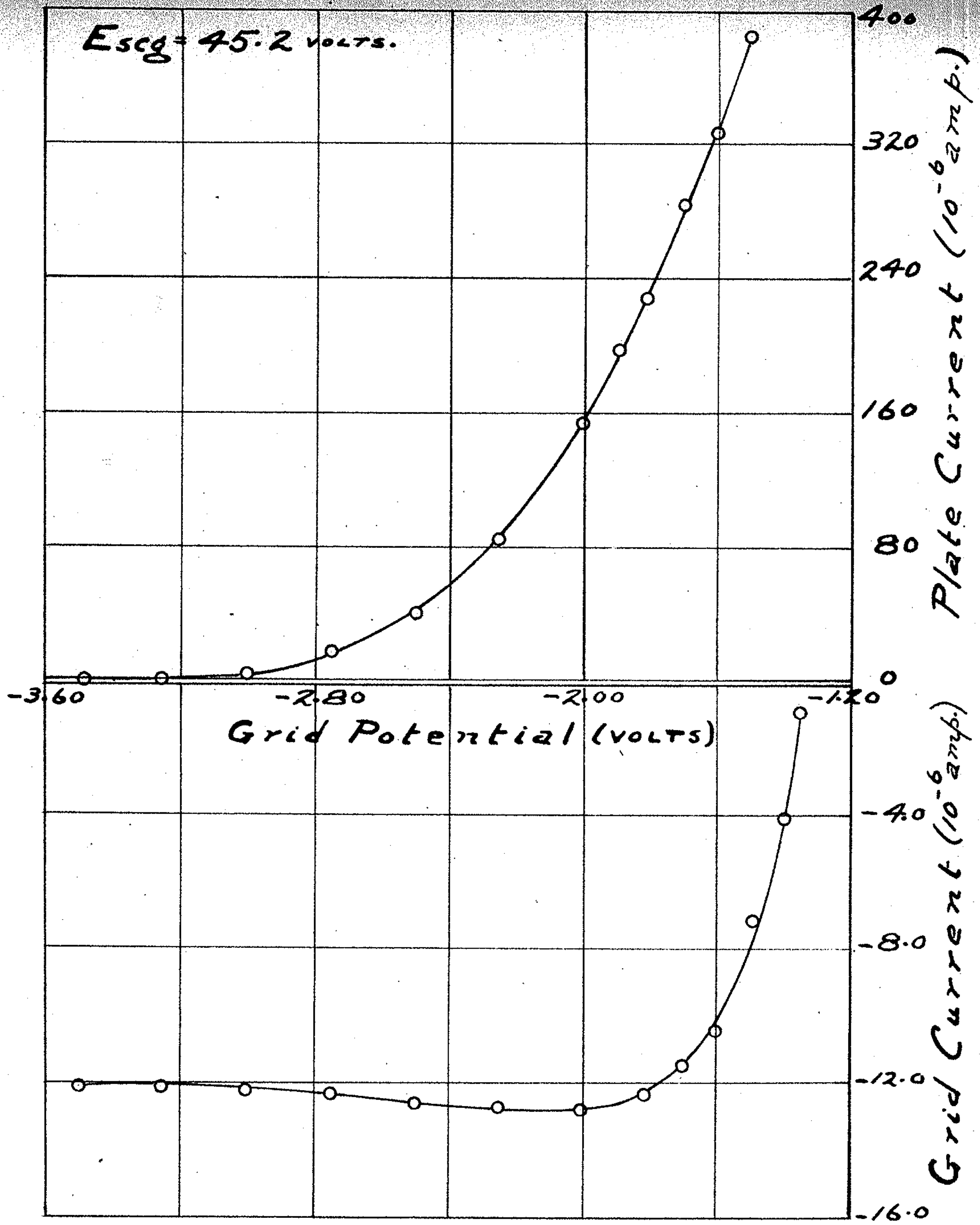


FIGURE 31.

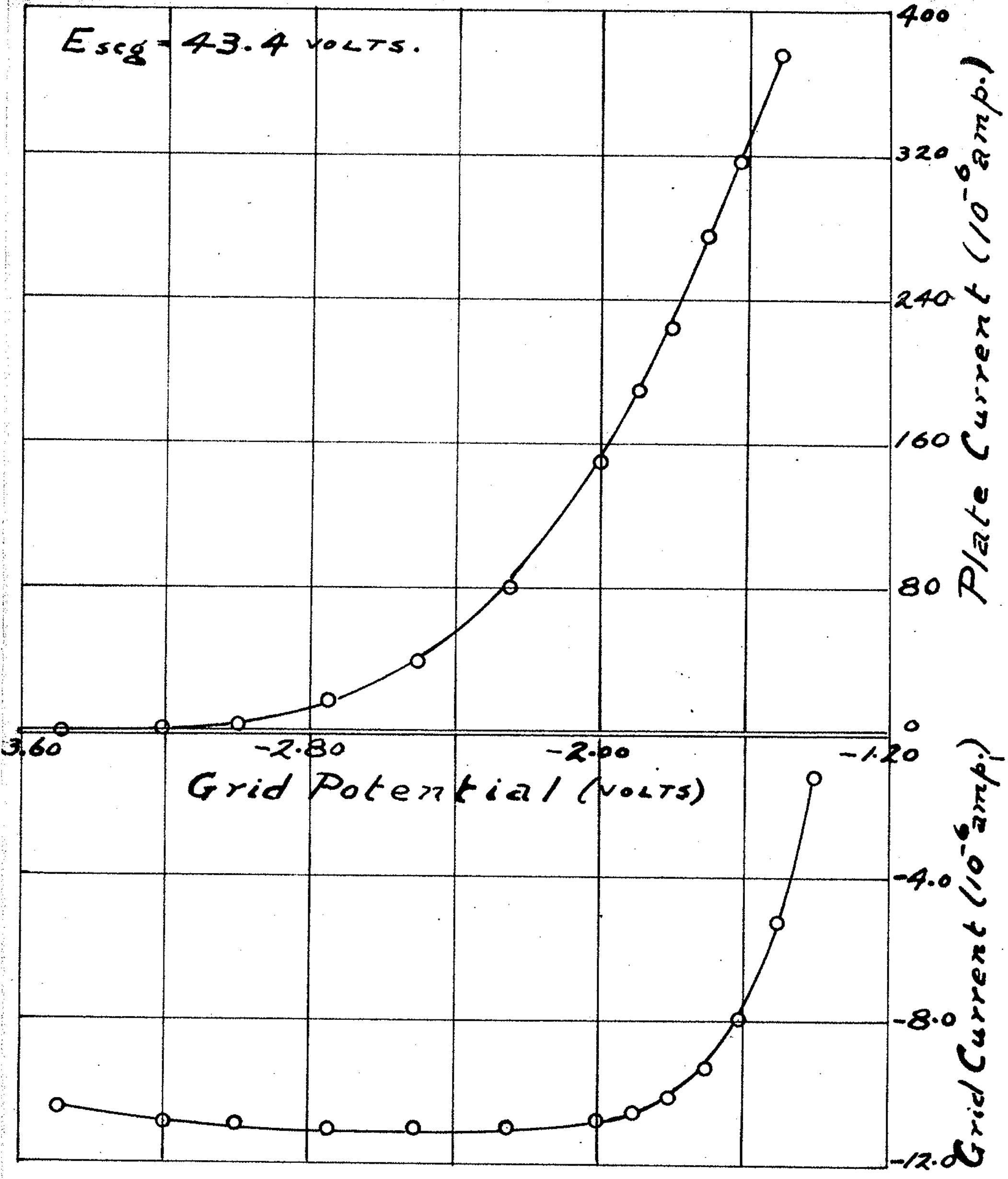


FIGURE 32.

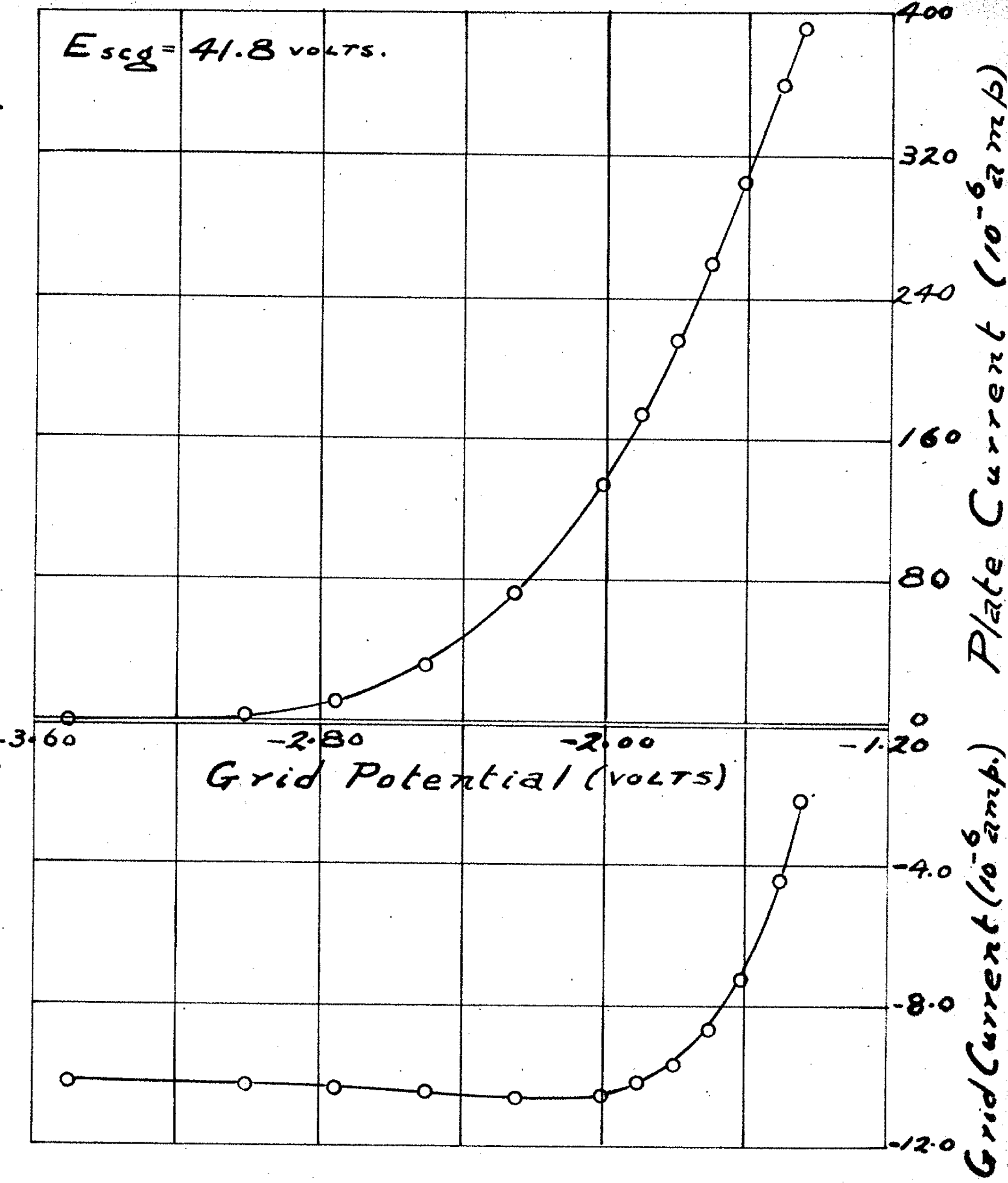


FIGURE 33.

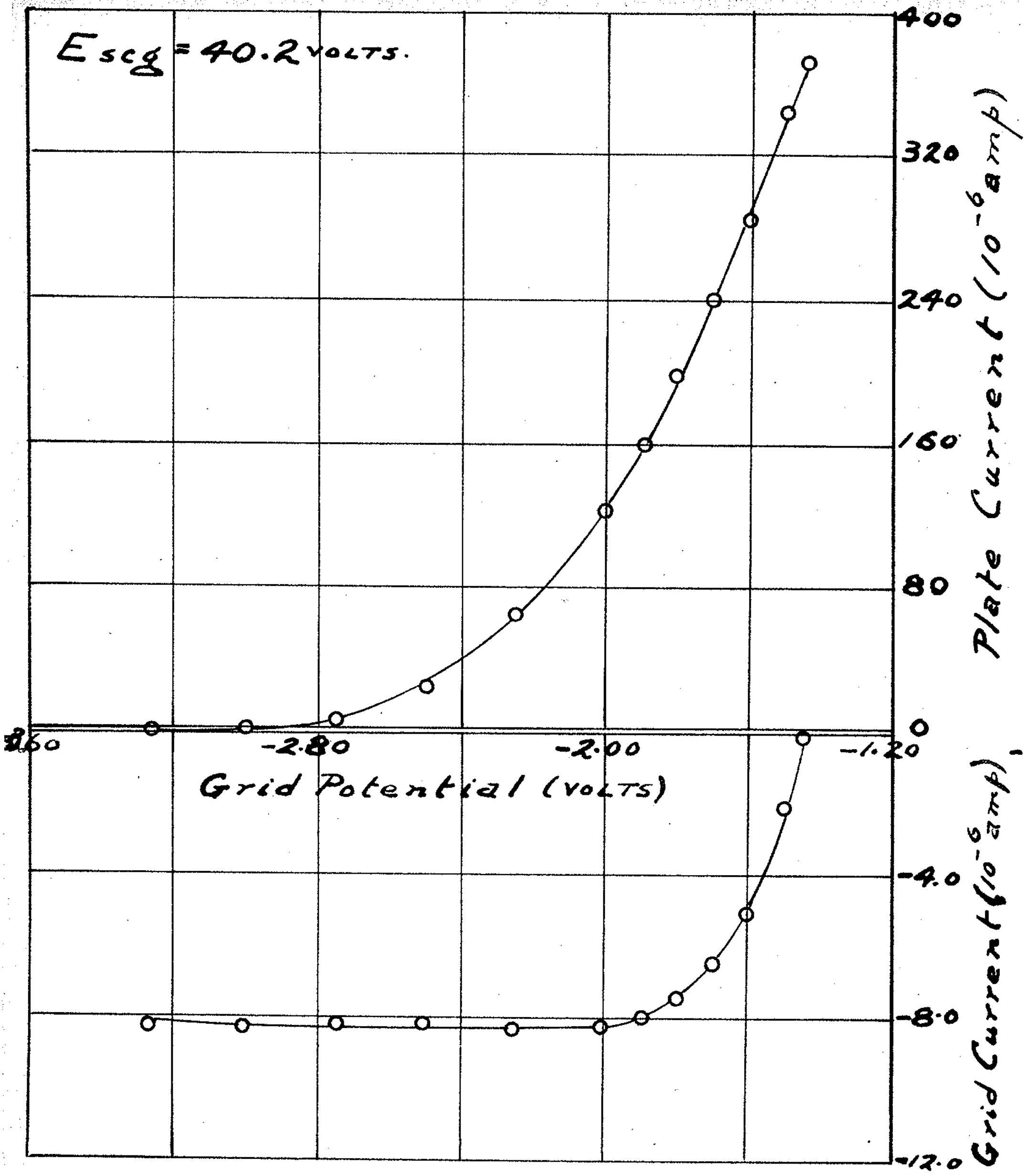


FIGURE 34.

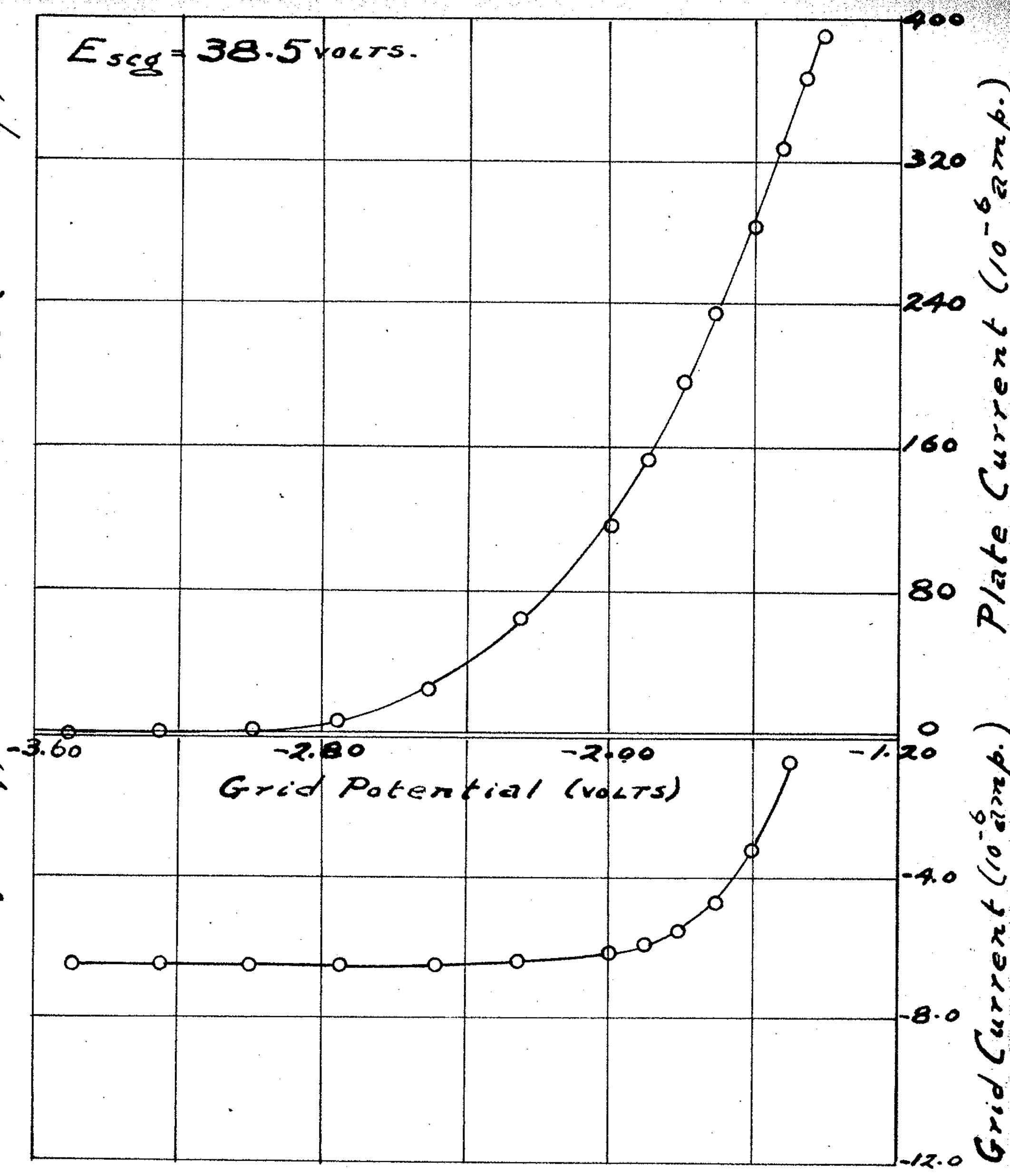


FIGURE 35.

