RCA MANUFACTURING COMPANY, INC.
A RADIO CORPORATION OF AMERICA SUBSIDIARY
Harrison, New Jersey

RCA RADIOTRON
DIVISION

APPLICATION NOTE NO. 78
July 28, 1937

APPLICATION NOTE
ON
USE OF THE PLATE FAMILY IN VACUUM-TUBE POWER-OUTPUT CALCULATIONS

The set of curves known as a plate family is useful in predicting the performance of a tube under a wide variety of operating conditions. After some experience with the use of plate families, much useful information can be obtained by graphical analyses. For example, a single graphical analysis yields data which can be used to calculate plate dissipation, screen dissipation, power output, and distortion. Additional simple analyses can be used to predict the effects of plate and screen regulation and to indicate the necessary corrections to minimize these effects.

Because a plate family represents the average of a large number of tubes, it should not be used to predict the performance of a particular tube under given operating conditions when high accuracy is desired. When the results of a graphical analysis which includes the use of a plate family is to be verified by test, a representative number of tubes should be used. This Note describes several useful graphical methods for predicting the performance of single-tube amplifiers when grid current does not flow during any portion of the input-voltage cycle. A later Note will describe graphical methods for predicting the performance of push-pull amplifiers.

The Load Line

When the voltage across a resistor R_1 of constant value is varied throughout a given range, the relation between current through the resistor and voltage across it is a straight line, as shown in Fig. 1. Given the straight-line relationship, it is evident that R_1 is constant and is equal to e/i at any point. When the applied voltage is adjusted to a value E and the current is reduced to the value i by means of a series resistor R_2, the voltage drop across R_2, is (E - e), because the sum of the voltage drops across R_1 and R_2 equals E. This condition is represented by the diagram in Fig. 2. The straight line connecting points 0 and E is the voltage-current characteristic of R_2 using the point E as the origin. Thus $R_2 = (E-e)/i = \cot b$.

The values of the resistors need not be constant in order to represent their voltage-current characteristics on a diagram. In Fig. 3, for example, the voltage-current characteristics of R_3 and of R_4 are functions of the applied voltage. When the resistors are connected in series across an ap-

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plied voltage E_1, the value of the current is i_1, the voltage drop across R_3 is e, and the voltage drop across R_4 is $(E_1 - e)$. The value of the current and the voltage across each resistor is determined by the point of intersection (O) of the two curves. The a-c value of R_3 at the point O is cot a', where a' is the angle between the voltage axis and the tangent to the curve at point O; the value of R_4 at this same point is cot b'. The d-c resistances of R_3 and R_4 at point O are e/i_1 and $(E_1 - e)/i_1$, respectively.

The curve R_3 in Fig. 3 may represent the plate-voltage vs plate-current characteristic of a vacuum tube for a given value of grid voltage. A number of such curves, each corresponding to a different value of grid voltage, constitute a plate family. A typical plate family for a pentode is shown in Fig. 4A. Because each curve represents a voltage-current characteristic of the tube, the intersection of any curve in the family with a line representing a load resistance connected in series with the plate circuit determines a point of operation.

When a voltage E is applied to the plate of a pentode through a load resistance R, the plate current varies with bias in accordance with the intersections of the "load line" R and the grid-bias curves. The relation between grid-voltage and plate current is shown by curve R in Fig. 4B. For a zero-signal bias of -15 volts, the operating point is O, the voltage at the plate is e_o = 250 volts, and the plate current is 105 ma. It is seen that when an alternating voltage having a peak value of 15 volts is applied to the grid of the tube, the plate voltage falls to a minimum value e_{min} = 50 volts and rises to a maximum value e_{max} = 395 volts; the corresponding plate-current change is $(i_{max} - i_{min}) = 205 - 30 = 175$ ma.

When the B-supply voltage E is applied to the plate through a choke of negligible resistance, the operating point is O' for a bias of -15 volts. A reduction of the B-supply voltage to the value e_o = 250 volts shifts the operating point to O. When the choke is shunted by a resistance R, operation with a-c signals takes place along the load line R, provided the reactance of the choke is much greater than the value of R. Thus, when the load consists of a choke shunted by a resistance R, the tube operates as though a series resistance R is connected in the plate circuit and the B-supply voltage is increased by an amount $(E - e_o)$. When a second resistor R_1 is shunted across R through a condenser of low reactance, as shown in Fig. 4C, the zero-signal operating point is O; it is determined only by the intersection of the d-c load line and the operating-bias curve. The a-c operating line is then determined by a new load line, R', which passes through O and has a value $RR_1/(R + R_1)$. In an output-tube circuit, however, R' = R when the d-c resistance of the choke can be neglected.

