Theory of Multi-Electrode Vacuum Tubes *

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Physical principles underlying the characteristics and performance of multi-electrode vacuum tubes are presented in simple form in this paper. Presentation of the subject is based, as far as possible, on the well-known theory of the three-electrode tube. It is shown that the definitions of electrical tube parameters applicable to triodes are, with certain modifications in their interpretation, also applicable to tubes having more than three electrodes.

The characteristics of the screen-grid tetrode are discussed in detail since they are typical of those found in a number of multi-electrode structures. Except for the effects produced by the emission of secondary electrons from the plate and screen, it is shown that the characteristics of the screen-grid tetrode are in general accord with those to be expected from the application of simple theory. The presence of the electrostatic screen in such structures inherently results in high values of the plate resistance and amplification factor, but the transconductance remains normal and has about the same value as in comparable triodes.

One of the necessary modifications in the screen-grid tetrode to produce a satisfactory output power tube is some means of removing the fold in the plate current-plate voltage characteristics, which limits the permissible plate voltage swings. This is accomplished in the power pentode by the addition of a suppressor grid between the plate and screen grid. The efficiency of power pentodes, and of some other tubes having positive grids, is higher than that usually found in triodes. The reason for this is discussed and also certain peculiarities in the harmonic output of pentodes.

The arrangement of electrodes in the space-charge-grid pentode corresponds to that of the screen-grid tetrode with an additional grid inserted between the cathode and control grid. This space-charge grid, which is maintained at a positive potential of 10 to 20 volts with respect to the cathode, reduces the effects of space charge near the cathode surface. This results in extraordinarily high values of transconductance and, consequently, in high amplification. Practically, such tubes are limited to use as voltage amplifiers, since operation over the wide range necessary for large output power results in prohibitive distortion.

In the co-planar-grid tetrode the lateral wires of the positive grid are arranged in the same planes as those of the control grid. This results in comparatively low plate resistance while retaining the advantages of a positive grid. The plate efficiency is comparable with that in the power pentode but the available amplification is lower.

INTRODUCTION of the three-electrode vacuum tube into the field of communications and in other applications represented such a tremendous advance over the possibilities of any other known device that, despite some of its rather obvious limitations, it proved entirely adequate for the service required until comparatively recent years. However, with increasing demands made by service requirements for larger power output at higher efficiency, reduced distortion, higher

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gain, amplification at higher frequencies and greater frequency discrimination, it eventually became necessary to investigate the possibilities of making changes in vacuum tubes enabling them to meet these requirements more satisfactorily. Measures taken to meet this situation have included improvements in the three-electrode tube that reduce the effects of some of its limitations, and the development of vacuum tubes having more than three electrodes.

The purpose of this paper is to present, in simple form, the physical principles underlying the characteristics and performance of multi-electrode vacuum tubes. For present purposes, such tubes may be defined as those having more than the three electrodes of the conventional triode. The procedure will be to show that the definitions of electrical tube parameters applicable to triodes are, with certain modifications in their interpretation, also applicable to tubes having more than three electrodes; and, utilizing the theory of the triode, to analyze the characteristics of a few typical multi-electrode structures that illustrate the types of characteristics found in many such tubes. No attempt is made to present new material in the paper or to discuss in detail the many different types of multi-electrode tubes now in use. The author has attempted to present the subject from the viewpoint of those readers who have a satisfactory understanding of the physical principles, characteristics, and operation of the triode, but who do not have a similarly clear analysis available for the more complex structures.

Multi-electrode tubes may be divided conveniently into two classes. In the first class are those the purpose of which is to perform some function that cannot be performed readily by a triode, or which perform some function better by reason of the elimination or reduction of some limitation in triodes. The second class includes those structures in which additional electrodes are introduced to permit them to perform simultaneously more than one function, or to permit them to function in two or more ways, depending on the voltages applied to the various electrodes and on the manner of their operation. This paper will deal exclusively with typical structures of the first class.

FUNDAMENTAL DEFINITIONS AND TUBE EQUATIONS

Regardless of the type of multi-electrode tube considered, the space current to any electrode may be expressed as some function of the voltages applied to the various electrodes. However, in the operation of any multi-electrode device, or any section of such a device performing a single function, one usually is concerned with variations in the voltages and corresponding currents of only two of the electrodes, the other electrodes being maintained at fixed potentials. One of these two electrodes, which usually is maintained at a negative operating potential, is connected to the input circuit and acts as a control electrode. The second of these two electrodes, which is maintained at a positive potential with respect to the cathode, acts as an anode or collector of electrons and is connected in the output circuit. Just as in the case of the triode, then, a study of the characteristics of multi-electrode tubes is concerned with variations in the current collected by the anode with variations in the potential applied to the control grid.