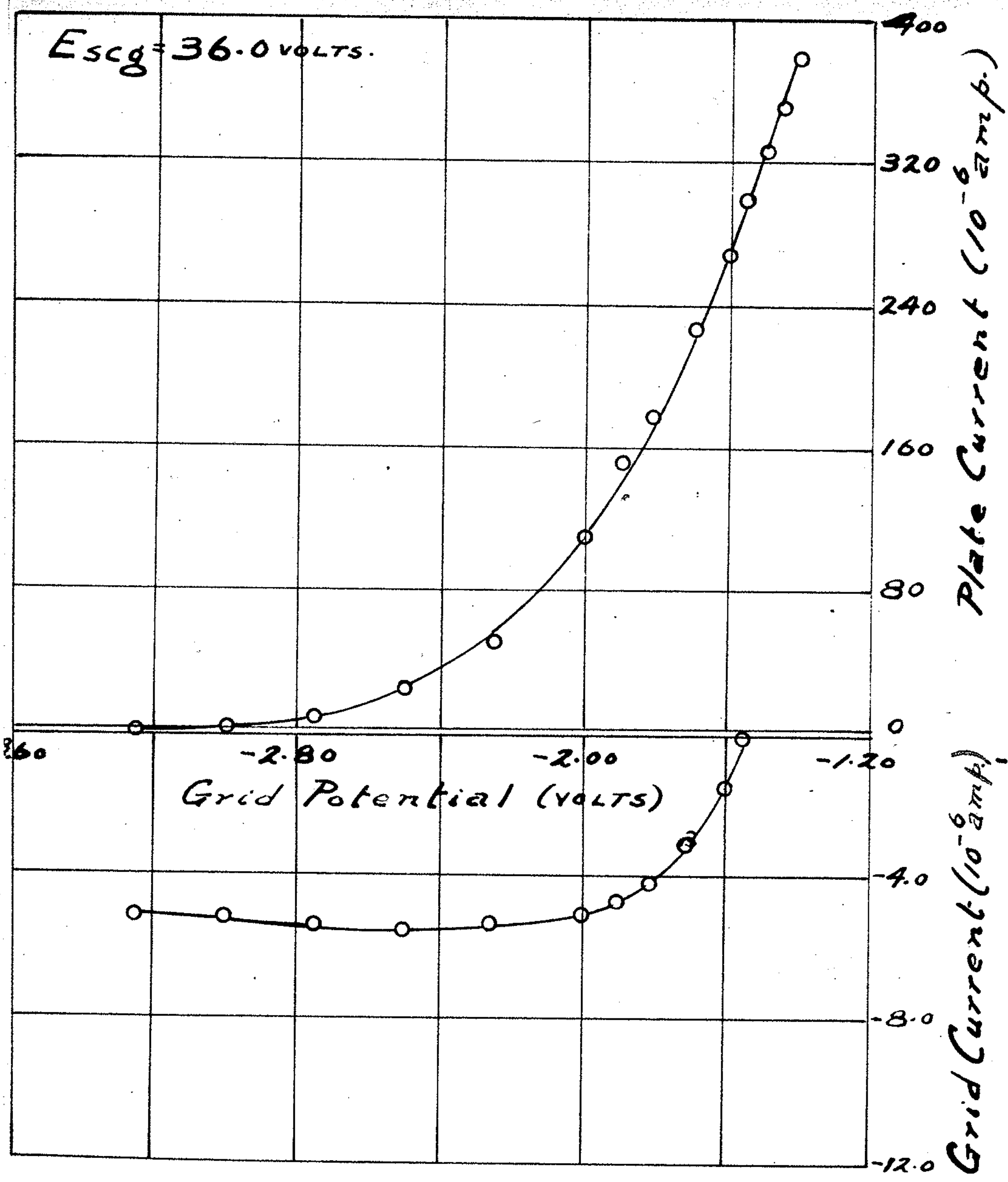


FIGURE 36.

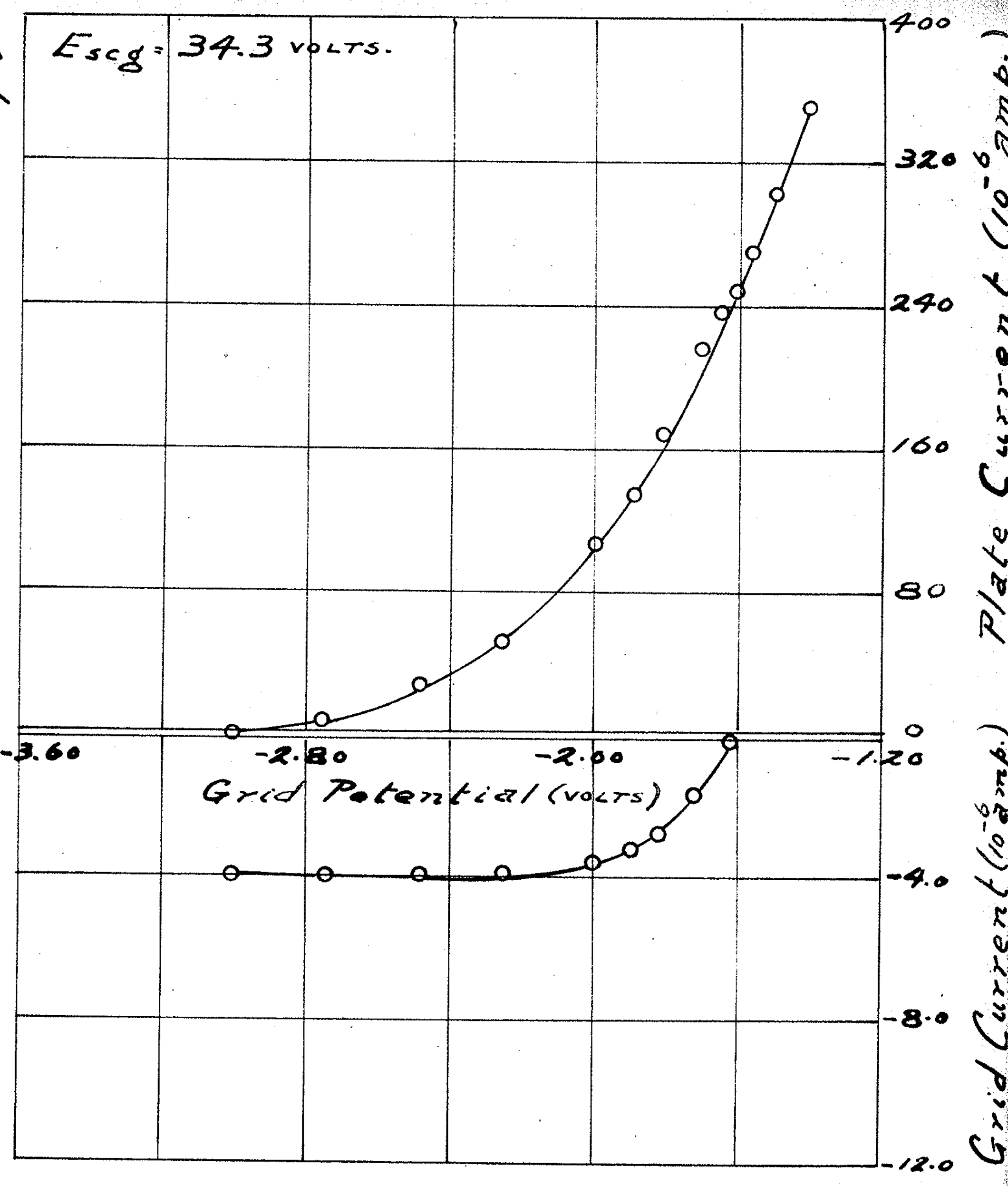


FIGURE 37.

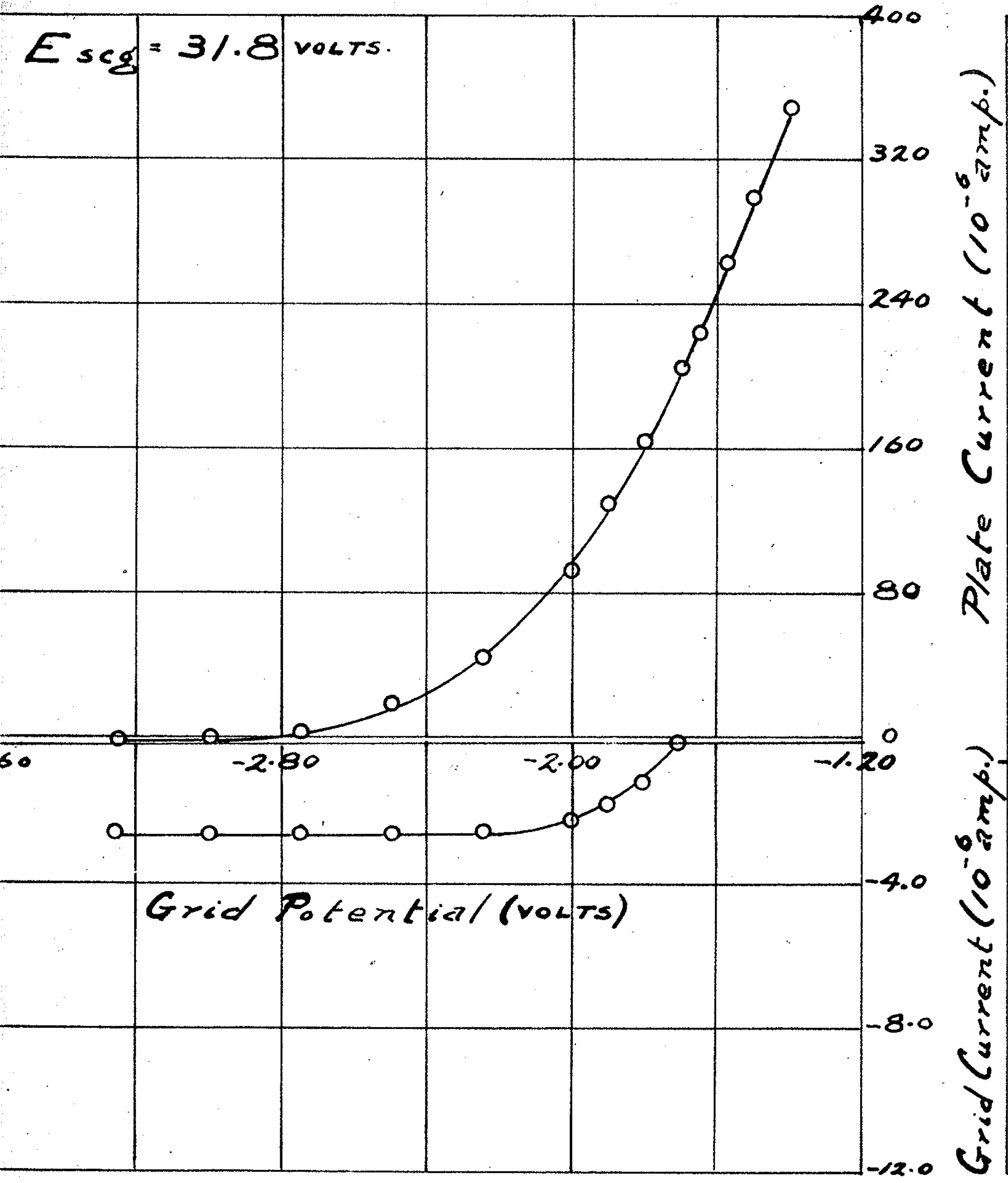


FIGURE 38.

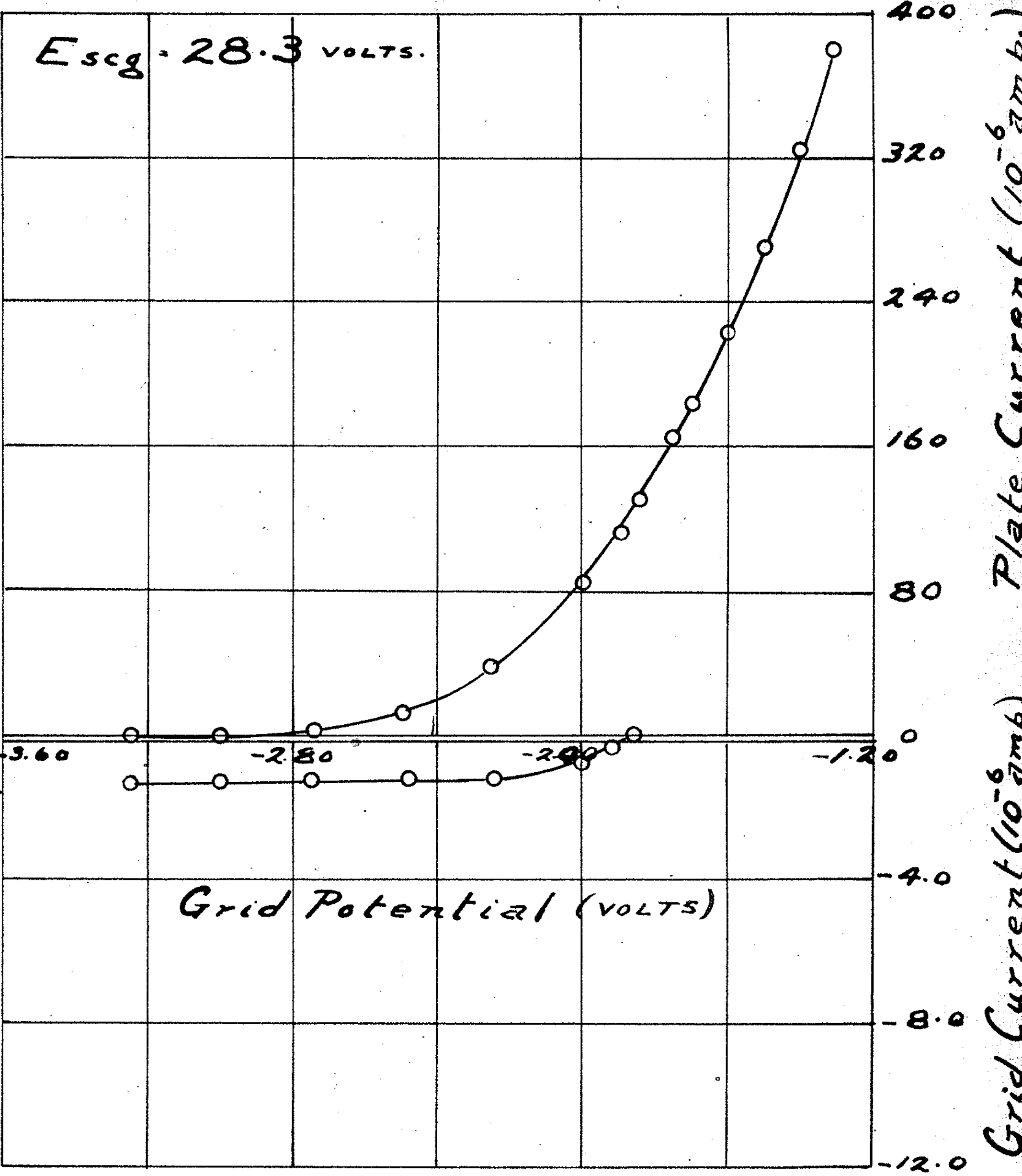


FIGURE 39.