Determining Power Output When Distortion is Negligible

In the practical use of a plate family for output-tube calculations, the load line R is drawn through the point determined by the plate voltage E and zero-signal plate current or zero-signal bias. When an alternating voltage is applied to the grid, the plate current varies between i_{max} and i_{min}, the plate voltage varies between e_{min} and e_{max}, and the voltage across R varies between $(E - e_{min})$ and $(e_{max} - E)$. The alternating power in R is the product of the alternating voltage across R and the alternating current through R. In this example, the peak value of the alternating component of the plate current is

$$\frac{i_{max} - i_{min}}{2};$$

the peak value of the alternating component of the voltage across R is

$$\frac{(E - e_{min}) + (e_{max} - E)}{2} = \frac{e_{max} - e_{min}}{2}.$$

Thus, the peak power is

$$\frac{(i_{max} - i_{min})(e_{max} - e_{min})}{4};$$

the average power, P, as indicated by a wattmeter, is

$$P = \frac{(i_{max} - i_{min})(e_{max} - e_{min})}{8} \qquad (1)$$

This expression for power is independent of tube type; it gives good accuracy only when the distortion is nominal.

Optimum Load for Pentodes

An output tube should be operated for highest power output at minimum distortion. To satisfy this condition, plot the grid-voltage vs plate-current characteristics for a number of load resistances and biases from the plate family, as shown in Figs. 5A and 5B; a computation of approximate power output for each operating condition should also be made, as illustrated in Fig. 5C. It is assumed that grid current does not flow during any portion of the input-voltage cycle.

For zero plate-circuit distortion, the dynamic characteristic should be a straight line over the operating range; for high efficiency, the power output should be a maximum. The curves in Fig. 5 show that a bias of -15 volts and a load (No.2) of 2000 ohms represent a good operating condition, provided plate and screen dissipations are not exceeded. It should be noted that the load line representing 2000 ohms passes through the knee of the zero-bias characteristic and through an operating point determined by approximately $i_{max}/2$. That this load and operating point are suitable can be predicted by an inspection of Fig. 5A; a reduction in the value of R causes a nearly proportional decrease in the plate-voltage swing with no appreciable change in plate current; an increase in the value of R causes a large decrease in i_{max} and a small increase in plate-voltage swing. From these considerations, several short-cuts can be used to obtain quickly a satisfactory value of load and bias.

Determining Optimum Load for Pentodes

In Fig. 6A, from a point A which is just above the knee of the zero-bias characteristic, draw load lines to the plate-voltage axis; these lines should surround an operating point whose coordinates are (E, $i_{max}/2$). Along any load line, say R_2, measure the distance AO_2; lay off an equal distance O_2A_2 along R_2. For optimum operation, the change in bias from A to O_2 should nearly equal the change in bias from O_2 to A_2. The value of the load, R, is:

$$R = \frac{e_{max} - e_{min}}{i_{max} - i_{min}} .$$

It is well at this time to determine the change in power output with load by means of equation (1), because it may be desirable in some cases to obtain high power at the expense of increased distortion. When the knee of the zero-bias characteristic is not well-defined, several points should be used, in turn, until the proper one is found. The results should be checked by actual test using a reasonable number of tubes. It may be necessary to increase the bias above the value determined by this test in order to satisfy plate- and screen-dissipation requirements.

Optimum Load for Triodes

The method shown in Fig. 5 for determining the proper load and bias is independent of the characteristics of the tube type. Because the plate characteristics of a triode do not have "knees" at negative control-grid biases, the use of approximate relations which serve to reduce the number of trials is advisable.