This anode or plate current may be expressed as a function of the various electrode voltages by the following equation:

$$I_p = f(E_p, E_{g_1}, E_{g_2}, E_{g_3}, \text{etc.}), \tag{1}$$

in which E_p is the operating voltage applied to the output anode or plate, and E_{g_1}, E_{g_2}, E_{g_3}, etc., are the operating voltages applied to the various grids numbered outward from the cathode. The variation in the anode current, neglecting second and higher order terms, is given by

$$dI_p = \frac{\partial I_p}{\partial E_p} dE_p + \frac{\partial I_p}{\partial E_{g_1}} dE_{g_1} + \frac{\partial I_p}{\partial E_{g_2}} dE_{g_2} + \frac{\partial I_p}{\partial E_{g_3}} dE_{g_3} + \text{etc.} \tag{2}$$

The partial differential coefficients in equation 2 have the physical dimensions of conductances and, if these conductances be designated by the letter S with appropriate subscripts, the equation may be written

$$dI_p = S_{pp} \cdot dE_p + S_{p1} \cdot dE_{g_1} + S_{p2} \cdot dE_{g_2} + S_{p3} \cdot dE_{g_3} + \text{etc.} \tag{3}$$

The plate or output anode conductance of a multi-electrode tube is defined in the same manner as for the three-electrode tube. It is the rate of change of plate current with plate voltage, that is, it is the slope of the plate current-plate voltage characteristic at the selected operating point, the potentials of all the other electrodes remaining constant. Under this condition, from equations 2 and 3

$$\text{Plate conductance} = \frac{\partial I_p}{\partial E_p} = S_{pp} = S_p. \tag{4}$$

Obviously, the plate resistance also must be defined in the same manner as in the triode, that is

$$\text{Plate resistance} = R_p = \frac{1}{\dfrac{\partial I_p}{\partial E_p}} = \frac{1}{S_p} \cdot \tag{5}$$

In a similar manner, the transconductance from the control grid to the output anode or plate of a multi-electrode tube is defined, as it is in the triode, by the rate of change of plate current with variation of the control-grid voltage; that is, it is the slope of the plate current-grid voltage characteristic at the given operating point, the potentials of all electrodes other than the control grid remaining constant.

In conventional screen-grid tetrodes and pentodes, the grid next to the cathode is the control grid. Consequently, for such structures, the transconductance is defined from equations 2 and 3 by

$$\text{Transconductance} = \frac{\partial I_p}{\partial E_{g_1}} = S_{p1}. \tag{6}$$

In space-charge-grid tetrodes and pentodes, the grid next to the cathode is maintained at a fixed positive potential and the second grid acts as the control grid. Consequently, in these and similar structures

$$\text{Transconductance} = \frac{\partial I_p}{\partial E_{g_2}} = S_{p2}. \tag{7}$$

Similarly, considering the control grid (assumed to be the first grid) and the output electrode of a multi-electrode tube, the amplification factor is defined, as it is in the triode, by the ratio of the transconductance to the plate conductance. It is expressed by

$$\text{Amplification factor} = \mu_{pg_1} = \frac{\dfrac{\partial I_p}{\partial E_{g_1}}}{\dfrac{\partial I_p}{\partial E_p}}. \tag{8}$$

Or, assuming that E_{g_1} and E_p are varied in such a manner that I_p remains constant, the amplification factor is expressed in the usual form by

$$\mu_{pg_1} = -\left.\frac{dE_p}{dE_{g_1}}\right]_{I_p = \text{constant}}. \tag{9}$$

Combining equations 5 and 6 with equation 8 gives

$$\text{Transconductance } S_{p1} = \frac{\mu_{pg_1}}{R_p} \tag{10}$$

just as in the case of the triode. Exactly similar equations apply if g_2 is used as the control grid.

Obviously, the currents to the other electrodes in a multi-electrode tube may be expressed by functions of the electrode voltages, similar to equations 1 and 2. The various differential coefficients of these equations define transconductances, electrode resistances, and amplification (or reflex) factors analogous to those just given. Since these quantities are not used in this paper, they will not be given further consideration here. The voltage applied to the control grid will be designated by E_g, regardless of the grid employed for the purpose; and the transconductance (or mutual conductance) and the amplification factor, applying to the control grid and plate, will be designated by S_m and μ, respectively.