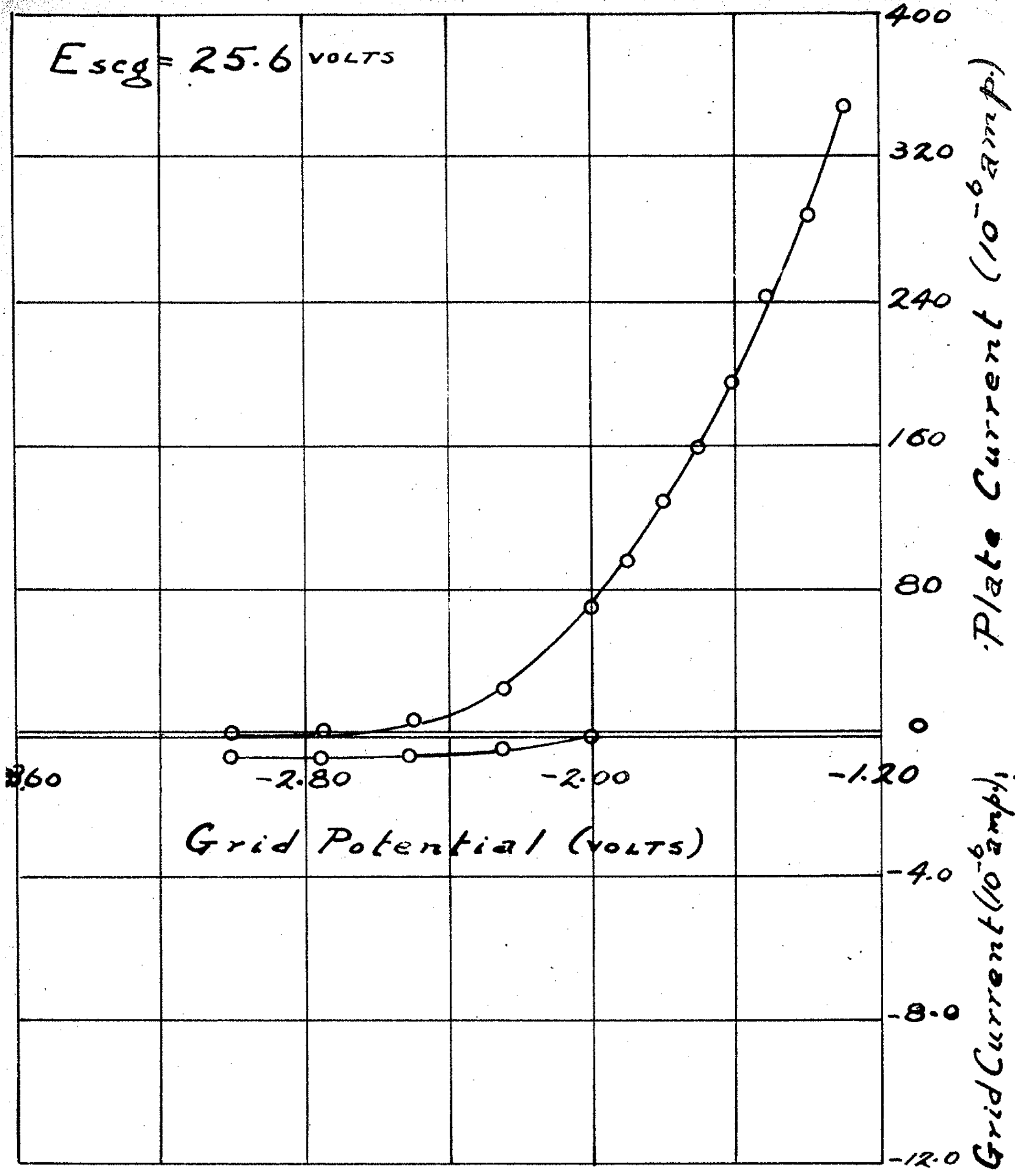


FIGURE 40.

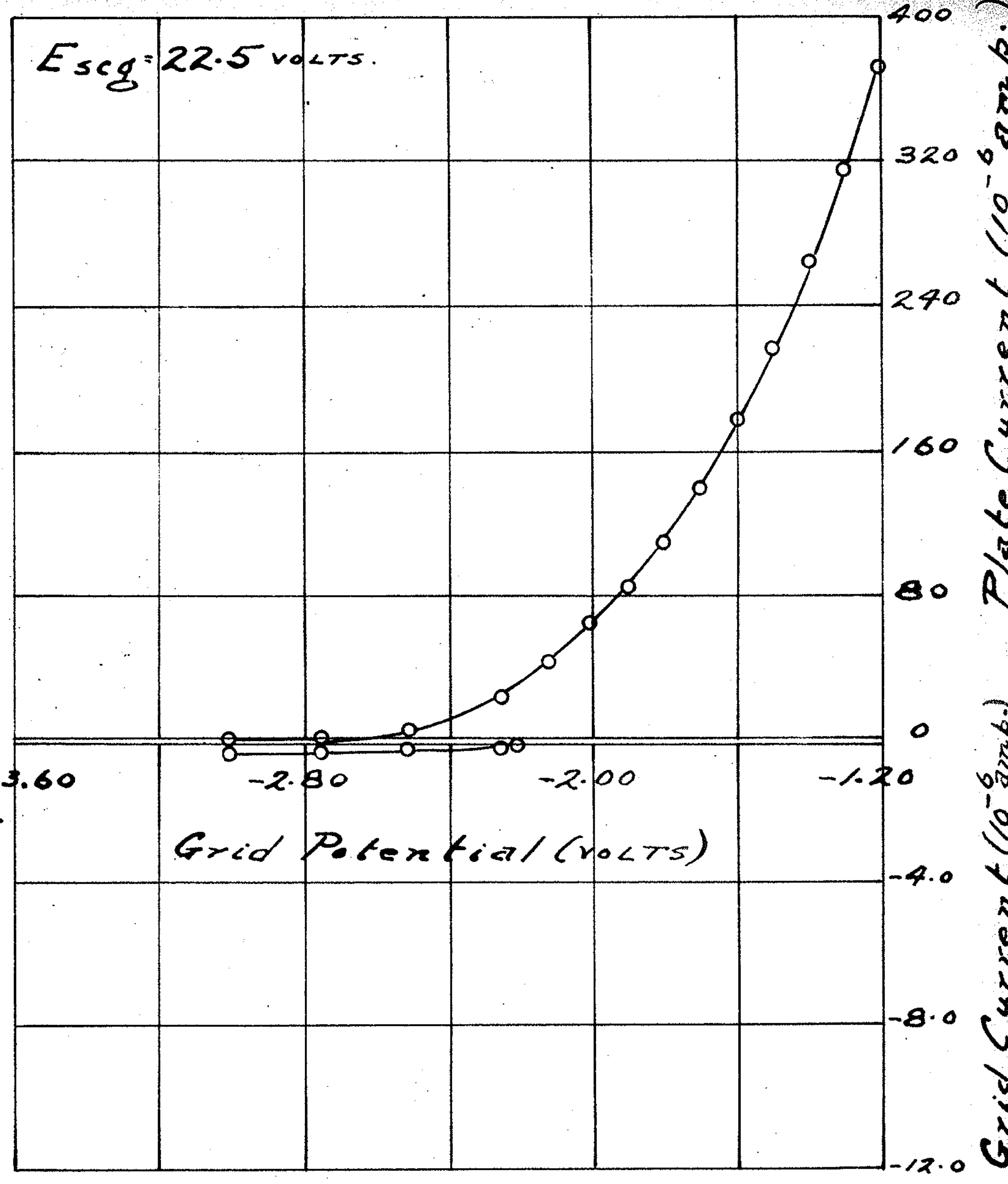


FIGURE 41.

TABLE XIII

Tube UX222 employed as a Space Charge Tube
Filament Volts 3.3
Plate Volts 90.0
Various Space Charge Grid Potentials.

(a) Space Charge Grid Potential 45.2 volts

Grid Potential(volts)	Grid Current (amps. x 10^{-9})	Plate Current (amperes x 10^{-6})
-3.500	-12.150	0.00
-3.250	-12.204	1.08
-3.000	-12.276	4.35
-2.750	-12.384	17.40
-2.500	-12.636	41.30
-2.250	-12.744	84.70
-2.000	-12.870	154.00
-1.900	-12.636	198.00
-1.810	-12.420	228.50
-1.700	-11.520	285.00
-1.600	-10.440	329.00
-1.500	- 7.100	385.00
-1.400	- 4.140	452.00
-1.350	- 0.900	484.00
-1.300	2.844	511.00
-1.250	7.100	541.00
-1.200	15.390	589.00
-1.100	42.430	698.00
-1.000	75.600	765.00
-0.900	137.700	857.00
-0.800	246.600	962.00
-0.700	456.300	1067.00
-0.600	723.600	1200.00
-0.500	1155.600	1330.00
-0.400	1877.400	1460.00
-0.350	2412.000	1522.00
-0.300	3060.000	1590.00
-0.200	4680.000	1750.00
-0.100	6750.000	1900.00
-0.060	7560.000	1950.00

(b) Space Charge Grid Potential 43.4 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-8})	Plate Current (Amperes x 10^{-6})
-3.500	-10.44	0.00
-3.250	-10.84	1.08
-3.000	-10.89	3.25
-2.750	-10.93	16.30
-2.500	-10.94	38.10
-2.250	-10.96	79.40
-2.000	-10.80	150.00
-1.900	-10.53	192.50
-1.800	-10.13	224.50
-1.700	- 9.36	276.00
-1.610	- 8.07	315.00
-1.500	- 5.31	375.00
-1.400	- 1.26	435.00
-1.345	2.52	470.00
-1.300	6.03	496.00
-1.250	11.43	531.00
-1.200	19.44	592.00
-1.100	43.20	670.00
-1.000	81.00	740.00
-0.900	148.50	841.00
-0.800	260.10	932.00
-0.750	344.70	1010.00
-0.700	432.00	1030.00
-0.600	747.00	1178.00
-0.500	1197.00	1286.00
-0.400	1917.00	1410.00
-0.300	3078.00	1535.00
-0.200	4320.00	1650.00
-0.100	6660.00	1820.00
-0.060	7614.00	1875.00

(c) Space Charge Grid Potential 41.8 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-9})	Plate Current (amperes x 10^{-6})
-3.500	-10.13	0.00
-3.000	-10.26	3.25
-2.750	-10.35	10.85
-2.500	-10.44	32.55
-2.000	-10.44	72.69
-1.900	-10.53	132.37

(c) contined

-1.800	-10.22	174.68
-1.700	- 9.72	217.00
-1.610	- 8.78	260.40
-1.500	- 7.38	303.80
-1.450	- 4.46	361.30
-1.400	- 2.19	391.68
-1.380	0.61	429.66
-1.340	1.47	436.17
-1.300	4.98	461.12
-1.255	8.55	486.08
-1.200	14.40	511.03
-1.150	18.90	542.85
-1.100	34.51	610.06
-1.000	46.80	641.08
-0.900	82.80	728.97
-0.800	154.80	816.86
-0.700	259.10	917.67
-0.600	450.00	1023.66
-0.500	757.80	1132.23
-0.400	1224.00	1235.63
-0.300	1945.80	1344.20
-0.200	3078.00	1463.11
-0.100	4530.00	1592.36
-0.010	6650.00	1731.95
	7200.00	1762.97

(d) Space Charge Grid Potential 40.2 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-8})	Plate Current (amperes x 10^{-6})
-3.500	- 8.22	0.00
-3.250	- 8.28	0.00
-3.000	- 8.28	2.17
-2.750	- 8.19	6.51
-2.500	- 8.12	23.87
-2.250	- 8.44	63.93
-2.000	- 8.29	122.60
-1.900	- 7.97	160.58
-1.810	- 7.56	195.30
-1.700	- 6.58	240.87
-1.600	- 5.16	284.27
-1.500	- 2.27	343.94
-1.450	- 0.13	371.07
-1.400	1.98	392.77

(d) continued

-1.360	4.64	422.06
-1.300	10.53	463.30
-1.200	23.76	520.80
-1.150	37.08	588.00
-1.100	47.34	638.40
-1.000	85.50	722.40
-0.900	156.24	823.20
-0.800	267.84	901.60
-0.750	360.00	985.60
-0.700	464.60	1013.60
-0.600	752.40	1125.60
-0.500	1109.60	1237.60
-0.400	1944.00	1355.20
-0.300	3132.00	1472.80
-0.250	3870.00	1545.60
-0.200	4770.00	1607.20
-0.100	6804.00	1719.20
-0.050	8028.00	1792.00

(e) Space Charge Grid Potential 38.5 volts

Grid Potential (volts)	Grid Current (amperes x 10^{-8})	Plate Current (amperes x 10^{-6})
-3.500	- 6.52	0.00
-3.250	- 6.52	1.08
-3.000	- 6.52	2.17
-2.750	- 6.52	8.68
-2.500	- 6.52	24.95
-2.250	- 6.50	62.93
-2.000	- 6.23	117.18
-1.900	- 5.90	154.07
-1.800	- 5.56	195.30
-1.700	- 4.77	235.44
-1.600	- 3.26	282.40
-1.500	- 0.68	327.67
-1.450	1.71	366.73
-1.400	3.73	388.43
-1.300	12.08	453.53
-1.200	26.76	520.80
-1.150	37.98	588.00
-1.100	49.68	632.80
-1.000	84.78	722.40
-0.900	151.74	823.20
-0.800	262.98	907.20

(e) continued

-0.750	365.40	980.00
-0.700	466.20	1024.80
-0.600	756.00	1131.20
-0.500	1236.60	1243.20
-0.400	1922.40	1355.20
-0.300	3072.60	1467.20
-0.250	3925.80	1562.40
-0.200	4698.00	1624.00
-0.100	6786.00	1736.00
-0.050	8028.00	1803.20

(f) Space Charge Grid Potential 36.0 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-8})	Plate Current (amperes x 10^{-6})
-3.500	- 5.22	0.00
-3.250	- 5.22	0.00
-3.000	- 5.22	2.17
-2.750	- 5.40	8.68
-2.500	- 5.58	22.78
-2.250	- 5.17	58.59
-2.000	- 4.73	110.67
-1.900	- 4.23	151.90
-1.810	- 3.15	177.15
-1.700	- 1.63	228.85
-1.600	- 0.18	278.99
-1.550	1.71	298.37
-1.500	4.25	325.50
-1.450	6.64	351.54
-1.400	12.18	377.58
-1.345	16.20	415.55
-1.300	33.84	439.42
-1.200	57.78	509.95
-1.100	100.98	622.60
-1.000	180.00	718.82
-0.900	304.20	809.38
-0.800	396.90	905.60
-0.750	505.10	962.20
-0.700	810.00	1018.80
-0.600	1314.00	1132.00
-0.500	2091.60	1245.20
-0.400	3385.80	1358.40
-0.300	5040.00	1471.60
-0.200	7164.00	1590.46
-0.100	8100.00	1709.32

(g) Space Charge Grid Potential 24.3 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-8})	Plate Current (amperes x 10^{-6})
-3.500	-4.01	0.00
-3.250	-4.01	0.00
-3.000	-4.01	0.00
-2.750	-3.99	5.42
-2.500	-3.96	20.61
-2.250	-3.91	48.82
-2.000	-3.60	106.23
-1.900	-3.31	133.54
-1.820	-2.88	168.17
-1.700	-1.71	217.00
-1.650	-0.94	237.61
-1.610	-0.32	249.55
-1.570	0.64	271.25
-1.550	1.46	283.48
-1.500	3.97	303.80
-1.400	7.51	352.62
-1.300	16.65	415.55
-1.200	32.22	496.25
-1.100	56.15	576.58
-1.000	97.56	654.05
-0.900	193.52	751.90
-0.800	295.20	829.00
-0.750	339.16	880.00
-0.700	495.00	932.00
-0.600	801.00	1035.00
-0.500	1281.60	1140.00
-0.400	2052.00	1240.00
-0.300	3324.60	1355.00
-0.250	4168.80	1425.00
-0.200	4914.00	1495.00
-0.100	7218.00	1605.00
-0.060	8010.00	1650.00

(h) Space Charge Grid Potential 31.8 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-8})	Plate Current (amperes x 10^{-6})
-3.500	-2.56	0.00
-3.250	-2.56	0.00
-3.000	-2.56	2.17
-2.750	-2.56	5.42
-2.500	-2.56	19.53

(h) continued

-2.250	-2.50	45.60
-2.000	-2.25	92.50
-1.900	-1.30	130.50
-1.805	-1.22	163.50
-1.700	-0.04	204.50
-1.650	0.77	224.00
-1.575	2.61	262.00
-1.500	5.18	299.00
-1.400	10.64	349.00
-1.300	20.70	412.00
-1.200	37.26	470.00
-1.100	65.16	571.00
-1.000	109.80	642.00
-0.900	192.96	725.00
-0.800	331.20	810.00
-0.750	450.00	862.00
-0.700	525.60	912.00
-0.600	882.00	990.00
-0.500	1440.00	1118.00
-0.400	2264.40	1215.00
-0.300	3636.00	1322.00
-0.200	5310.00	1445.00
-0.100	7650.00	1559.00
-0.060	8676.00	1602.00

(i) Space Charge Grid Potential 28.3 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-8})	Plate Current (amperes x 10^{-6})
-3.500	-1.35	0.00
-3.250	-1.35	0.00
-3.000	-1.33	1.08
-2.750	-1.29	3.25
-2.500	-1.28	10.85
-2.250	-1.22	38.00
-2.000	-0.81	84.80
-1.900	-0.36	111.00
-1.850	-0.04	129.00
-1.810	0.27	141.50
-1.750	0.94	163.00
-1.700	1.71	184.20
-1.600	3.89	222.50
-1.500	7.38	270.00
-1.400	13.77	324.00
-1.300	25.38	378.00
-1.250	33.39	409.50

(i) continued

-1.200	43.20	436.00
-1.100	75.60	494.00
-1.000	124.56	569.00
-0.900	222.66	663.00
-0.800	369.00	747.00
-0.700	594.00	847.50
-0.600	995.00	942.50
-0.500	1062.00	1022.00
-0.400	2484.00	1120.00
-0.300	4014.00	1225.00
-0.200	5796.00	1347.50
-0.100	8478.00	1465.00
-0.050	9540.00	1505.00

(j) Space Charge Grid Potential 25.6 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-8})	Plate Current (amperes x 10^{-6})
-3.500	- 0.66	0.00
-3.250	- 0.66	0.00
-3.000	- 0.64	0.00
-2.750	- 0.61	2.17
-2.500	- 0.57	8.68
-2.250	- 0.50	24.95
-2.000	- 0.09	69.60
-1.950	0.09	84.30
-1.900	0.27	95.60
-1.800	0.95	129.30
-1.700	2.16	159.73
-1.610	3.82	195.50
-1.500	7.83	243.40
-1.400	13.50	290.00
-1.300	25.20	348.70
-1.200	44.55	404.00
-1.100	74.70	474.50
-1.000	125.10	541.50
-0.900	215.10	589.50
-0.800	374.40	652.50
-0.700	603.00	744.00
-0.600	990.00	845.00
-0.500	1575.00	942.00
-0.400	2547.00	1100.00
-0.300	4122.00	1141.50
-0.200	5940.00	1303.00
-0.100	8550.00	1410.00
-0.050	9450.00	1440.00

(k) Space Charge Grid Potential 22.5 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-8})	Plate Current (amperes x 10^{-6})
-3.500	- 0.27	0.00
-3.250	- 0.27	0.00
-3.000	- 0.27	0.00
-2.750	- 0.25	1.08
-2.500	- 0.21	5.42
-2.250	- 0.14	22.75
-2.200	- 0.09	25.00
-2.100	0.02	42.30
-2.000	0.27	63.00
-1.900	0.72	84.50
-1.800	1.35	108.50
-1.700	2.70	141.00
-1.600	5.04	180.00
-1.500	8.46	217.00
-1.400	15.21	264.00
-1.300	26.73	314.00
-1.250	36.00	344.00
-1.200	45.90	371.00
-1.100	81.36	436.00
-1.000	135.90	493.00
-0.900	238.20	581.00
-0.800	414.00	660.00
-0.700	662.40	745.00
-0.600	1080.00	835.00
-0.500	1764.00	926.00
-0.400	2745.00	1022.00
-0.300	4392.00	1120.00
-0.200	6390.00	1235.00
-0.100	8946.00	1338.00
-0.060	10080.00	1382.00

These characteristics of the output tube, obtained from the simple circuit as given in Figure 30, although they do not represent the true account of the phenomenon underlying the operation of the two-stage amplification circuit, do, however, show that the high amplification obtained is not dependent upon the reversal of direction of the grid current of the output tube as concluded by Macdonald and Macpherson. The results obtained above indicate rather that the amplification is dependent in some manner upon the positive ion grid current of the output tube, as it may be seen that the grid current of this tube consists entirely of a positive ion current when the amplification of the unit takes place.