Consider the typical triode plate family shown in Fig. 7. The proper load line R intersects the operating-bias curve at point O and the $E_{c1} = 0$ curve at point A. The following relations may be used as guides; final values should be obtained by the methods described for Fig. 5.

$$\text{Zero-Signal Bias} = \frac{0.675\ E}{\mu}$$

$$i_{max} = 2\ I_o$$

Compensating for Rise in D-C Plate Current

When the change in plate current due to rectification in the plate circuit is appreciable, the load line should be shifted from its zero-signal position for improved accuracy in calculating power output and distortion at full output. Consider the plate family shown in Fig. 8A. The load line A is drawn through the zero-signal operating point O. Calculate the change in plate current using point O as the operating point; this change is designated ΔI_b at full output.

$$\Delta I_b = \frac{i_{max} + i_{min} - 2\ I_o}{4} = 16.25 \text{ ma.} \qquad (2)$$

When ΔI_b is positive, the d-c plate current at full output is greater than I_o; when ΔI_b is negative, the d-c plate current at full output is less than I_o. In this problem, ΔI_b is positive. Now, shift the load line to another, arbitrarily chosen, position B. With O' as the operating point, obtain another value of calculated plate-current rise $\Delta I_b'$.

$$\Delta I_b' = \frac{210 + 5 - 150}{4} = 16.75 \text{ ma.}$$

A very good approximation to the actual position of the load line is determined from these values of ΔI_b and $\Delta I_b'$ in the following manner. The plate current at the original operating point O is $I_o = 70$ ma.; ΔI_b for this condition is 16.25 ma. Then, $I_b = I_o + \Delta I_b = 86.25$ ma.; this condition is represented by point A in Fig. 8B. For the line B, a calculated value of $I_b' = I_o' + \Delta I_b' = 75 + 16.75 = 91.75$ ma. is obtained for a value of I' of 97.5 ma. This condition is designated by point B in Fig. 8B. Points A and B are connected by a straight line. From the origin, draw another straight line inclined 45 degrees. The point of intersection C of these two lines is a very good approximation to the actual measured value of full-signal plate current I_b''. The final location of the load line (line C) is then determined by the plate voltage and the calculated value of I_b''.

The ordinate of Fig. 8B represents calculated values of full-signal plate current determined from the operating points O and O', respectively; the abscissa represents the plate current determined by a load line and the zero-signal plate voltage. For the example of Figs. 8A and 8B, the actual rise in plate current, as read by a d-c meter, is $I_b'' - I_o = 20$ ma.

Determination of Distortion and Power Output

The distortion in a single-tube amplifier can be determined from a plate family and a corrected load line. As a first step in calculating distortion, determine the rise in d-c plate current and draw the load line through the proper operating point. Then plot the relation between grid voltage and plate current, as shown in Fig. 9; this curve was plotted from the plate family and corrected load line of Fig. 8A.

The full-signal plate current is I_b''. The value of plate current corresponding to I_b'' is used as a new plate-current axis from which currents in the harmonic analysis are measured. Thus, the actual value of I_o'' is 75 ma.; its value in the harmonic analysis is -15 ma. All values of plate current below the new plate-current axis are negative in the harmonic analysis.

The abscissa of Fig. 9 is divided into ten parts; ordinates are erected from each point of division to the plotted curve, as shown. In terms of the zero-signal bias E_c, these points are 0, $-0.2E_c$, $-0.3E_c$, $-0.5E_c$, $-0.7E_c$, $-E_c$, $-1.3E_c$, $-1.5E_c$, $-1.7E_c$, $-1.8E_c$, $-2E_c$. The value of the current at each of these points is designated by I_o, $I_{0.2}$, $I_{0.3}$, etc. Designating the fundamental component of the plate current as H_1, and the harmonic components of plate current as H_2, H_3, H_4, and H_5, we have

$$H_2 = \frac{I_o + I_2 - 2\ I_1}{4}$$

$$H_3 = \frac{2\ I_{0.5} + I_2 - I_o - 2\ I_{1.5}}{6}$$

$$H_4 = \frac{I_o + 2\,I_1 + I_2 - 2\,I_{0.3} - 2\,I_{1.7}}{8}$$

$$H_5 = \frac{2\,I_{0.7} + I_o + 2\,I_{1.8} - 2\,I_{0.2} - I_{1.3} - I_2}{10}$$

$$H_1 = \frac{I_o - I_2}{2} + H_3 - H_5$$

Because H_1 is the fundamental component of the plate current, the power, P, due to the fundamental, is:

$$P = \frac{H_1{}^2\,R}{2}$$

Plate and Screen Dissipation in Tetrodes and Pentodes

The power dissipated in the screen circuit is added to the power in the plate to obtain the total B-supply input power. With full-signal input, the power delivered to the plate circuit is the product of the full-signal plate-supply voltage and the full-signal d-c plate current. The power dissipated by the plate in heat is the difference between the power supplied to the plate circuit and the power supplied to the load.