If a load resistance, R, is inserted in the plate circuit of a multielectrode tube, and if the potentials of all of the elements other than the control grid and plate are maintained constant, equation 3 reduces to

$$dI_p = S_p \cdot dE_p + S_m \cdot dE_g = \frac{1}{R_p} \cdot dE_p + \frac{\mu}{R_p} \cdot dE_g. \qquad (11)$$

In this case, the only independent variable is E_g, and E_p varies by reason of the changing potential drop across the external load resistance, R, due to variations in the plate current, I_p, produced by the varying grid potential. Consequently

$$dE_p = -\, dI_p \cdot R. \qquad (12)$$

Substituting equation 12 in equation 11 and reducing,

$$dI_p = \frac{\mu}{R_p + R} \cdot dE_g. \qquad (13)$$

For vacuum tubes having curvilinear characteristics, equation 13 applies rigorously, of course, only to infinitesimal variations in I_p and E_g. However, as in the case of the triode, the output from multielectrode tubes may be expressed by a power series in terms of finite voltage variations applied to the elements, the coefficients in the series being functions of the static characteristics. If these finite variations in I_p and E_g are designated by i_p and e_g, respectively, the output current is expressed to the first order by

$$i_p = \frac{\mu e_g}{R_p + R}, \qquad (14)$$

which is identical with the equation expressing the output current from a triode.

Letting e_p represent the variable voltage across the load resistance, R, the voltage amplification is given by

$$A_v = \frac{e_p}{e_g} = \frac{i_p \cdot R}{e_g} = \frac{R}{R_p + R} \cdot \mu. \qquad (15)$$

It may also be written in the following form which will be found useful later:

$$A_v = \frac{R_p \cdot R}{R_p + R} \cdot \frac{\mu}{R_p} = \frac{R_p \cdot R}{R_p + R} \cdot S_m. \tag{16}$$

It should be emphasized, perhaps, that the electrical parameters of multi-electrode tubes and the output current, as defined by the foregoing equations, are subject to the condition that the voltages applied to all of the electrodes other than the plate and control grid are maintained constant. The satisfactory operation of multi-electrode tubes in circuits also usually requires that this condition be fulfilled. It requires that the impedance to alternating current components in each of these circuit branches be very low. This is accomplished in practice by connecting these electrodes to ground, so far as alternating currents are concerned, through reasonably large capacitances.

From the foregoing analysis it is apparent that, with proper interpretation, the definitions of plate resistance, transconductance, and amplification factor applicable to triodes are also applicable to multi-electrode tubes; in addition, the same expressions for output current and voltage amplification are applicable. This follows from the fact that these quantities are expressed in terms of the differential coefficients of the static characteristics, that is, they depend only upon the slopes of these characteristics at the given operating voltages and not upon their form. However, as will appear later, the difference in the shape of the static characteristics of multi-electrode tubes from those of triodes is very important in determining great differences not only in the magnitude of the electrical parameters, but also in the character and amount of distortion resulting when the tubes are operated under conditions such that large portions of the characteristics are traversed.

In multi-electrode tubes, as well as in triodes, the total space current drawn from the cathode is determined by the extent to which the resultant field, due to the electrodes, overcomes the opposing field produced by space charge. While space charge extends throughout the interelectrode space, it is relatively so much more dense in regions of very low electron velocity that, as a first approximation, its effect usually may be neglected in other regions. Except in space-charge-grid tubes and a few other special tubes, the only important space-charge region is confined to a relatively thin sheath near the cathode surface. Consequently, in such structures the total space current is determined largely by the extent to which the resultant positive field due to the electrodes neutralizes the negative field near the cathode surface produced by space charge. An appreciation of this fact is essential to a clear understanding of the characteristics of multi-electrode tubes.

SCREEN-GRID TETRODES

Utilizing the simple theory of triodes, which has been shown to be applicable to multi-electrode tubes also, the characteristics of a multi-electrode tube will be analyzed next. For this purpose the screen-grid tube is chosen, since it admirably illustrates the type of characteristics found in several types of multi-electrode tubes.

The objective in this case is to reduce the direct capacitance between the plate and control grid through which energy is fed back from the plate to the input circuit. This is accomplished by inserting an electrostatic shield between the plate and control grid of what otherwise would be a three-electrode tube. The condition that such a screen must allow an electron stream to flow through it to the plate, is satisfied by making it of fine mesh or in the form of a finely wound grid structure. To be effective, it must be maintained at some constant potential with respect to ground.