This is shown to be the case by determining the grid potentials impressed on the control grid of the output tube (in this instance, the screen grid) at which the high amplification of the unit is experienced. These grid potentials may be determined by an examination of grid potential-plate current characteristics of the amplifying unit (Figure 28) in conjunction with the grid potential-plate current characteristics of the output tube (Figures 31 to 41) for the corresponding space charge grid potentials. Having thus determined the values of these grid potentials, the composition of the grid current of the output tube at these potentials may be readily ascertained from the grid potential-grid current characteristics of the output tube (Figures 31 to 41).

The next step undertaken was to determine the manner in which this positive ion grid current controls the amplification encountered in the operation of the two-stage circuit. With this in view, the sensitive galvanometer employed to measure the grid current of the output tube was inserted in the two-stage circuit as shown in Figure 42. The data, given in Table XIV, showing the relation between the grid potential of the input tube and the grid current of the output tube was observed simultaneously with the data, also given in Table XIV, expressing the relation existing between the grid potential of the input tube and the plate current of the output tube for various positive potentials impressed on the space charge grid of the output tube.

TABLE XIV

Input Tube RCA232	Output Tube UX222 used as a space charge tube
Filament Volts 1.95	Plate Volts 90.0
Plate or B Volts 7.25	Various space charge grid voltages.
Screen Grid Volts 5.90	

(a) Space Charge Grid Potential 45.2 volts

Grid Potential (volts)	Grid Current (amperes x 10-9)	Plate Current (amperes x 10-6)
-2.0000	- 0.00	488.0
-1.9000	- 0.55	488.0
-1.8000	- 1.67	485.0
-1.7000	- 4.16	482.0
-1.5900	- 9.38	479.0
-1.5000	- 18.40	476.0
-1.4000	- 37.60	456.0
-1.3000	- 75.20	416.0
-1.2500	-104.10	371.0
-1.2000	-145.60	261.0
-1.1952	-151.70	226.0
-1.1916	-152.60	195.0

(a) continued

-1.1881	-153.90	125.0
-1.1846	-153.90	21.7
-1.1822	-153.10	00.0

(b)
Space Charge Grid Potential 43.4 volts

Grid Potential (volts)	Grid Current	Plate Current
-2.000	0.00	440.0
-1.900	- 0.83	440.0
-1.800	- 1.67	440.0
-1.700	- 4.18	444.0
-1.610	- 7.52	436.0
-1.500	- 17.10	426.0
-1.400	- 35.80	404.0
-1.350	- 50.50	386.0
-1.300	- 72.00	351.0
-1.250	-100.50	293.0
-1.220	-122.00	168.5
-1.215	-123.80	87.0
-1.210	-124.80	19.6
-1.200	-125.50	00.0

(c) Space Charge Grid Potential 41.8 volts

Grid Potential (volts)	Grid Current (amperes x 10^{-9})	Plate Current (amperes x 10^{-6})
-2.0000	0.00	402.0
-1.9000	- 0.84	402.0
-1.7500	- 2.84	396.0
-1.6000	- 9.18	390.0
-1.5000	- 17.50	383.0
-1.4000	- 36.00	359.0
-1.3500	- 50.00	336.0
-1.3000	- 69.00	302.0
-1.2500	- 96.20	217.0
-1.2376	-103.70	156.4
-1.2327	-106.20	106.5
-1.2303	-106.90	59.8
-1.2291	-106.20	27.1
-1.2267	-106.20	3.0
-1.2255	-106.10	0.0

(d) Space Charge Grid Potential 40.2 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-9})	Plate Current (amperes x 10^{-6})
-2.0000	0.0	376.0
-1.9000	- 0.67	376.0
-1.8000	- 1.67	374.0
-1.7000	- 3.85	372.0
-1.6000	- 8.70	367.0
-1.5000	-16.70	354.0
-1.4500	-22.50	346.0
-1.4000	-34.20	328.0
-1.3500	-49.50	302.0
-1.3000	-71.30	245.0
-1.2871	-79.00	215.0
-1.2745	-86.00	160.0
-1.2621	-91.20	38.1
-1.2594	-90.70	5.42
-1.2572	-90.00	0.00

(e) Space Charge Grid Potential 38.5 volts

Grid Potential (volts	Grid Current (amperes x 10^{-9})	Plate Current (amperes x 10^{-6})
-2.0000	0.00	337.0
-1.9000	- 0.55	337.0
-1.7500	- 2.00	331.0
-1.6500	- 5.96	326.0
-1.5500	-11.70	321.0
-1.5000	-16.70	309.0
-1.4500	-22.50	296.0
-1.4000	-35.10	276.0
-1.3500	-48.60	238.0
-1.3235	-58.30	196.0
-1.3107	-64.10	163.0
-1.2931	-69.10	97.5
-1.2918	-71.00	27.1
-1.2894	-71.00	5.4
-1.2881	-70.50	0.0

(f) Space Charge Grid Potential 36.0 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-9})	Plate Current (amperes x 10^{-6})
-2.0000	- 0.00	285.0
-1.9000	- 0.36	285.0
-1.7500	- 2.34	282.00
-1.6500	- 5.32	276.0
-1.5500	-11.32	263.0
-1.5000	-16.70	254.0
-1.4500	- 22.00	239.0
-1.4000	-34.70	198,0
-1.3725	-42.30	160.0
-1.3461	-50.10	76.0
-1.3410	-51.50	32.6
-1.3334	-51.90	10.8
-1.3258	-51.50	00.0

(g) Space Charge Grid Potential 34.3 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-9})	Plate Current (amperes x 10^{-6})
-2.000	0.00	244.0
-1.900	- 0.83	244.0
-1.810	- 1.50	244.0
-1.750	- 2.17	242.0
-1.700	- 3.51	240.0
-1.650	- 4.18	235.0
-1.600	- 4.85	227.0
-1.550	- 9.05	214.0
-1.500	-11.18	202.0
-1.450	-15.02	185.0
-1.400	-20.40	114.0
-1.375	-28.40	000.0
-1.320	-35.30	000.0
-1.300	-37.30	000.0

(h) Space Charge Potential 31.8 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-9})	Plate Current (amperes x 10^{-6})
-2.0500	- 0.00	197.5
-1.9500	- 0.35	197.5
-1.9000	- 0.67	197.2
-1.7500	- 2.56	193.5
-1.6500	- 5.51	183.0

(h) continued

-1.5500	-11.37	160.0
-1.5000	-16.22	134.0
-1.4563	-22.50	88.0
-1.4423	-25.10	59.8
-1.4326	-26.10	21.7
-1.4285	-26.70	5.4
-1.4272	-26.70	0.0

(i) Space Charge Grid Potential 23.3 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-9})	Plate Current (amperes x 10^{-6})
-2.000	- 0. 0	115.0
-1.900	- 0.33	115.0
-1.800	- 1.01	115.0
-1.700	- 1.69	112.5
-1.650	- 1.90	107.0
-1.600	- 4.17	95.0
-1.550	- 6.29	83.0
-1.500	- 8.35	62.5
-1.450	-11.70	30.0
-1.400	-13.02	00.0
-1.350	-13.20	00.0
-1.300	-13.40	00.0

(j) Space Charge Grid Potential 25.6 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-9})	Plate Current (amperes x 10^{-6})
-2.000	-0.00	72.0
-1.900	-0.53	72.0
-1.800	-0.83	71.0
-1.750	-1.51	68.5
-1.650	-2.34	58.0
-1.600	-3.85	48.0
-1.550	-5.85	31.0
-1.500	-7.70	6.0
-1.450	-8.35	0.0
-1.400	-8.70	0.0

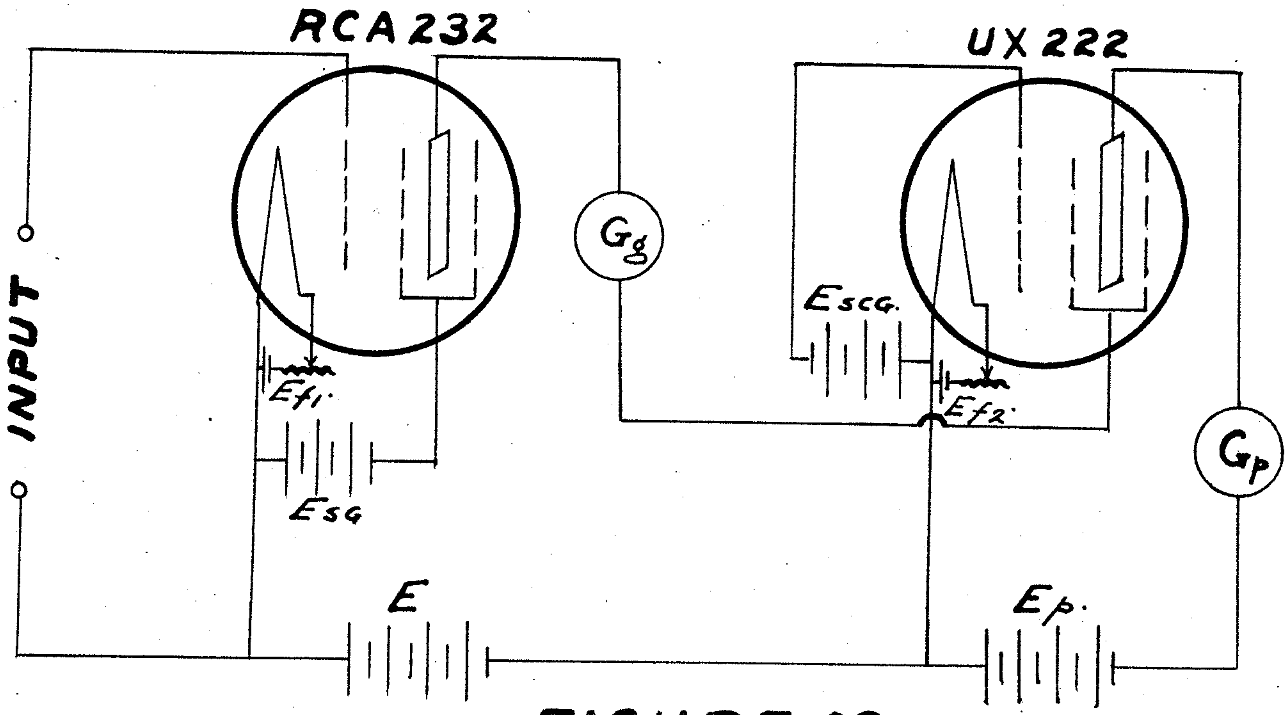


FIGURE 42.

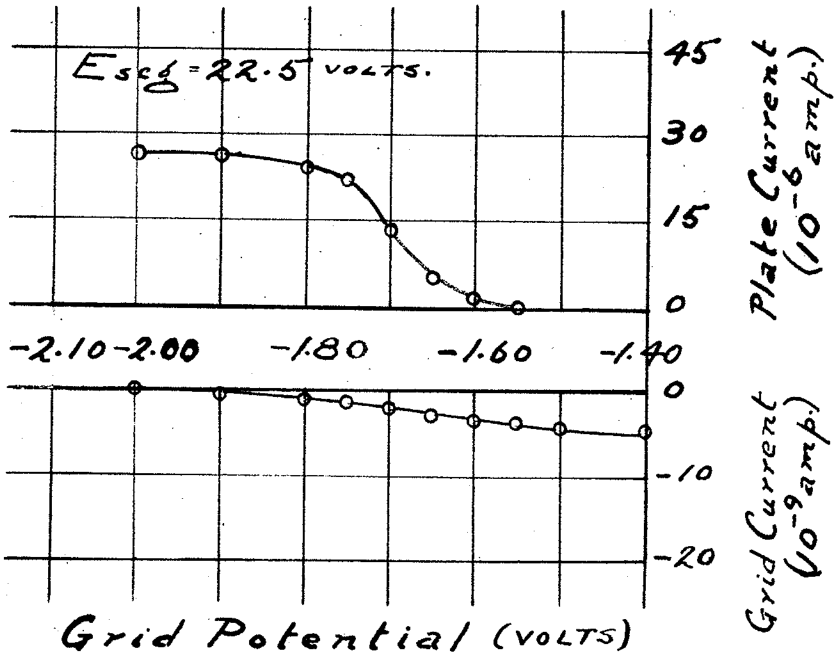


FIGURE 43.

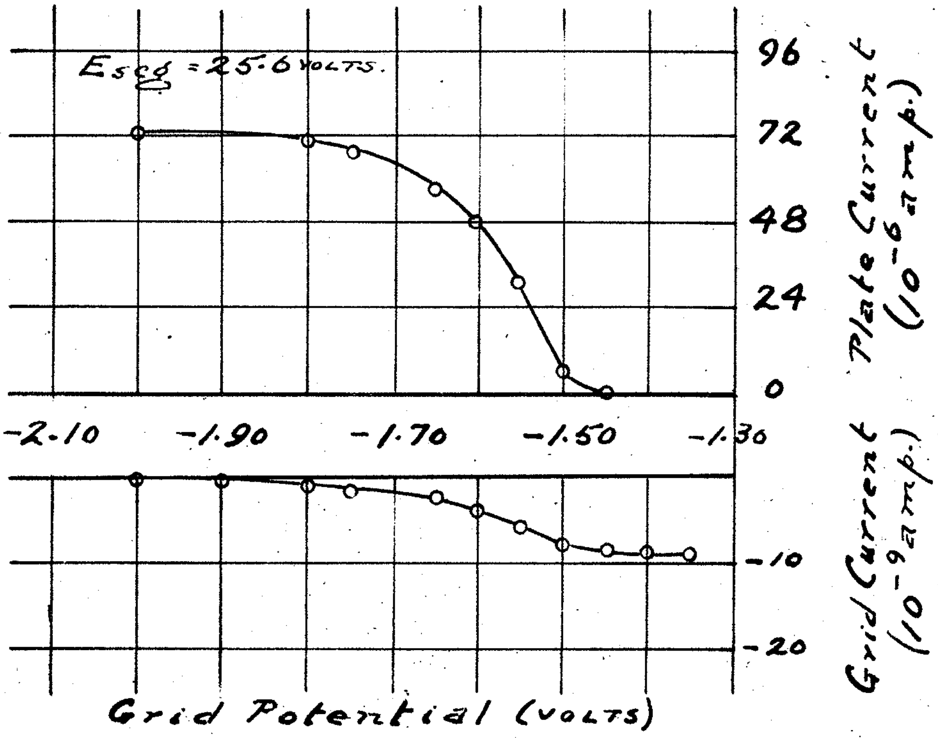


FIGURE 44.

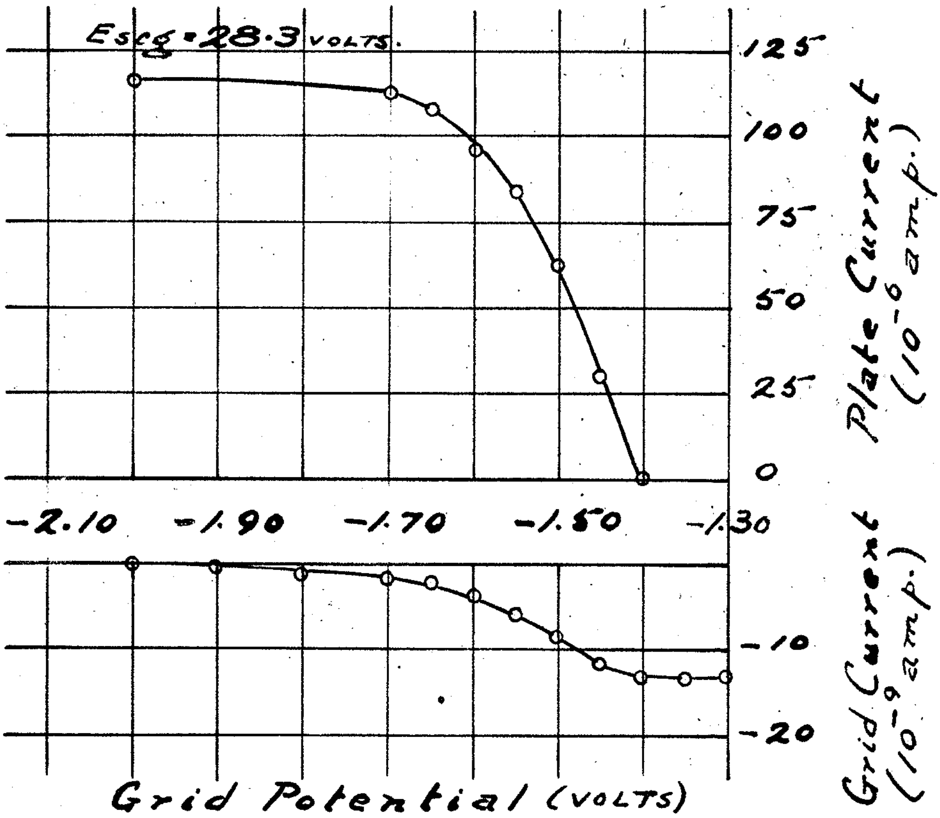


FIGURE 45.