Screen dissipation increases with load resistance. In order to visualize this relation, assume that the sum of the screen and plate current is independent of plate voltage for zero control-grid bias or for a negative value of it. A decrease in plate voltage causes a certain decrease in plate current; it is assumed that the screen current rises by an equal amount. Hence, when a screen-grid tube operates with a load which intersects the zero-bias characteristic below the knee, the screen current rises to high values during low plate-voltage excursions of the output voltage. This action produces a rise in the d-c value of screen current with signal. Therefore, the screen dissipation with full-signal input may be several times the zero-signal value. To reduce screen dissipation, the load should always be chosen so that it passes through the knee of the zero-bias characteristic.

Increasing the applied signal voltage to a value higher than that for which the load is designed also increases screen dissipation. For this reason, it may be advisable to use a value of load which is slightly less than the optimum value. This precaution has another advantage, which is especially important at high audio frequencies. The impedance of a loudspeaker increases with frequency. When the load is adjusted for the proper value at 400 cycles, the load is usually too high at 2000 cycles; thus, a screen-dissipation limit may be exceeded at 2000 cycles even though operation is normal at 400 cycles. The use of a load which passes through the zero-bias characteristic somewhat above the knee is desirable for these reasons.

The curves of Fig. 10 consist of a zero-bias plate characteristic and a zero-bias screen characteristic. This screen-current curve is the only one required for the determination of full-signal screen dissipation. Draw in the corrected load line, as previously described. Project point A on the plate-voltage axis to e, as shown in Fig. 10. The projecting line intersects the zero-bias screen curve at i_{c2}. The full-signal screen current is then approximately $(i_{c2}/4) + (i_o/2)$, where i_o is the zero-signal screen current at normal bias; the full-signal screen dissipation is $E\left\{(i_{c2}/4) + (i_o/2)\right\}$. It is evident from an inspection of Fig. 10 that the screen current rises rapidly with increasing load resistance.

Effects of Plate and Screen Regulation

When the internal resistances of plate- and screen-supply sources are high, plate and screen voltages decrease with increasing power output. It is possible to determine approximate full-signal plate and screen voltages when the value of the internal resistance of the B-supply unit is known.

Consider the zero-bias characteristic of a pentode, shown in Fig. 11A; assume that plate and screen voltages are equal and that they are obtained from the same power-supply unit. Draw the corrected load line AB through point O and determine the rise in cathode (plate plus screen) current ($\Delta I_k'$), as previously described. The product of the increment in cathode current and the value of the internal resistance of the B-supply source is the approximate decrease in plate and screen voltage, ΔE_b and ΔE_{c2}, respectively. The zero-bias characteristic of Fig. 11A should now be redrawn to correspond to the new screen voltage $E_{c2}' = E_{c2} - \Delta E_{c2}$. The load for this new value of screen voltage is represented by CD; the new operating point is now O'. Calculate the rise in cathode current using CD as the load; a new value $\Delta I_k''$ is obtained. A good approximate value for the final cathode-current rise ($\Delta I_k'''$) is obtained by the method described in Fig. 11B. The product of the full-signal cathode current I_k''' and the internal resistance of the B-supply source determines the final operating point and the new location of the plate family.

The change in location of a plate characteristic and an operating point for a change in screen voltage can be found. Consider the point X on the zero-bias characteristic at which the plate voltage equals the screen voltage (Fig. 11A). The plate current corresponding to point X is 235 milliamperes. If the screen voltage is reduced to 90 volts, for example, the value of the plate current at the corresponding point on the new zero-bias characteristic is approximately $235 \times (90/100)^{3/2} = 235 \times 0.854 = 200$ milliamperes; the corresponding plate voltage at which this point occurs is 90 volts. Hence, the new location of X is at X'. By a similar computation, the point X_2 shifts to X_2' and the point A shifts to A'. The operating point O located at $E = 100$ volts, $I_b = 100$ ma., $E_{c1} = -15$ volts, shifts to O' located at $E = 0.9 \times 100 = 90$ volts, $I_b = 0.854 \times 100 = 85.4$ ma., $E_{c1} = -0.9 \times 15 = -13.5$ volts. By proceeding in this manner, the $E_{c1} = -27$ volt curve, which is necessary for the determination of $\Delta I_b''$, can be obtained from the given $E_{c1} = -30$ volt curve.