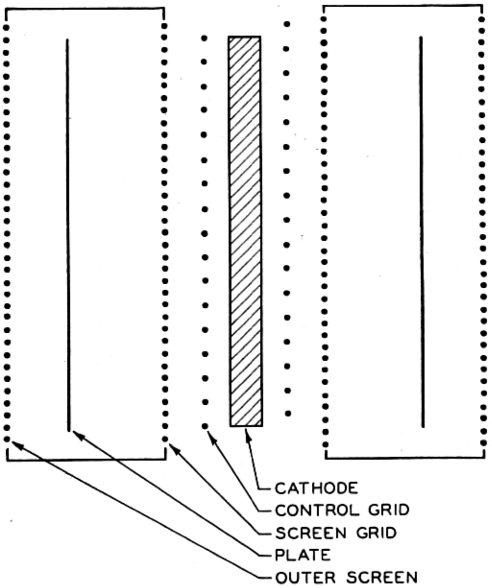

Fig. 1—Schematic diagram showing the arrangement of electrodes in a screen-grid tetrode.

The arrangement of the electrodes in such a tube is shown diagrammatically in Fig. 1. The screen structure outside the plate is added for the purpose of completing the electrostatic isolation of the plate and its leads from the grid, thus reducing the capacitance between these two elements to the lowest practicable value. This outer screen is of no further concern, since it has no effect on the static characteristics of the tube. The usual characteristics of a typical screen-grid tetrode are shown in Figs. 2, 3, and 4. In this case, as is usual in screen-grid tubes, the shielding is very complete, reducing the direct capacitance between the plate and control grid to a few thousandths of what its value would be in the absence of the screen.

First, the characteristics of Fig. 2 will be considered. Since the direct capacitance between the plate and the control grid, g_1, is extremely small, the electric field in the immediate vicinity of the latter, produced by any potential on the plate, also must be extremely small. The cathode is electrically even more remote from the plate than the control grid, because it not only is shielded from the former by the screen grid, but also has some additional shielding from the control grid. Consequently, the field produced by the plate at points between the cathode and control grid is smaller even than the field produced at the control grid and, hence, is negligibly small. Since, as previously discussed, the total space current is determined almost wholly by the field very near the cathode surface, the plate in this case can have practically no effect on the total space current drawn from the cathode. This is shown by the curves giving the total space current, I_t, in Fig. 2. These curves are seen to be so flat as to be almost entirely independent of variations in the plate voltage.

The plate, then, in a screen-grid tube plays an essentially passive rôle which is to collect those electrons that succeed in passing through the screen. The remainder of the space current is collected by the screen, the sum of the plate and screen currents remaining nearly constant with changes in plate voltage.

There is nothing in the theory of the triode by which to determine the ratio in which space current divides between two or more positive electrodes in a multi-electrode tube. As a rough approximation, one might assume that when their potentials are nearly equal, the currents to the plate and screen would be proportional to the ratio of the area of the openings in the screen to the area subtended by its lateral wires. Also, it might be expected that this ratio would increase slightly with increasing voltage of the plate with respect to the screen, because of a tendency of the plate to pull more electrons through the screen. This effect should be less for very fine mesh screens than for coarse ones.

From this simple theory, one would expect the plate current-plate voltage characteristics to be very flat for plate potentials higher than the screen potential. Consequently, the plate conductance, given by

$$S_p = \frac{\partial I_p}{\partial E_p} = \frac{1}{R_p}$$

is a very small quantity; and the plate resistance, given by

$$R_p = \frac{1}{\dfrac{\partial I_p}{\partial E_p}}$$

is a very large quantity compared with its value in triodes, and increases with the fineness of mesh of the screen grid. The plate-current curves of Fig. 2 are seen to be in general accord with this simple theory at the higher values of plate voltage, although they are not quite as flat as might be expected from the theory. This, and the rapid falling off in the vicinity of 100 volts, will be discussed later.

Taken alone, the extremely high resistance of a screen-grid tube would seem to be a very serious disadvantage. From equation 14, the tube may be considered as analogous to a generator the electromotive force of which is μe_g and the internal resistance of which is R_p, working into an external load resistance R—a generator with extremely high internal resistance. Why this is not fatal to the usefulness of the tube will be pointed out later.

While the plate current in a screen-grid tube is nearly independent of plate voltage for values of the latter higher than the screen potential, this obviously cannot hold at low values of plate voltage. At zero plate voltage, the plate current must be zero. At this point the screen collects the entire space current and $I_s = I_t$. As the plate potential increases from zero, the plate current would be expected to rise rapidly, with a corresponding drop in the screen current, as the plate collects more and more of the electrons passing through the screen. However, two factors tend to prevent an abrupt rise in the plate current to its nearly constant value when the plate becomes slightly positive. The first of these is space charge in the region closely adjacent to the plate produced by the electrons that pass through the screen, reach zero velocity in the region adjacent to the plate, and return to the screen. Some of them may perform several oscillations to and fro through the screen before being captured by it. This space-charge effect is largely masked by the more important second factor which is the deflection of the majority of the electrons from their normal paths by the intense electric fields about the lateral wires of the screen. This results in large differences in the components of velocity of the electrons normal to the surface of the plate and, consequently, in the distance to which they approach the plate in their trajectories before being turned back to the screen. As a result, the plate must become positive by several volts with respect to the cathode before it captures substantially all of the electrons that pass through the screen.