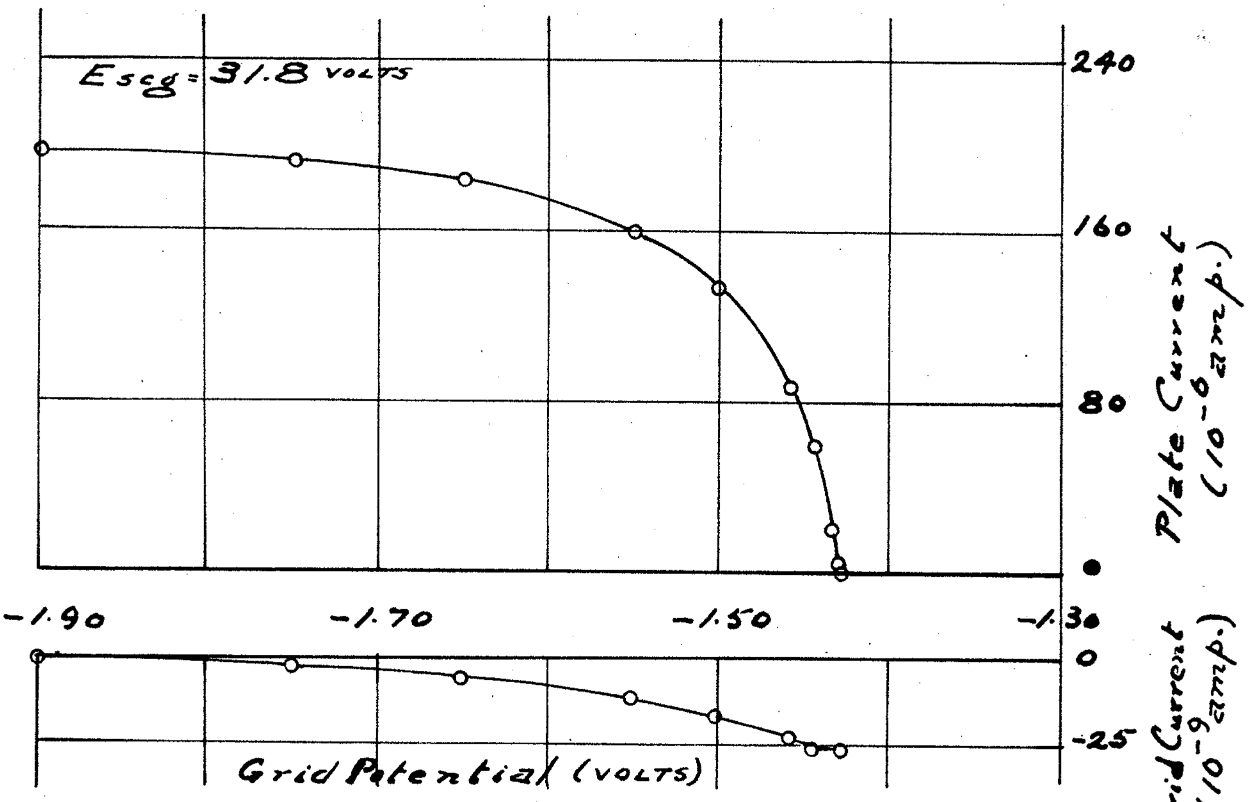


FIGURE 46.

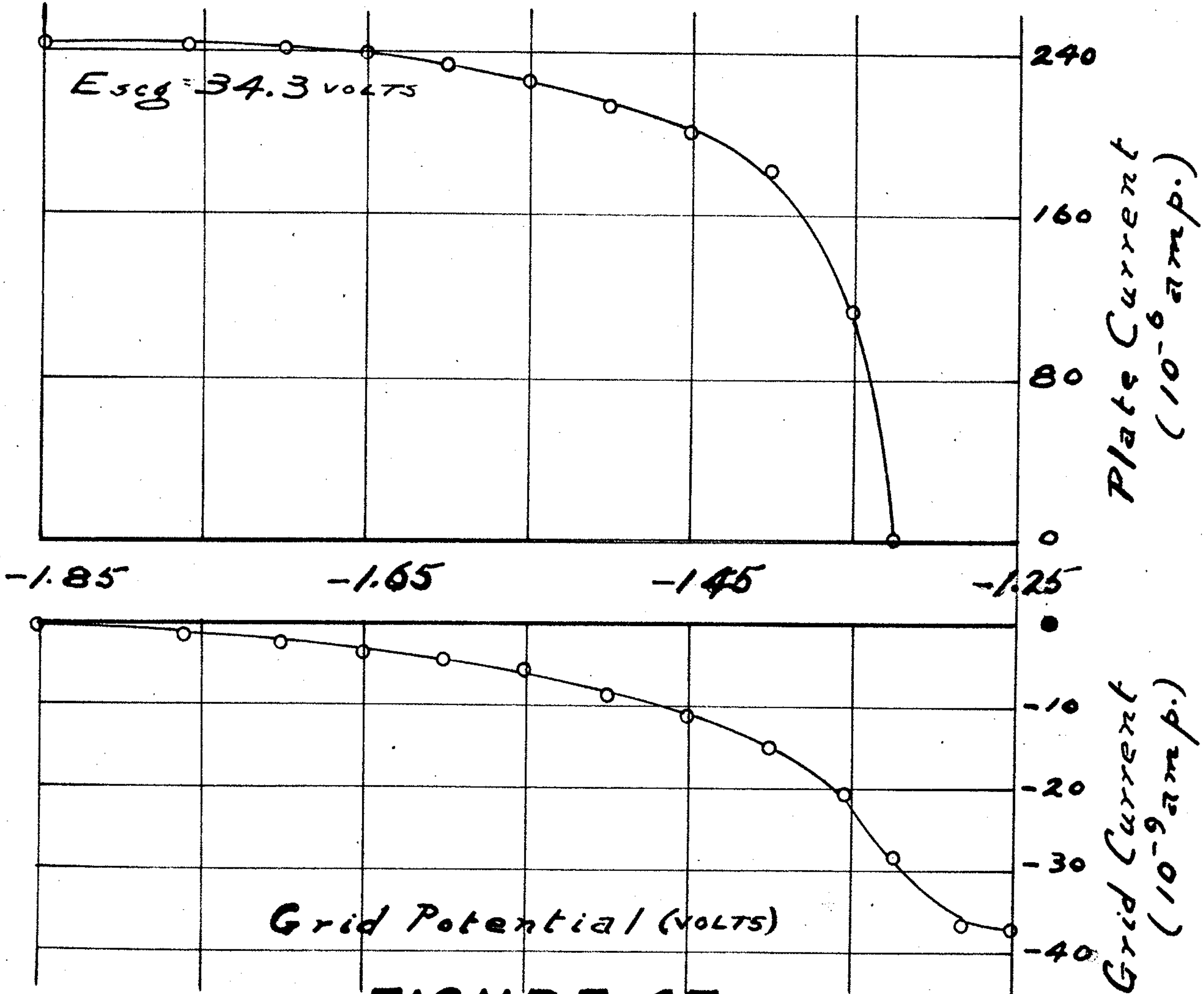


FIGURE 47.

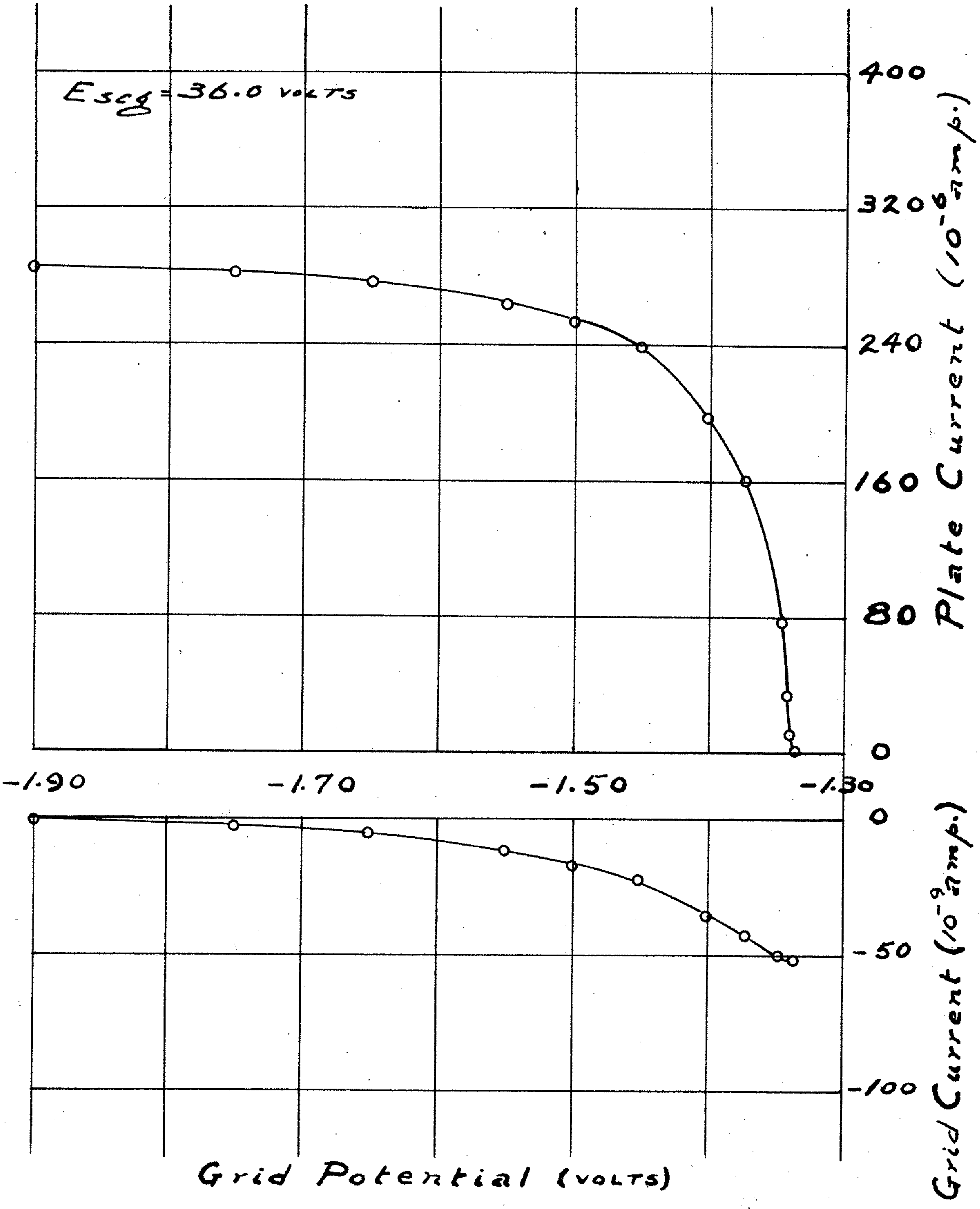

Escg = 36.0 volts
400
320
240
160
80
0
Plate Current (10⁻⁶ amp.)
-1.90
-1.70
-1.50
-1.30
0
-50
-100
Grid Current (10⁻⁹ amp.)
Grid Potential (volts)

FIGURE 48.

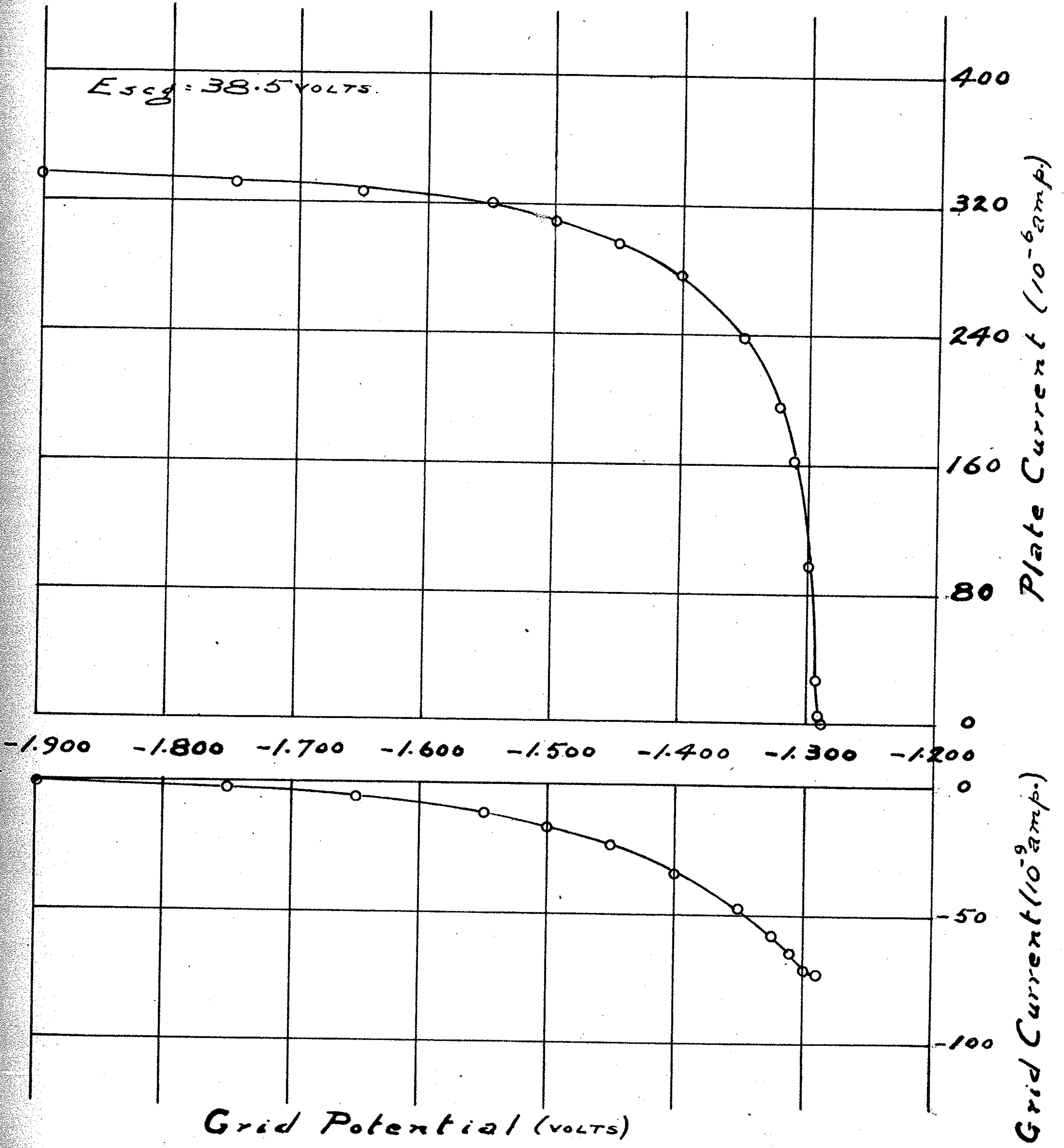

Escg: 38.5 VOLTS.
400
320
240
160
80
0
Plate Current (10^{-6} amp.)
-1.900
-1.800
-1.700
-1.600
-1.500
-1.400
-1.300
-1.200
0
-50
-100
Grid Current (10^{-9} amp.)
Grid Potential (VOLTS)

FIGURE 49.