The proper negative bias and peak input signal with 100 volts on the screen is 15 volts; the proper negative bias and peak input signal with 90 volts on the screen is $0.9 \times 15 = 13.5$ volts. Thus, one effect of power-supply resistance is to reduce the value of input signal required for full output; a second effect, as shown by Fig. 11A, is to reduce the power output with full-signal input. An increase in the value of load resistance may be necessary in order that the load line intersect the new zero-bias characteristic at the knee.

The effect of power-supply resistance is small when the output tube is a triode, because the load is usually adjusted for a small rise in d-c plate current with signal.

Conclusion

The analyses described in this Note are useful in determining with fair accuracy the operating conditions of single-tube power-output amplifiers. The analyses are also useful in determining the operation of a tube under given conditions. Although first approximations are accurate enough for most purposes, some second approximations are given for higher accuracy. Whenever possible, the results of the analyses should be checked by measurements with a reasonable number of tubes.

LOAD LINE CONSIDERATIONS

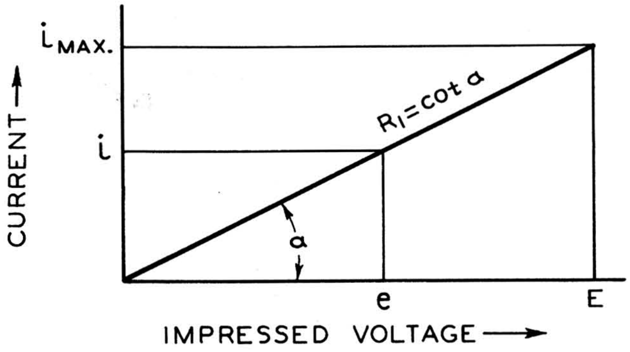

FIG. 1

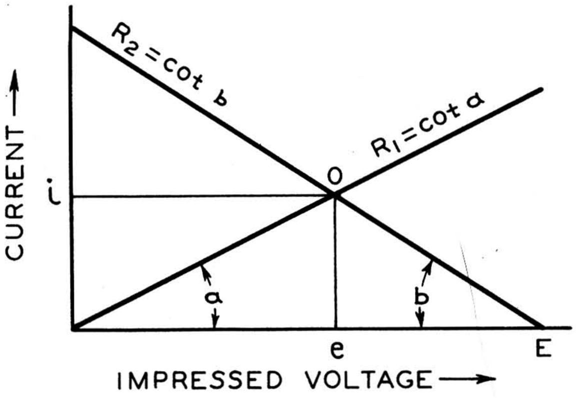

FIG. 2

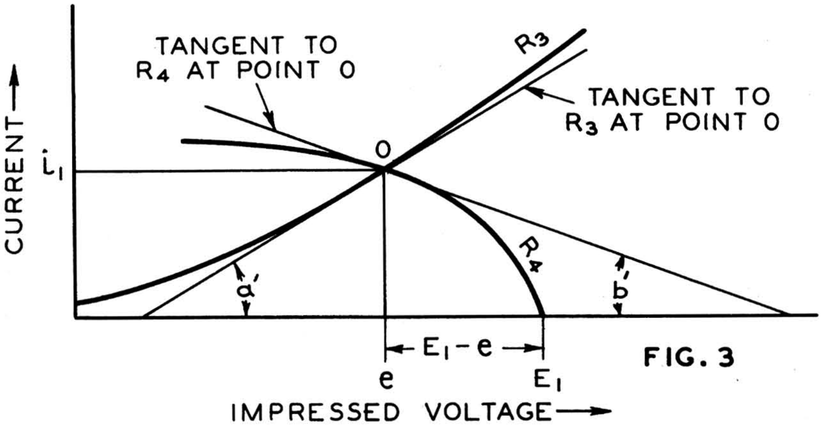

FIG. 3

LOAD LINE CONSIDERATIONS

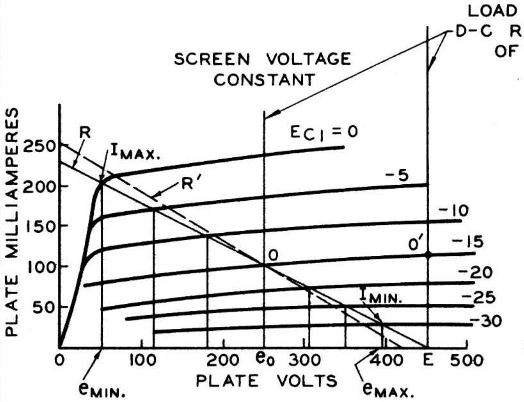

FIG. 4A

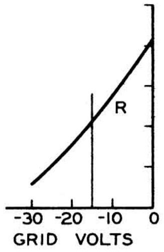

FIG. 4B

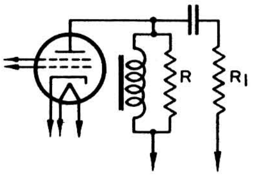

FIG. 4C

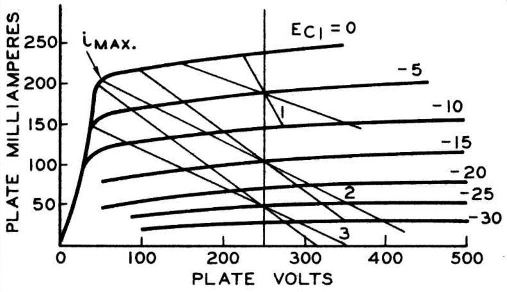

FIG. 5A

+ INDICATES OPERATING POINTS

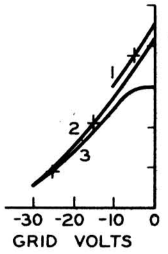

FIG. 5B

CURVE Nº	GRID VOLTS	POWER* OUTPUT WATTS	LOAD OHMS
1	-5	0.55	555
2	-15	7.7	2000
3	-25	4.1	1325

*AT GRID-CURRENT POINT

FIG. 5C

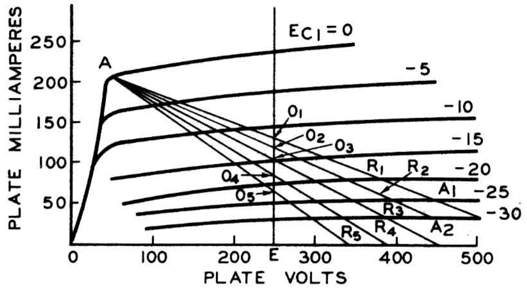

FIG. 6A

+ INDICATES OPERATING POINT

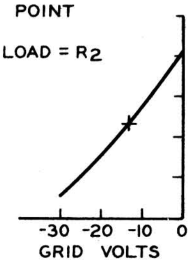

FIG. 6B

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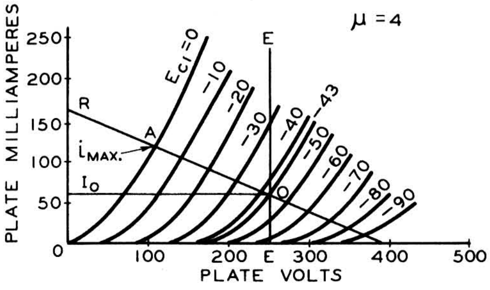


FIG. 7

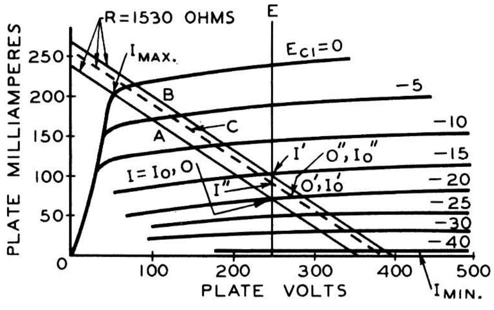


FIG. 8A

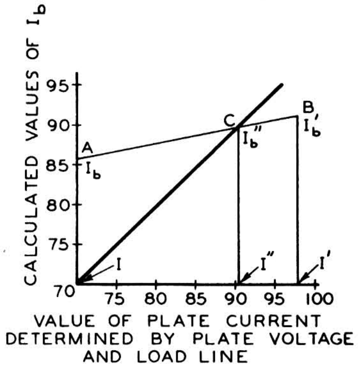
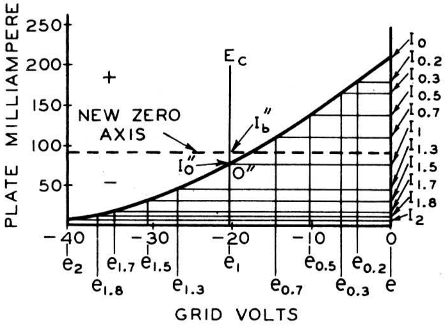