From this simple theory, the plate-current and screen-current curves would be expected to have the form shown by the ideal curves of Fig. 2. Obviously, the screen-current curves must be complementary to the plate-current curves since the sum of the two currents is substantially constant.

The difference between these ideal curves and the actual characteristics, in the region extending from a few volts to potentials somewhat higher than the screen voltage, is attributed to the phenomenon of secondary electron emission. When electrons strike a metal surface with velocities equivalent to more than a few volts, other electrons, known as secondary electrons, are liberated from the surface. The number of electrons so liberated varies not only with the velocity of the primary bombarding electrons, but also with the character of the metal surface, the amount of adsorbed gases and other materials on the surface, and other factors. The number of such electrons leaving the surface may even exceed the number of primary electrons striking it, in which case the net current to the metal surface is negative. The velocity of the secondary electrons varies greatly. A very few have velocities approaching that of the primary electrons. The great majority, however, have low velocities equivalent to only a few volts.

In the screen-grid tube, an appreciable number of secondary electrons is liberated from the plate at potentials between 5 and 10 volts, and they increase in number with plate voltage. For plate potentials lower than the screen potential, in this case 75 volts, the secondary electrons from the plate are drawn to the screen, thus increasing the screen current by the amount the plate current is decreased. When the plate reaches a potential equal to that of the screen, secondary electrons no longer can escape from the plate to the screen, except those emitted with appreciable velocities; consequently, the plate current rises rapidly to its normal value.

At plate potentials higher than the potential of the screen, secondary electrons emitted from the latter are drawn to the plate. Consequently, in this region the plate current is slightly higher than it would be in the absence of secondary electron emission from the screen. The gradual rather than abrupt rise in the plate current curves at 75 volts is attributed primarily to the distribution of velocities with which the secondary electrons are emitted; to a lesser extent, it is dependent also