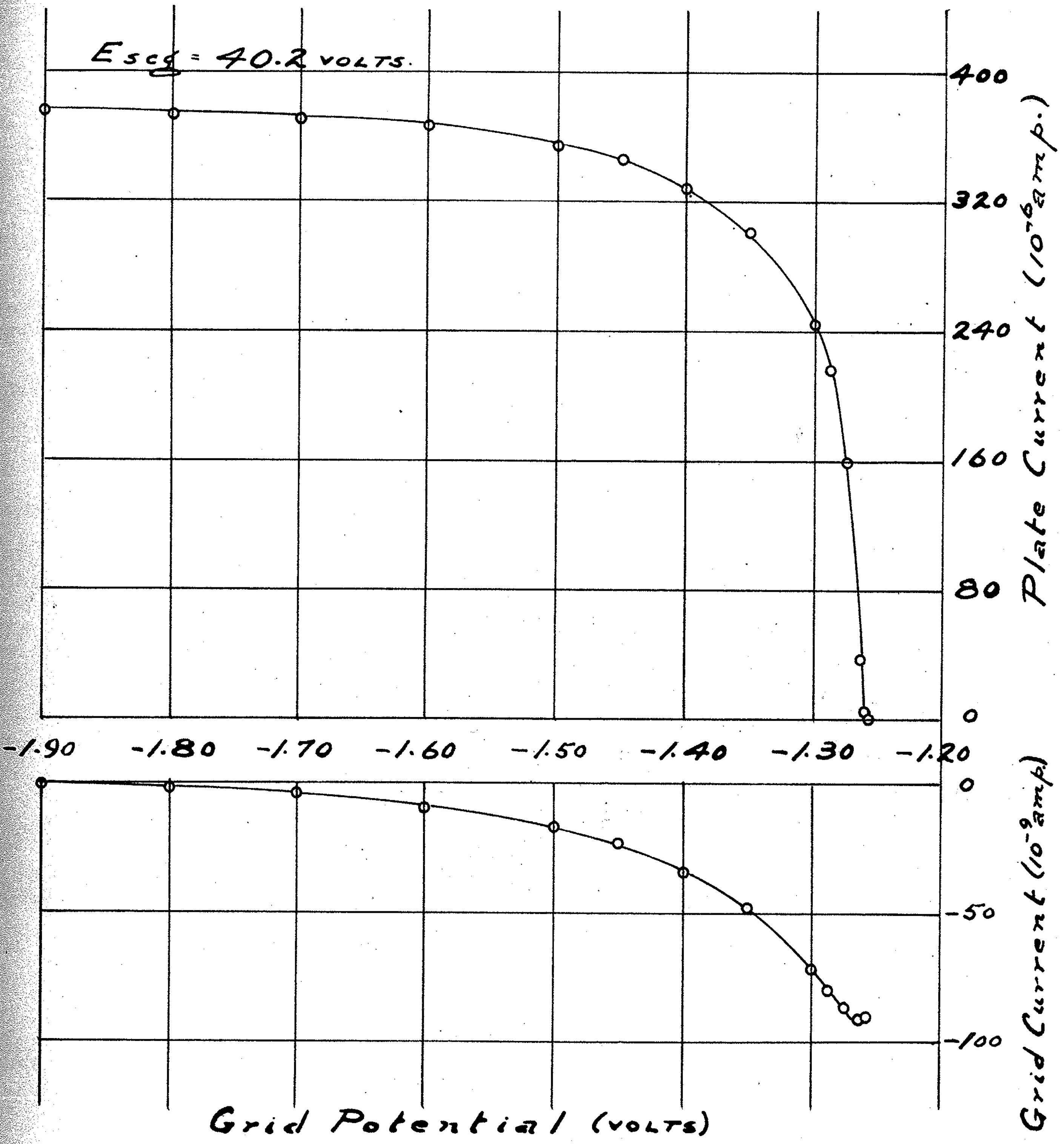
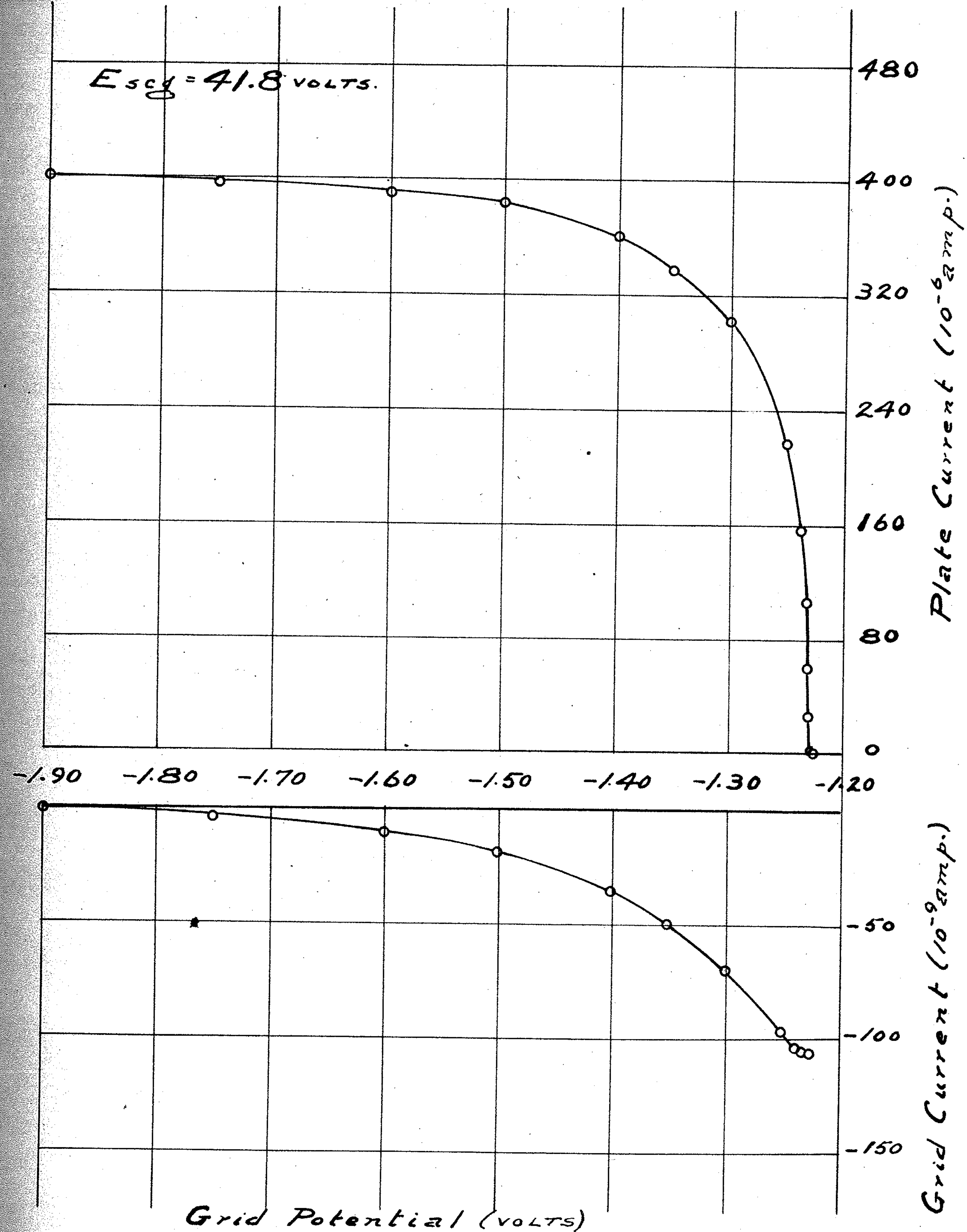

Escg = 40.2 VOLTS.
400
320
240
160
80
0
Plate Current (10^{-6} amp.)
-1.90
-1.80
-1.70
-1.60
-1.50
-1.40
-1.30
-1.20
0
-50
-100
Grid Current (10^{-9} amp.)
Grid Potential (VOLTS)

FIGURE 50.



Grid Potential (VOLTS)

FIGURE 51.

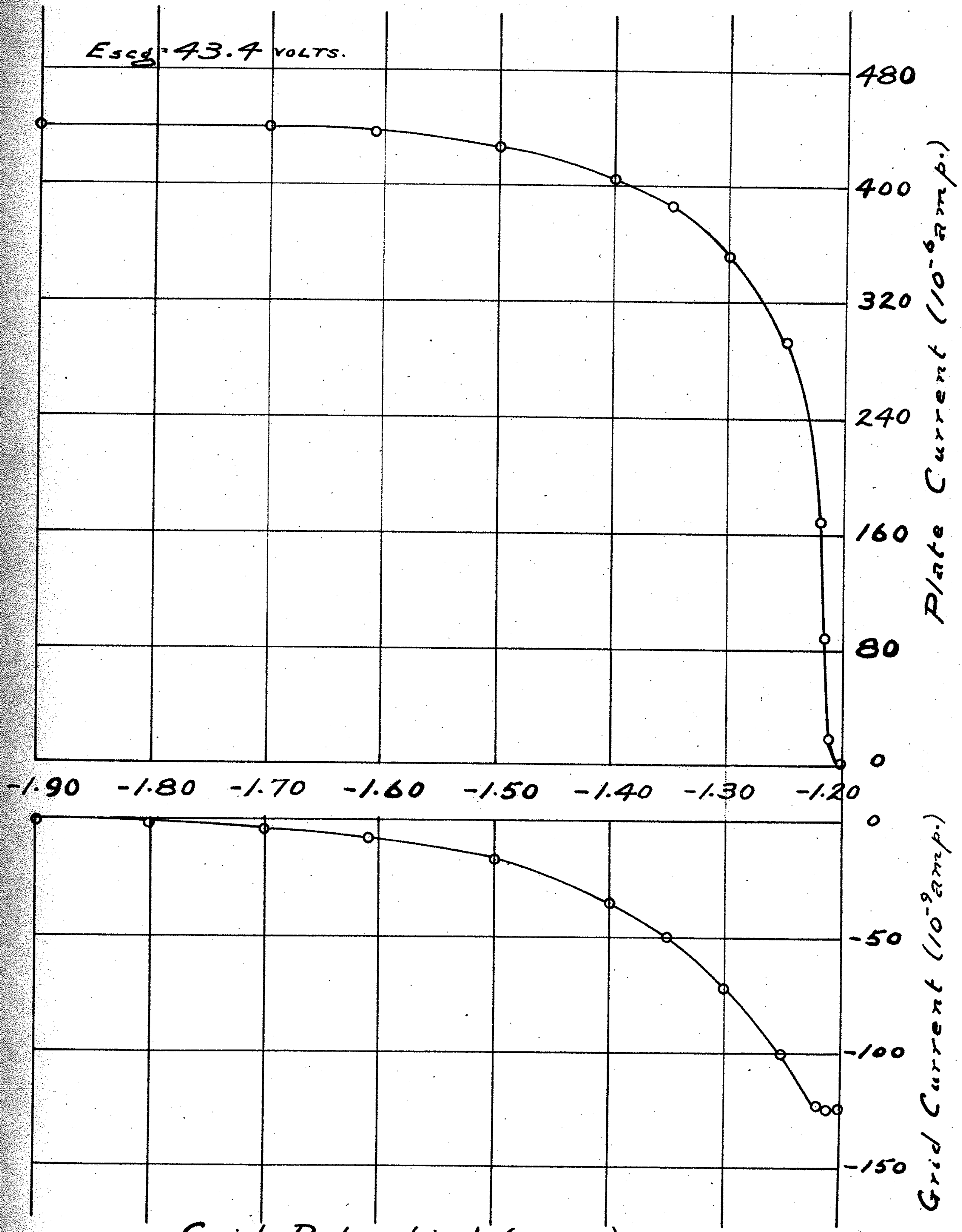

Escg=43.4 VOLTS.
480
400
320
240
160
80
0
Plate Current (10⁻⁶ amp.)
-1.90
-1.80
-1.70
-1.60
-1.50
-1.40
-1.30
-1.20
0
-50
-100
-150
Grid Current (10⁻⁹ amp.)
Grid Potential (volts)

FIGURE 52.

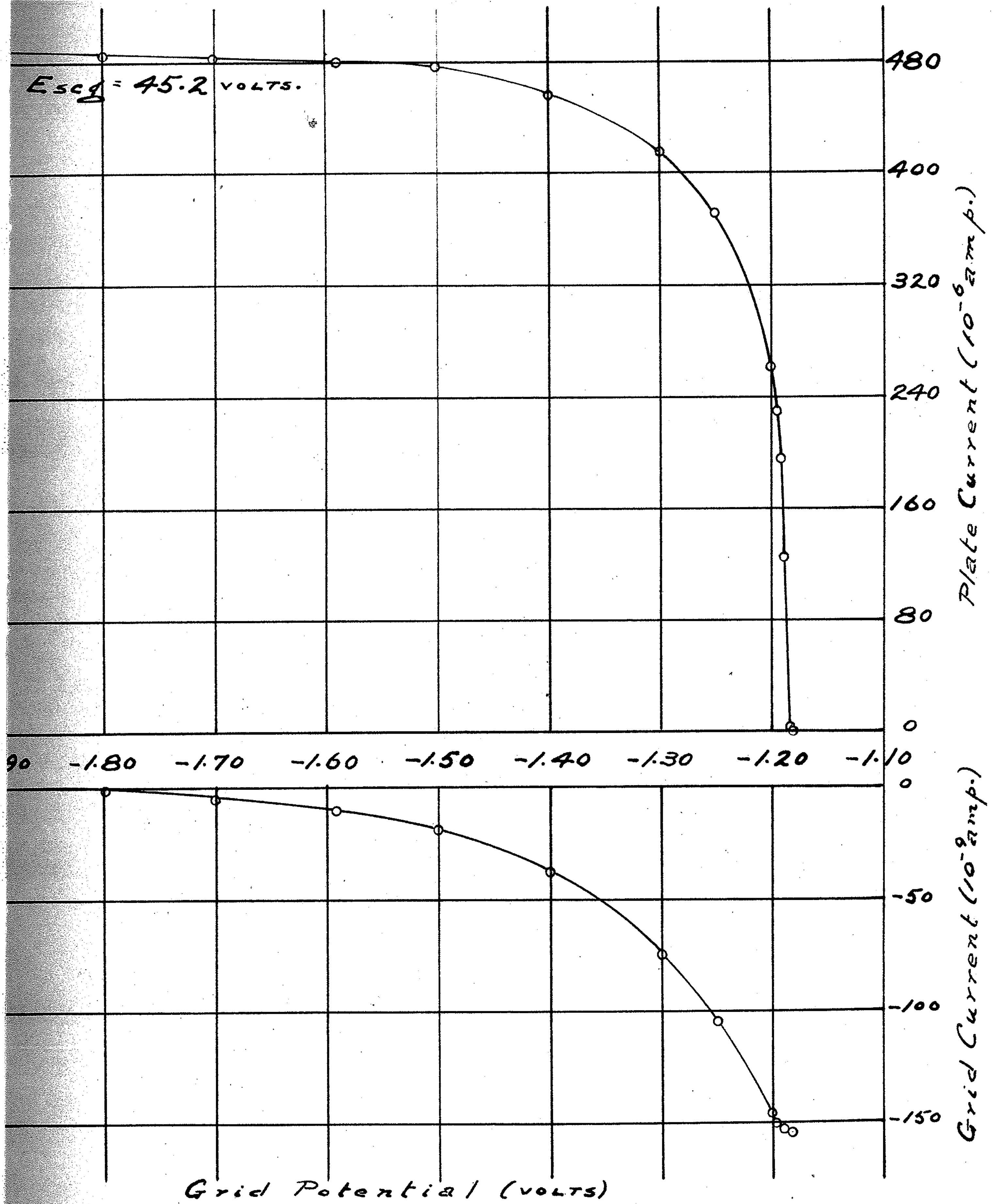

Escg = 45.2 volts.
480
400
320
240
160
80
0
Plate Current (10^{-6} amp.)
90
-1.80
-1.70
-1.60
-1.50
-1.40
-1.30
-1.20
-1.10
0
-50
-100
-150
Grid Current (10^{-9} amp.)
Grid Potential (volts)

FIGURE 53.

(k) Space Charge Grid Potential 22.5 volts

Grid Potential(volts)	Grid Current (amperes x 10^{-9})	Plate Current (amperes x 10^{-6})
-2.000	0.00	26.0
-1.900	-0.33	25.0
-1.800	-0.83	24.2
-1.750	-0.34	22.0
-1.700	-2.00	15.5
-1.650	-2.84	5.0
-1.600	-3.34	2.0
-1.550	-3.84	0.0
-1.500	-4.18	0.0
-1.400	-4.50	0.0

Figure 43 to 53 show this data when plotted. It was from this data that the phenomenon upon which the operation of the circuit is based was ascertained.

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 in the manner of Figure 54(a), is(36)

$$\frac{dI_p}{dE_g} = \frac{G_m}{1 + \frac{R_p}{Z_p}} \qquad (23)$$

where Ip 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.

If, as shown in Figure 54(b), the grid-filament system of a second thermionic tube be substituted in

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(36) Equation (16), Chapter I, Page 32

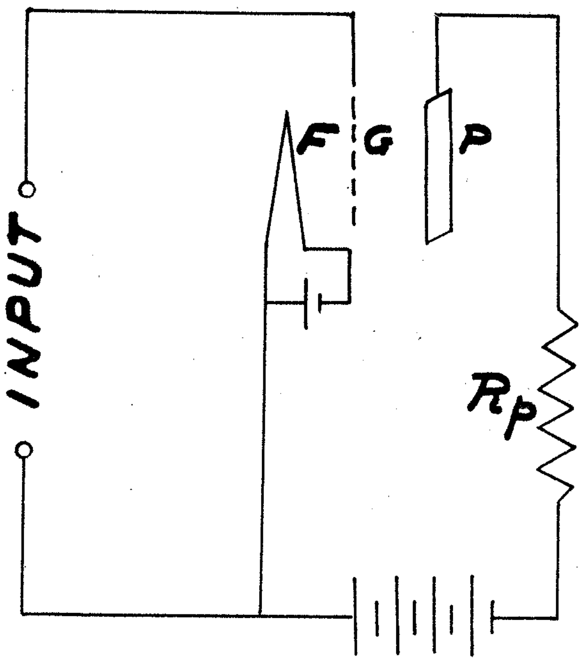

FIGURE 54a.

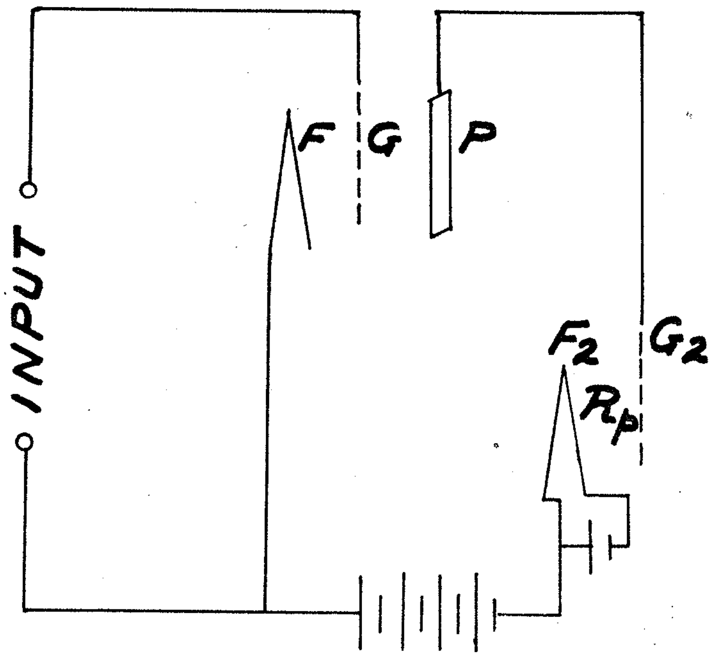

FIGURE 54b.

place of the ohmic resistance R_p it will be possible to give R_p a negative value by adjusting the constants of the circuit in such a way that this grid-filament system operates on the positive ion section of its grid potential vs. grid current curve. This is seen to be the condition under which the circuit described in this communication is operated, the output tube being operated on the positive ion section of its grid potential-grid current characteristic.

If R_p is made negative and numerically equal to Z_p then the numerical value of the above algebraic expression 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. The introduction of the plate circuit of the second tube as in Figure 25 will then result in a two tube amplifier of very high voltage sensitivity, the plate current of this tube being observed in relation to the grid potential of the first tube.