FIG. 8B



$e_0 = 0$
$e_{0.2} = -0.2\,E_c$
$e_{0.3} = -0.3\,E_c$
$e_{0.5} = -0.5\,E_c$
$e_{0.7} = -0.7\,E_c$
$e_1 = -E_c$
$e_{1.3} = -1.3\,E_c$
$e_{1.5} = -1.5\,E_c$
$e_{1.7} = -1.7\,E_c$
$e_{1.8} = -1.8\,E_c$
$e_2 = -2\,E_c$

FIG. 9

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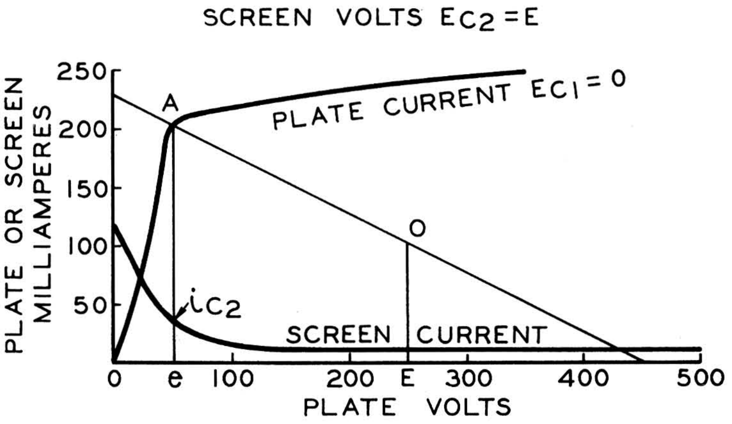
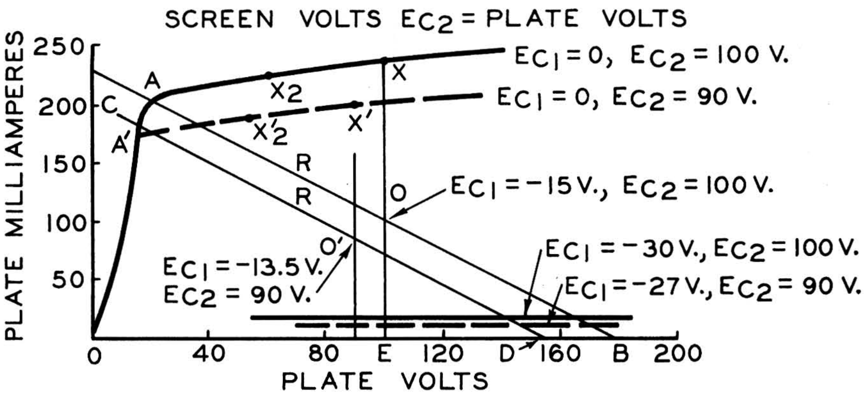


FIG. 10



PEAK INPUT SIGNAL FOR E_{C2} = 100 VOLTS IS 15 VOLTS
PEAK INPUT SIGNAL FOR E_{C2} = 90 VOLTS IS 13.5 VOLTS

FIG. 11A

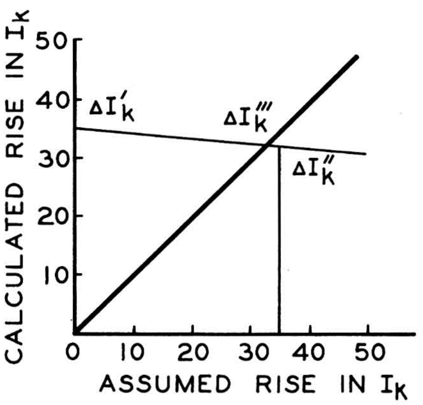


FIG. 11B