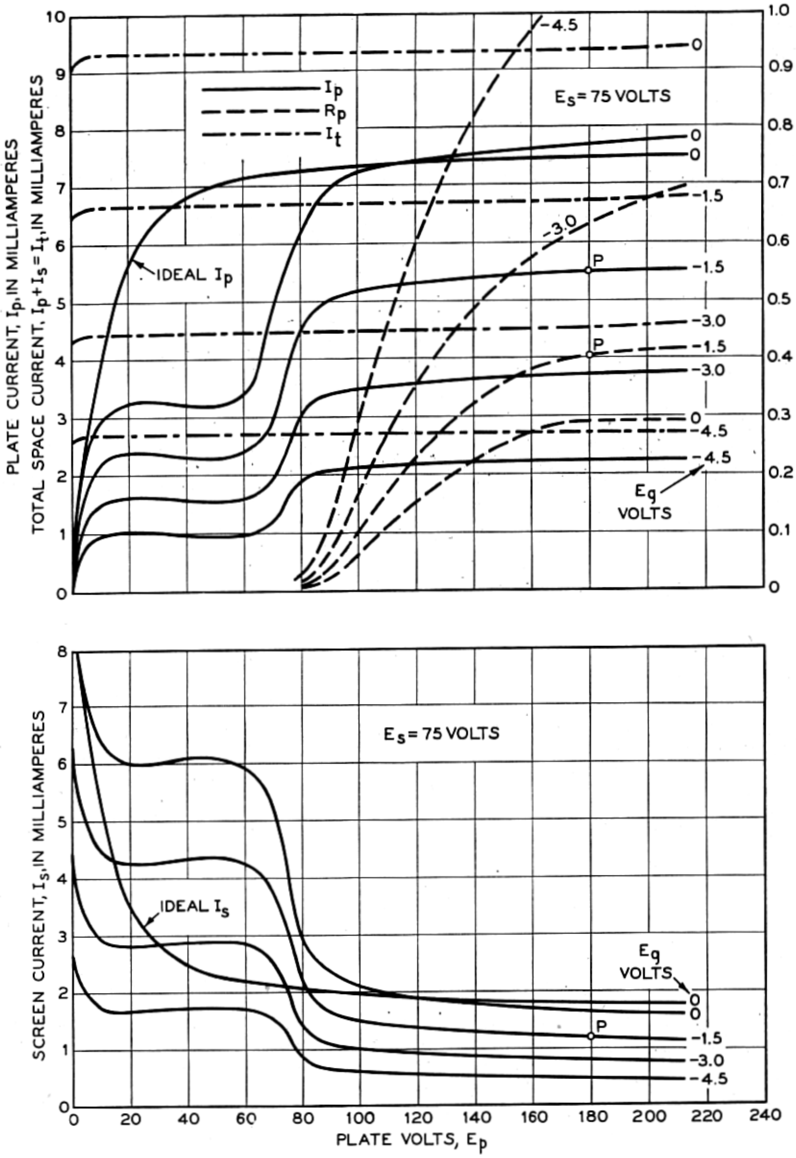

Fig. 2—Characteristics of a screen-grid tetrode. The curves show the plate current, I_p, screen current, I_s, total space current, $I_t = I_p + I_s$, and plate resistance, R_p, as functions of the plate voltage. Control-grid voltage, E_g, is indicated on the curves. Screen voltage, E_s, is maintained constant at 75 volts throughout.

on the combined effects of space charge, intensity and distribution of the field at the surface of the screen wires.

Normal operating conditions for the screen-grid tube the characteristics of which are shown in Fig. 2 are: $E_p = 180$ volts, $E_s = 75$ volts, and $E_g = -1.5$ volts. At this operating point P in Fig. 2, the plate current is 5.5 ma and the plate resistance is 400,000 ohms. The operating range is confined to the flat portion of the characteristics. If the tube is operated with plate-voltage swings sufficiently large that the instantaneous values of the plate potential extend into the region of rapidly falling plate current, serious distortion of the output results. This is a serious limitation in screen-grid tetrodes, because it requires that the operating plate potential be much higher than the screen potential. How this limitation may be removed by the introduction of an additional electrode in the tube will be shown later.

Curves showing the variation of plate resistance with plate voltage are shown in Fig. 2. The plate resistance decreases with plate voltage, falling off very rapidly as the plate voltage approaches the screen voltage. The ordinates of the plate-resistance curves give a measure of the flatness of the plate-current curves. That the latter are not as flat as the total-space-current curves, thus resulting in values of plate resistance approaching infinity, is attributed to two factors: secondary electron emission from the screen, and an increasing ratio of plate current to screen current with increasing plate voltage. The increasing percentage of the primary space current drawn to the plate with increasing plate voltage is an involved and undetermined function of several factors including: the ratio of the openings in the screen grid to the total conducting area subtended by it, the intensity and distribution of the field at the screen grid, the velocity and directional distribution of the electrons arriving at the screen grid, and space-charge effects in its vicinity.

Thus, there is the interesting situation in screen-grid tubes that, for any given set of operating voltages, the magnitudes of the plate resistance and amplification factor are determined largely by factors not directly determined by the geometry and design of the tube. This is quite different from triodes in which the plate resistance and amplification factor both are determined directly by geometrical dimensions and the arrangement of the electrodes.

Obviously, the number of electrical parameters in vacuum tubes increases rapidly with the number of electrodes. The curves of Fig. 2, which correspond to the usual plate current-plate voltage characteristics for a triode, were obtained with the screen maintained at a constant potential of 75 volts as a fixed parameter. To obtain a complete charting of the characteristics would require several such families of curves taken with different screen voltages. One such additional family of characteristics, in which E_s is maintained at 90 volts, is shown in Fig. 3.

Since the plate in a screen-grid tube has practically no effect on the total space current, so far as consideration of the latter is concerned, one may regard the plate as being removed from the structure and consider only the remaining elements. The cathode, control grid, and screen then may be regarded as constituting an ordinary triode. By maintaining the screen at a positive potential, it is enabled to perform the function usually performed by the plate of a triode, *viz.*, that of supplying the positive field necessary to produce the flow of space current against the opposing resistance due to space charge. This function does not interfere with its screening action, so long as its potential is not allowed to vary. In fact, there is an actual gain in efficiency, as will be shown later, in having the electrode that provides the main driving field for the space current maintained at a fixed potential instead of varying over the operating cycle, as it must in the triode.

Usual design principles and equations applicable to triodes are also applicable to screen-grid tetrodes. By making the spacings between the electrodes small, particularly that between the cathode and control grid, a high transconductance can be obtained. Using the subscript t to designate total space current, the transconductance is given by $S_t = \dfrac{\partial I_t}{\partial E_g}$ and has the same value as that for a triode of the same dimensions. Let f represent the fraction of the total space current that passes through the openings in the screen and is collected by the plate, which is assumed to be at a higher potential than the screen. By proper design, f can be made large, say from 0.7 to 0.9, in the normal operating range. The transconductance from the control grid to the plate is given by

$$S_m = \frac{\partial I_p}{\partial E_g} = f \cdot \frac{\partial I_t}{\partial E_G},$$

which is 0.7 to 0.9 of the normal value of transconductance for the three-electrode tube.