III. THE USE OF A SPACE CHARGE GRID TO REDUCE R_p

The preceding examination of the properties of the output tube, a UX222 using the screen grid as a control grid positively to act as a space charge grid, showed that the positive ion grid current increases with

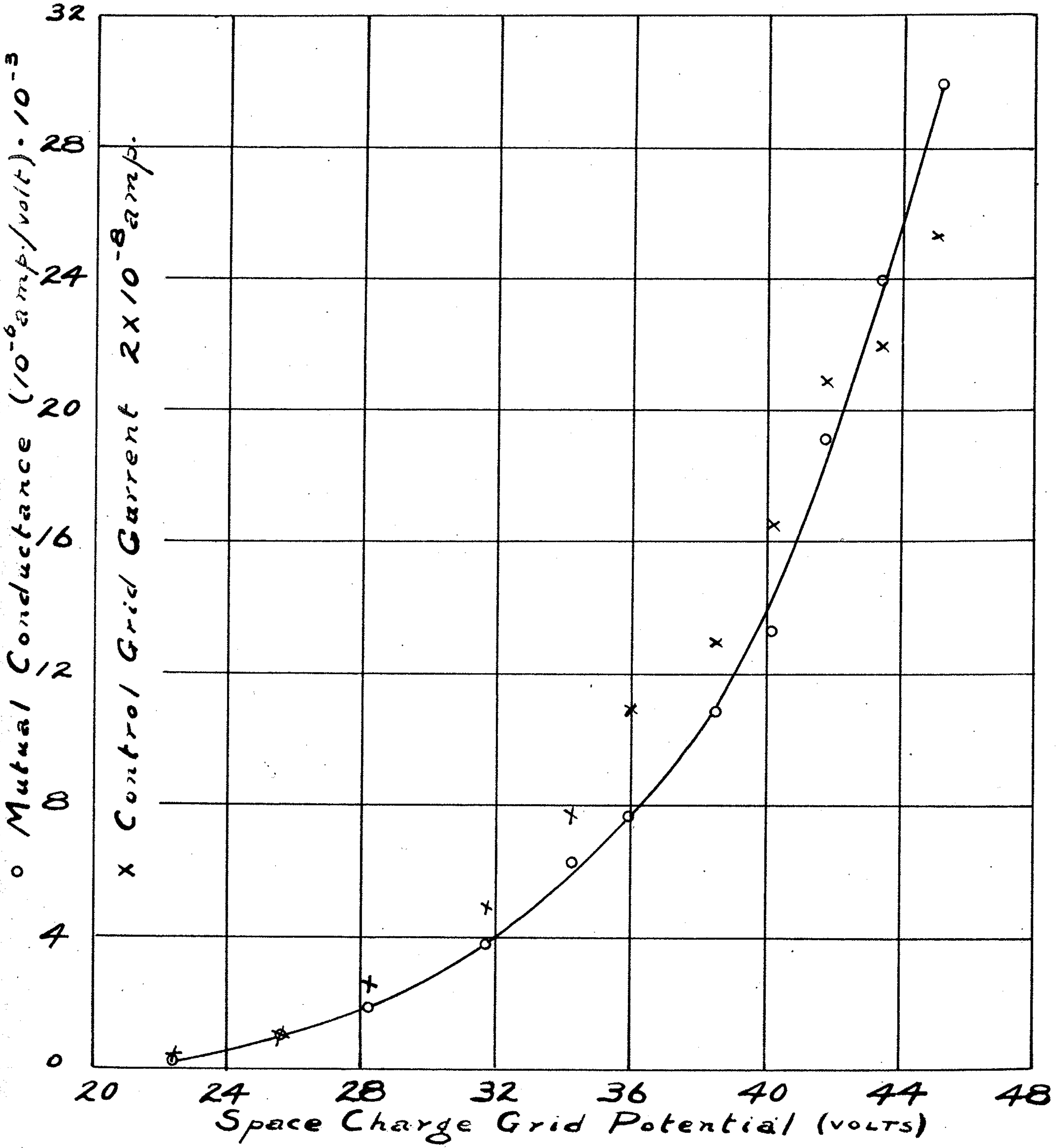
o Mutual Conductance (10⁻⁶ amp./volt) · 10⁻³
x Control Grid Current 2×10⁻⁸ amp.
0
4
8
12
16
20
24
28
32
20
24
28
32
36
40
44
48
Space Charge Grid Potential (volts)

FIGURE 55.

increasing space charge potential. The results are shown in Figure 55 (crosses) and indicate that the use of a space charge in the output tube should be a satisfactory method of reducing the value of R_p.

Figure 28 shows a family of grid potential vs. plate current characteristics of the amplifier, obtained with different potentials on the space charge. The maximum slope of each of these curves was measured(37) and is plotted in Figure 55 (circles) where the space charge potentials are used as abscissae. The close relation between the two sets of data plotted in this figure, considered in relation to Equation 28, indicates that with large space charge potentials $/R_p/ \longrightarrow /Z_p/$ and shows that the space charge grid offers an effective method of sensitivity control.

IV. THE USE OF ADDITIONAL PLATE RESISTANCE IN SERIES WITH THE OUTPUT TUBE TO GAIN HIGH SENSITIVITY

On further consideration of 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, namely

$$\frac{d\,I_p}{d\,E_g} = \frac{G_m}{1 + \frac{R_p}{Z_p}}, \qquad (28)$$

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(37) Chapter II, Table XII, Page 96

it may be seen that if R_p be compounded of a positive and a negative resistance in series their algebraic sum may be adjusted to any desired value.

Hence if the circuit of Figure 54 be opened between P and G_2 and a resistor of suitable value inserted, the value of R_p may be kept negative and made to approach arithmetic equality with Z_p with a resulting increase in the voltage sensitivity of the circuit.

With this end in view, a circuit was set up as in Figure 55 using a UX222 as a triode (screen grid tied to plate) as the input tube and a UX112A as the output tube. Various resistors ranging from 0 megohms to 1500 megohms were inserted in the plate circuit, that is, between the plate of the input tube and the grid of the output tube. This method of sensitivity adjustment is direct and simple.

The resistors employed consisted of both standard fixed resistors manufactured by scientific equipment manufacturing companies and resistors made up by the author by drawing thin lines on linen paper with "Higgins" India Ink. These latter resistors served equally as well as did the standard fixed resistors, both being found to be constant over a fairly lengthy period of time.

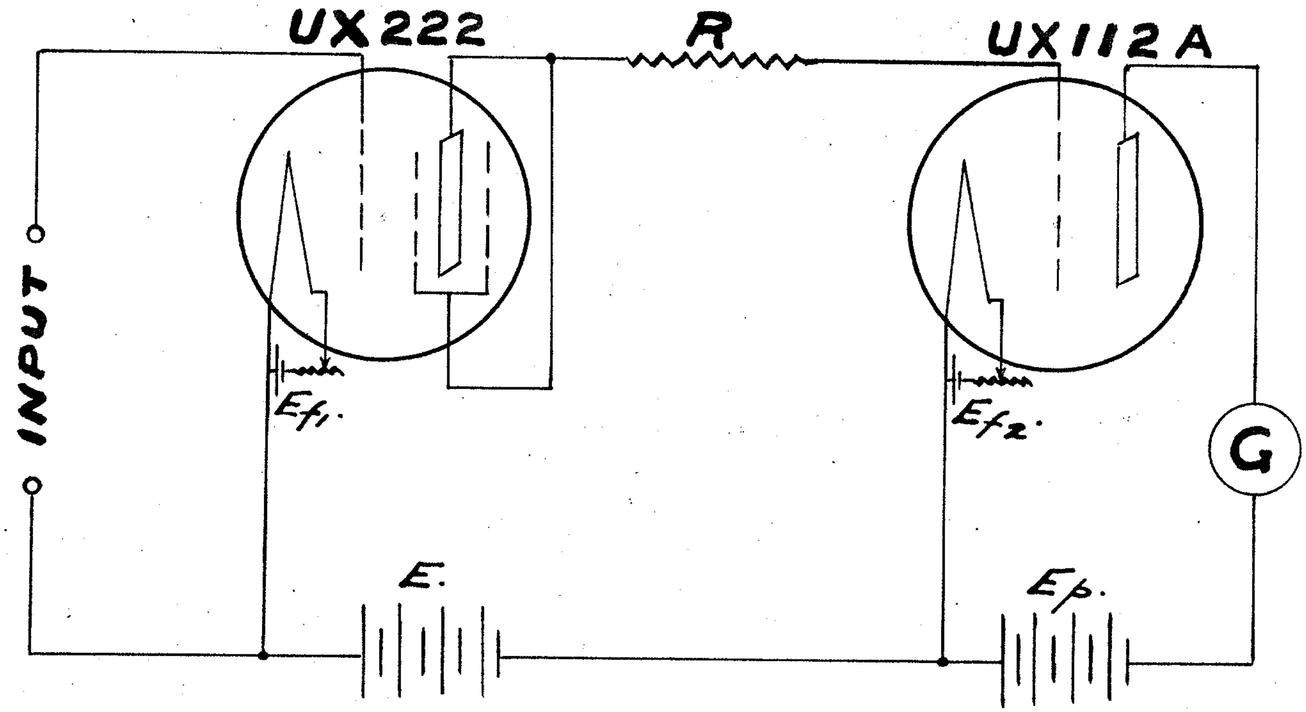


FIGURE 56.

The data showing the relation between the negative potential impressed on the control grid of the input tube and the plate current of the output tube for the various resistors employed in series with the output tube is given in Table XV.

TABLE XV

Input Tube UX232	Output Tube UX112A
Filament Volts 1.6	Filament Volts 3.5
Plate or B Volts 12.0	Plate Volts 90.0
Triode (Screen Grid tied to plate)	Various Resistors employed in series with this Tube.

(a) 0 Megohm Resistor

Grid Potential (volts)	Plate Current (amps x 10^{-6})
-4.300	7970.0
-4.200	7970.0
-4.100	7930.0
-4.000	7870.0
-3.900	7610.0
-3.800	7430.0
-3.700	7160.0
-3.600	6820.0
-3.500	6480.0
-3.400	6040.0
-3.300	5670.0
-3.200	5280.0
-3.100	4830.0
-3.000	4370.0
-2.900	3870.0
-2.800	3320.0
-2.700	2790.0
-2.600	2190.0
-2.500	1675.0
-2.400	1215.0
-2.300	870.0
-2.200	456.0
-2.100	279.0
-2.000	97.5
-1.900	19.9
-1.800	00.0

(b) 150 Megohm Resistor

Grid Potential(volts)	Plate Current (amps x 10^{-6})
-4.100	7490.0
-4.000	7490.0
-3.900	7410.0
-3.800	7300.0
-3.700	7030.0
-3.600	6900.0
-3.500	6670.0
-3.400	6190.0
-3.300	5920.0
-3.200	5410.0
-3.100	5000.0
-3.000	4570.0
-2.900	4060.0
-2.800	3430.0
-2.700	2770.0
-2.600	2160.0
-2.500	1525.0
-2.400	1045.0
-2.300	625.0
-2.200	299.0
-2.150	253.0
-2.100	134.0
-2.050	30.0
-2.000	00.0

(c) 300 Megohm Resistor

Grid Potential (volts)	Plate Current (amps x 10^{-6})
-4.300	7760.0
-4.200	7760.0
-4.100	7740.0
-4.000	7700.0
-3.900	7560.0
-3.800	7380.0
-3.700	7100.0
-3.600	6770.0
-3.500	6450.0
-3.400	6130.0
-3.300	5790.0
-3.200	5300.0
-3.100	4790.0
-3.000	4270.0
-2.900	3690.0
-2.800	3020.0

(c) continued

-2.700	2330.0
-2.600	1645.0
-2.500	1142.0
-2.400	737.0
-2.300	365.0
-2.200	97.0
-2.100	00.0

(d) 440 Megohm Resistor

Grid Potential (volts)	Plate Current (amps x 10^{-6})
-4.100	8500.0
-4.000	8500.0
-3.900	8455.0
-3.800	8380.0
-3.700	8270.0
-3.600	8100.0
-3.500	7730.0
-3.400	7290.0
-3.300	6890.0
-3.200	6420.0
-3.100	5890.0
-3.000	5230.0
-2.900	4550.0
-2.800	3800.0
-2.700	3080.0
-2.600	2410.0
-2.500	1480.0
-2.400	910.0
-2.300	465.0
-2.200	212.0
-2.150	42.5
-2.100	00.0

(e) 600 Megohm Resistor

Grid Potential (volts)	Plate Current (amps x 10^{-6})
-3.700	8450.0
-3.600	8450.0
-3.500	8290.0
-3.400	7980.0
-3.300	7590.0

(e) continued

-3.200	7110.0
-3.100	6610.0
-3.000	5700.0
-2.900	4950.0
-2.800	4010.0
-2.700	3040.0
-2.600	2100.0
-2.500	1305.0
-2.400	740.0
-2.300	339.0
-2.200	63.5
-2.150	00.0

(f) 900 Megohm Resistor

Grid Potential(volts)	Plate Current (amps x 10^{-6})
-4.200	8900.0
-4.100	8800.0
-4.000	8780.0
-3.900	8760.0
-3.800	8720.0
-3.500	8650.0
-3.300	8560.0
-3.200	8430.0
-3.100	8150.0
-3.000	7350.0
-2.900	6460.0
-2.800	5510.0
-2.700	4270.0
-2.600	2920.0
-2.500	1740.0
-2.400	900.0
-2.300	414.0
-2.200	180.0
-2.150	54.0
-2.100	16.0
-2.050	00.0

(g) 1500 Megohm Resistor

Grid Potential (volts)	Plate Current (amps x 10^{-6})
-2.400	10530.0
-2.350	10410.0
-2.300	10350.0

(g) continued

-2.225	10200.0
-2.200	10100.0
-2.175	9460.0
-2.150	1310.0
-2.125	1060.0
-2.100	669.0
-2.050	529.0
-2.000	230.0
-1.950	83.5
-1.900	28.0
-1.850	00.0

In Figure 57 is reproduced a family of grid potential vs. plate current curves obtained with these different resistors in the plate circuit. This illustrates how the use of high resistances in the plate circuit in conjunction with the negative resistance due to the output tube being operated on the positive ion section of its grid potential vs. grid current characteristic is made to gain high sensitivity. The curve shown using the 1500 megohm resistor shows that 1500 megohms is about the limiting value of resistance that may be employed under the aforementioned operating potentials.

Figure 58 shows graphically the relationship holding between the mutual conductance of the amplifier and the value of the resistance employed in series with the output tube,the data being given in Table XVI.