The amplification factor, μ, for the tetrode, is given by

$$\mu = \frac{\dfrac{\partial I_p}{\partial E_g}}{\dfrac{\partial I_p}{\partial E_p}} = S_m \cdot R_p. \tag{17}$$

Since the transconductance, S_m, has a value not greatly different from the normal value for a triode, and since R_p is very large, μ, which is proportional to R_p, also must be very large. Referring to equation 14 and its analogy with the generator equation, it may be seen that, despite the fact that the screen-grid tube considered as a generator has a very high internal resistance, it gives normal output because it is provided also with a very large electromotive force, μe_g.

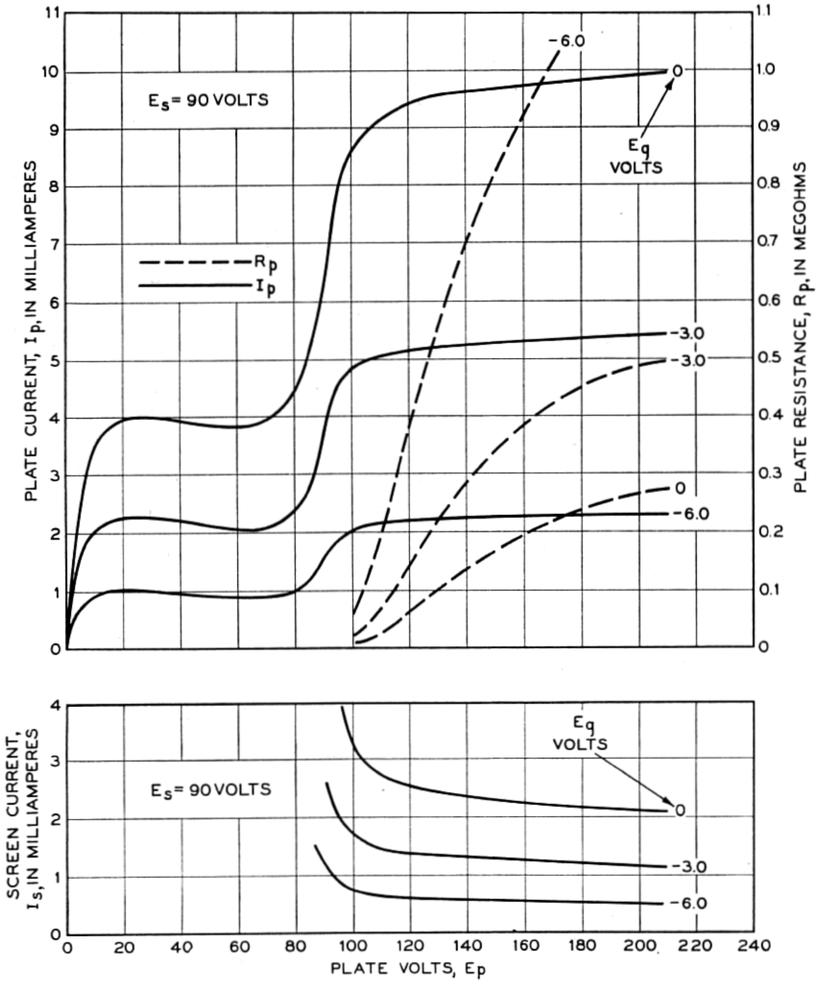

Fig. 3—Characteristics of a screen-grid tetrode similar to those shown in Fig. 2 except that $E_s = 90$ volts.

From this analysis of the characteristics of the screen-grid tube, based upon the simple theory of triodes, one would expect that families of characteristics corresponding very closely with those of ordinary triodes would be obtained if the total space current, or the plate current,