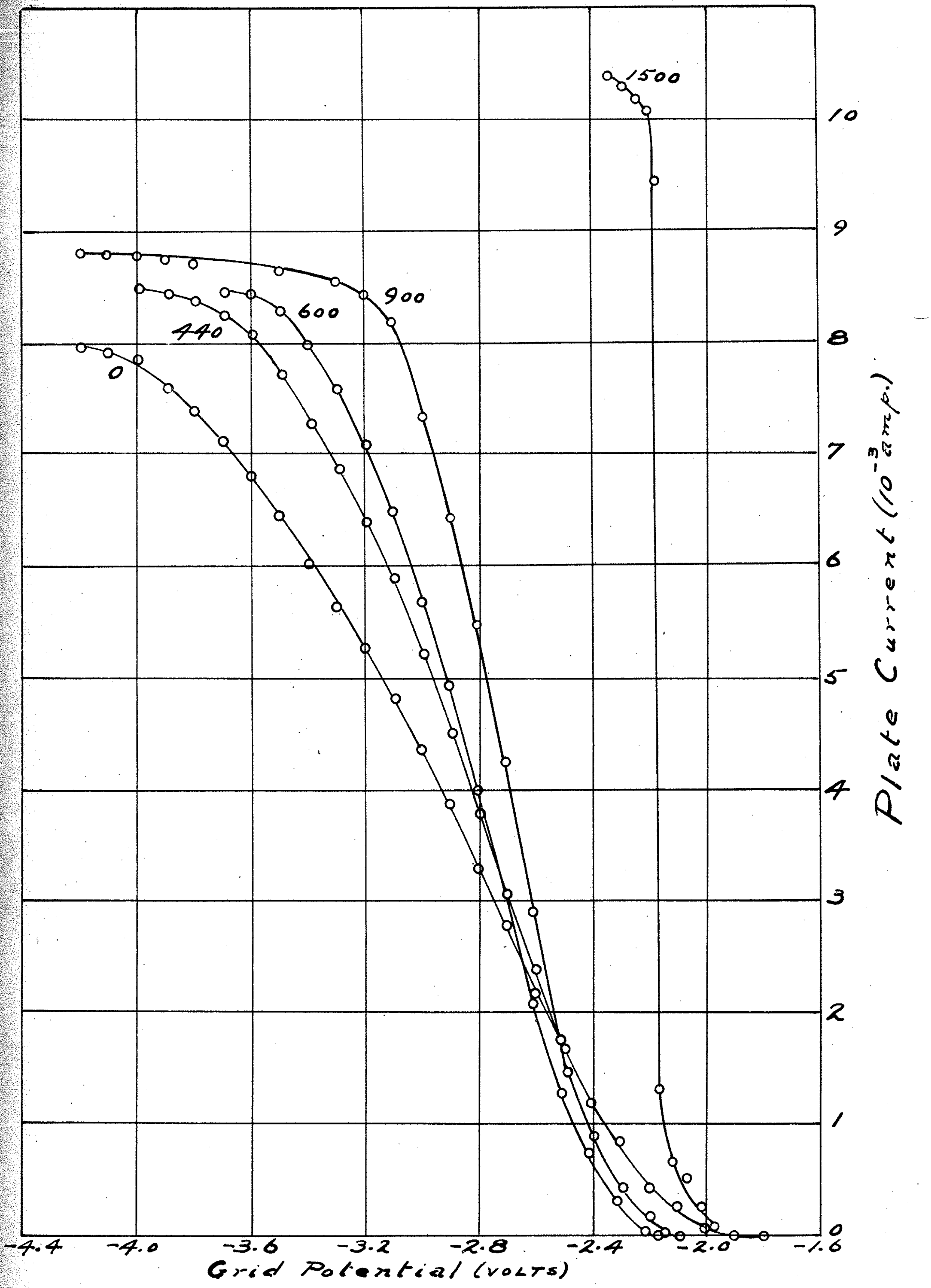
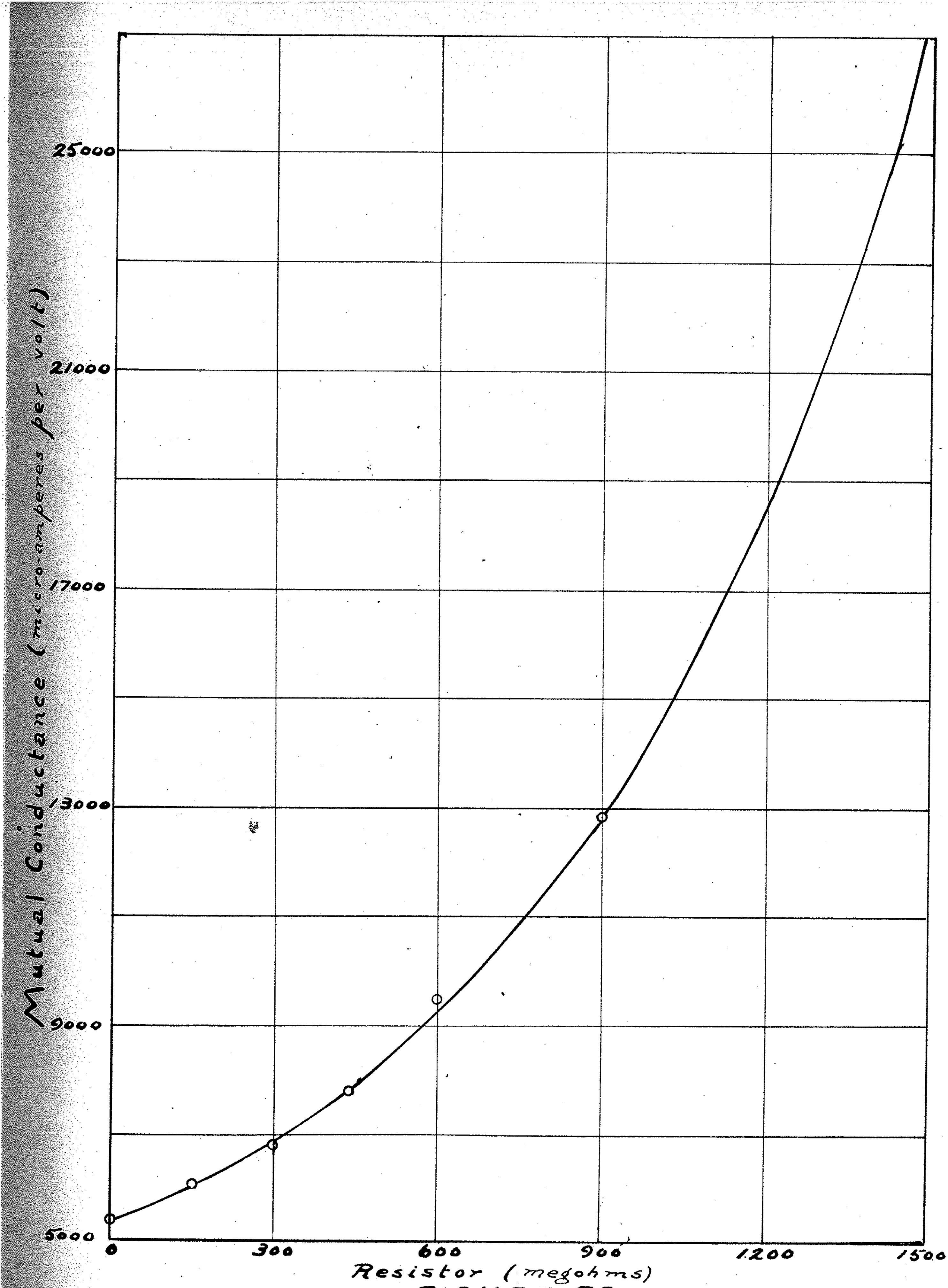

1500
900
600
440
0
10
9
8
7
6
5
4
3
2
1
0
Plate Current (10^{-3} amp.)
-4.4
-4.0
-3.6
-3.2
-2.8
-2.4
-2.0
-1.6
Grid Potential (volts)

FIGURE 57.



Mutual Conductance (micro-amperes per volt)
25000
21000
17000
13000
9000
5000
0
300
600
900
1200
1500
Resistor (megohms)

FIGURE 58.

TABLE XVI

Input Tube UX222 (triode)		Output Tube UX112A	
Filament Volts	1.6	Filament Volts	3.5
Plate or B Volts	12.0	Plate Volts	90.0

Resistor Employed in Series with the Output Tube		Mutual Conductance of the Amplifier	
0	megohms	5350	microamperes/volt
150	"	6100	"
300	"	6820	"
440	"	7810	"
600	"	9500	"
900	"	12850	"
1500	"	→ ∞	"

The mutual conductance is seen to increase with the value of resistor used up to an infinite limit when a resistor of 1.5 x 10^9 ohms is employed.

V. THE USE OF ADDITIONAL PLATE RESISTANCE IN PARALLEL WITH THE OUTPUT TUBE TO GAIN HIGH SENSITIVITY

Here, as was the case in the preceding section, R_p is compounded of a positive and a negative resistance. However, in this case, the positive resistance is inserted in parallel with the output tube, whereas, in the preceding section it was inserted in series with the output tube. If a suitable value of resistor be chosen then the mutual conductance of the unit may be made very high.

A circuit was set up as in Figure 59 employing a RCA222 four-element tube as the input tube and a UX112A as the output tube. It was found that best results were

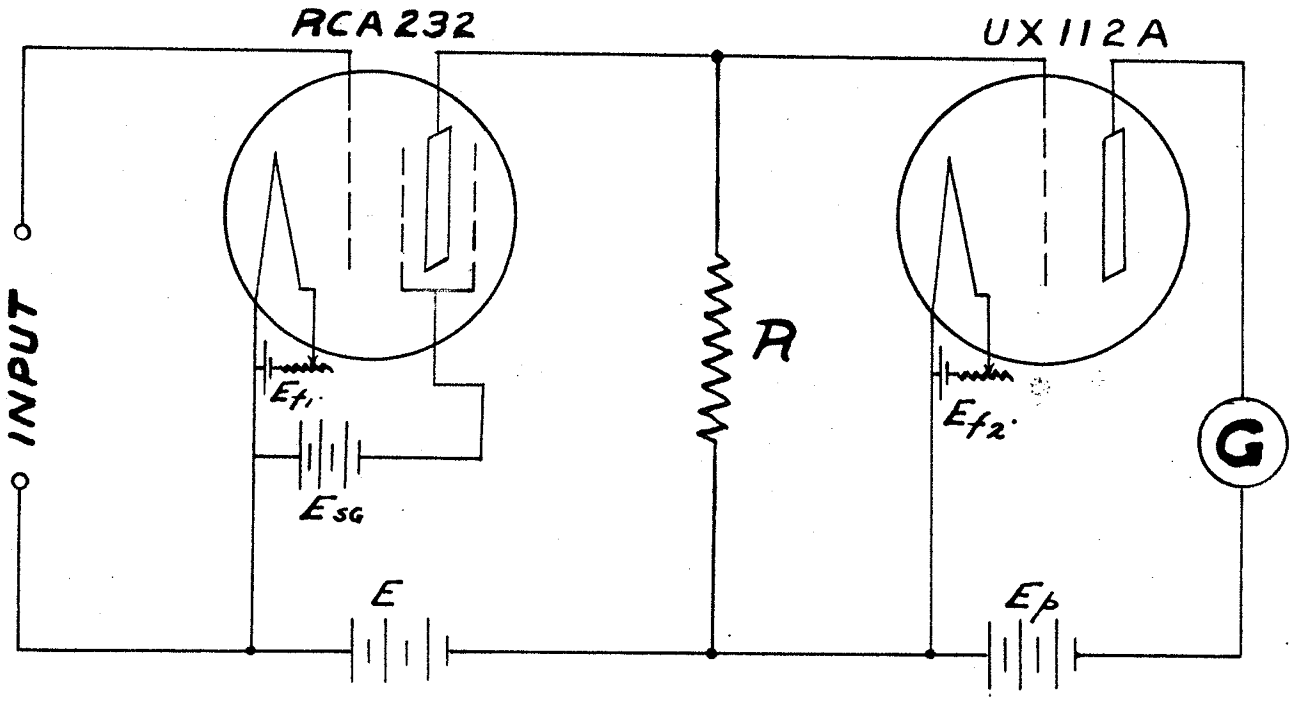


FIGURE 59.

obtained using a 10^8 ohm resistor. Table XVII shows the data obtained using this value of resistance in parallel with the UX112A for various plate potentials applied to this tube. Figure 60 shows this data when plotted.

TABLE XVII

Input Tube RCA232 Filament Volts 2.0 Plate Volts 6.0 Screen Grid Volts 10.0	Output Tube UX112A Filament Volts 5.0 Various Plate Voltages Resistor Employed in parallel with output Tube 10^8 ohms.

(a) Plate Potential 45.0 volts

Grid Potential (volts)	Plate Current (amps x 10^{-6})
-2.200	3360
-2.100	3360
-2.000	3310
-1.900	3160
-1.850	3060
-1.820	2890
-1.800	2690
-1.780	2450
-1.760	2310
-1.740	2160
-1.720	1840
-1.700	1580
-1.680	1365
-1.660	1250
-1.640	1023
-1.620	813
-1.600	580
-1.580	500
-1.560	315
-1.540	298
-1.520	263
-1.500	263

(b) Plate Potential 67.0 volts

Grid Potential(volts)	Plate Current(amps x 10^{-6})
-2.200	6890
-2.100	6890
-2.000	6865
-1.900	6840
-1.800	5910
-1.770	5470
-1.750	5100
-1.730	4740
-1.710	4340
-1.690	3950
-1.670	3630
-1.650	3210
-1.630	2830
-1.610	2330
-1.600	2070
-1.590	1860
-1.580	1710
-1.570	1580
-1.560	1525
-1.550	1460
-1.540	1380
-1.530	1350
-1.520	1335
-1.510	1320
-1.500	1300
-1.490	1300

(c) Plate Potential 90.0 Volts

Grid Potential(volts)	Plate Current (amps x 10^{-6})
-2.200	11610
-2.100	11610
-2.000	11560
-1.900	11420
-1.800	11000
-1.770	10560
-1.750	10140
-1.730	9600
-1.710	9100
-1.690	8580
-1.670	7950
-1.650	7420

(c) continued

-1.630	6780
-1.610	6190
-1.590	5490
-1.570	4650
-1.550	4200
-1.530	3950
-1.520	3910
-1.510	3890
-1.500	3870
-1.490	3870

TABLE XVIII

Plate Potential (volts)	Mutual Conductance of Amplifier
45.0	10700 $\frac{\text{microamps.}}{\text{volt}}$
67.0	22000
90.0	35000 "

The mutual conductance is seen from Table XVIII above to increase from 10700 $\frac{\text{microamperes}}{\text{volt}}$ at 45.0 volts to 35000 $\frac{\text{microamperes}}{\text{volt}}$ at 90.0 volts plate potential on the output tube.

At plate potentials exceeding 90.0 volts the circuit could not be successfully operated, the sensitivity being too large to be controlled by the negative control grid potential of the input tube.

The employment of higher resistors in parallel with the output tube also rendered an uncontrollable amplifier even with plate potentials as low as 45.0 volts, whereas if lower plate voltages are used, the sensitivity attained is lower than that attained under the operating conditions specified in Table XVII.

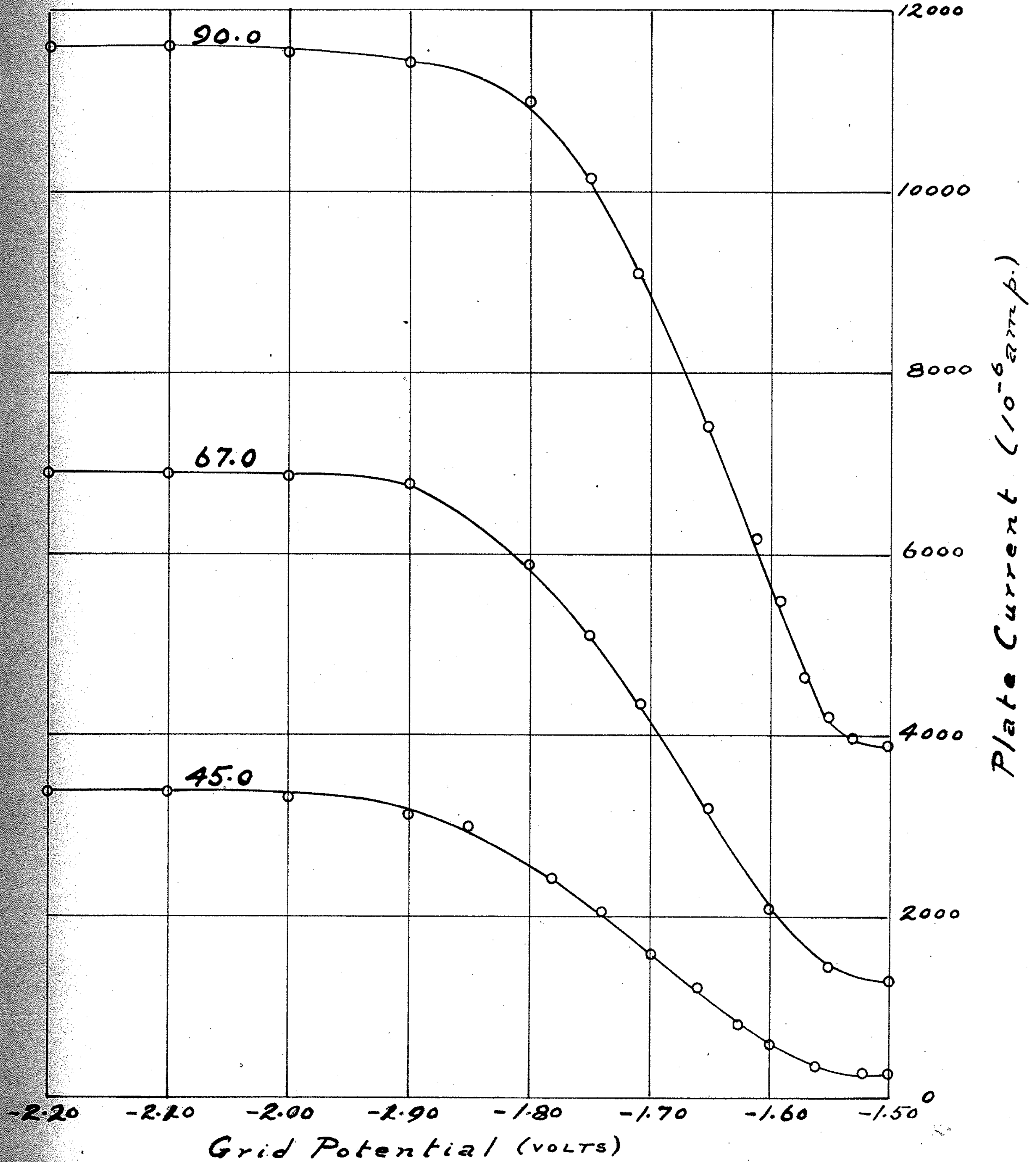

90.0
67.0
45.0
12000
10000
8000
6000
4000
2000
0
Plate Current (10^{-6} amp.)
-2.20
-2.10
-2.00
-1.90
-1.80
-1.70
-1.60
-1.50
Grid Potential (VOLTS)

FIGURE 60.

A loss of sensitivity was also encountered when lower resistors were employed even when potentials exceeding 90.0 volts were applied to the plate of the output tube.

In conclusion it may be stated that while the material here presented shows the mechanism of adjustment of the voltage sensitivity to any desired value, one may obtain characteristics suitable for many purposes by the careful choice of tube combinations.

The final conclusion, therefore, is that direct current amplifiers possessing high mutual conductances may be constructed consisting of no more elaborate details than the simple two-stage circuits herein described.

It is claimed that these instruments are reliable, i.e., the readings are accurately reproducible, provided certain ordinary precautions familiar to every investigator in this field of research are taken.

The instrument should be allowed to run at the operating voltages for a period of from 30 to 60 minutes so that a state of equilibrium may be attained before readings are attempted.

The plate potential and any other potentials applied to the tubes should always be applied before the filament potential, and the filament switch should be the first thrown open when the work is completed.

A minimum amount of shielding is necessary with these set-ups, the tubes only requiring shielding in a metal-covered box to eliminate electro-static and photoelectric effects, the control grids being sensitive to sunlight.

Thus with careful but not elaborate construction, and a little care used in the operation of the instruments, accurate and reliable results may be guaranteed. Beside the reliability and sensitivity of the circuits, there are other properties that these set-ups may claim, which are equally important, namely:

- Ease of construction.- They do not require any particular skill to construct, as no elaborate details are necessary, the shielding of the tubes being most important.

- Cost of construction.- Small. The only expensive item involved being the galvanometer used in the plate circuit, an instrument usually available in any laboratory.

- Ease of operation.- In order to operate these amplifiers successfully, one requires only a working knowledge of the galvanometer.

Thus, the simple measuring devices described in this paper may prove to be invaluable instruments in a laboratory where accuracy and speed of operation are of prime importance.

At the time of writing, one of the circuits described in this communication is being installed in the Radium Laboratory of the Manitoba Cancer Relief and Research Institute as an instrument to be employed in the daily measurement of radon seeds.

In this lengthy discussion there has been an attempt to sketch the history and development of the thermionic vacuum tube and its use as an amplifying agent for small direct currents. The fundamental experimental and theoretical facts that must be employed to explain the phenomena encountered in this field of research have been touched on. Finally, the development of an amplification circuit and two modifications of it have been described, which surpass any others of their kind in mutual conductance, simplicity of design and operation, stability and reliability.

In conclusion, I wish to express my gratitude to Dr. P. A. Macdonald, Assistant Professor of Physics,

for the suggestion of the problem and for his generous advice: also to Dr. 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.