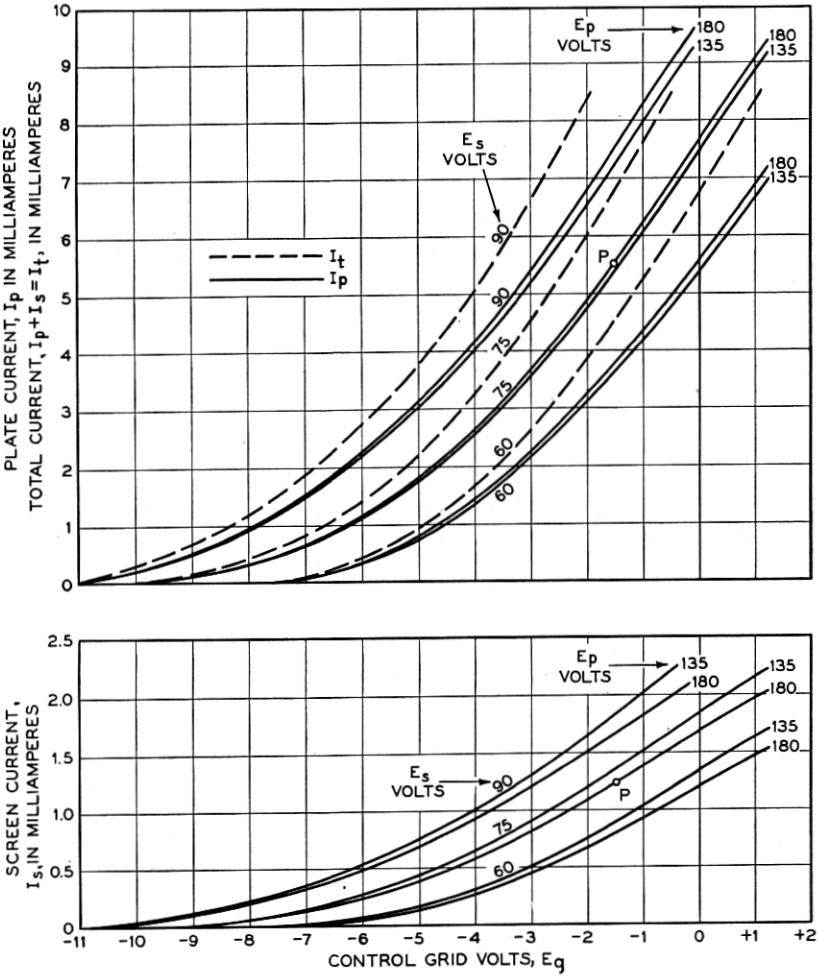

Fig. 4—Characteristics of a screen-grid tetrode. Plate current, I_p, screen current, I_s, and total space current, I_t, as functions of the control-grid voltage, with various values of plate voltage and screen voltage as parameters.

were plotted as functions of the control-grid voltage and screen-grid voltage, with the plate maintained at any fixed potential higher than the screen potential. It would be expected further that the family of curves showing total space current would remain practically invariant with variations in plate voltage. The plate-current family of characteristics should show only small variations with plate voltage (so long as E_p is higher than E_s), depending on the magnitude of the change in the ratio of I_p to I_s.

Families of such characteristics are shown in Fig. 4. They are seen to correspond very closely indeed with similar characteristics for a triode. The I_t curves vary so little with plate voltage that the families of characteristics taken at $E_p = 135$ volts and $E_p = 180$ volts, coincide within the breadth of the curves. The plate current curves show a small variation with E_p, as was discussed previously.

In Fig. 5 the transconductance and amplification factor are shown as functions of the plate voltage for four different values of grid bias and with the screen potential maintained constant at 75 volts. At the normal operating point P, the transconductance is 1375 micromhos and the amplification factor is 550. The shape of these curves is typical of that for screen-grid tubes and pentodes. Throughout the normal operating range, the transconductance curves have about the same degree of flatness as the plate-current curves. This is to be expected from consideration of the plate-current curves of Fig. 4. Since these curves change only slightly with variations in plate potential, their slopes or transconductance values also change but slightly. The amplification-factor curves are very similar in form to the plate-resistance curves of Fig. 2. This follows at once from equation 17, for since S_m remains nearly constant with variations in E_p, μ must vary in the same manner as R_p.

In Fig. 6 the transconductance, plate resistance, and amplification factor are shown as functions of grid voltage for three different values of the screen voltage and with the plate voltage maintained constant at 180 volts. These curves are also typical of those found for several multi-electrode tubes. The transconductance curves agree in form with those for a triode, as would be expected from the plate-current curves of Fig. 4. The plate-resistance curves are similar in form to those for a triode, but rise more rapidly with increasing negative grid bias. The amplification-factor curves, however, are entirely different in form from those for a triode, since they rise with increasing negative grid bias, whereas in triodes the amplification factor decreases with increasing negative grid bias. The reason for this difference is that the plate resistance in many multi-electrode tubes, over the normal range of operation, increases more rapidly with decreasing plate current than in triodes. At sufficiently large negative values of grid bias and very low plate currents, the amplification-factor curves frequently reach maxima and then fall rapidly as they do in triodes.

In the operation of triodes as voltage amplifiers, it is usually possible to have the external load resistance large with respect to the plate resistance. Consideration of equation 15 shows that this results in a voltage amplification ratio approaching the amplification factor. In the operation of screen-grid tubes and conventional pentodes as well, which have high plate resistances, it is usually necessary that the load resistances be much smaller than the plate resistances. This limitation

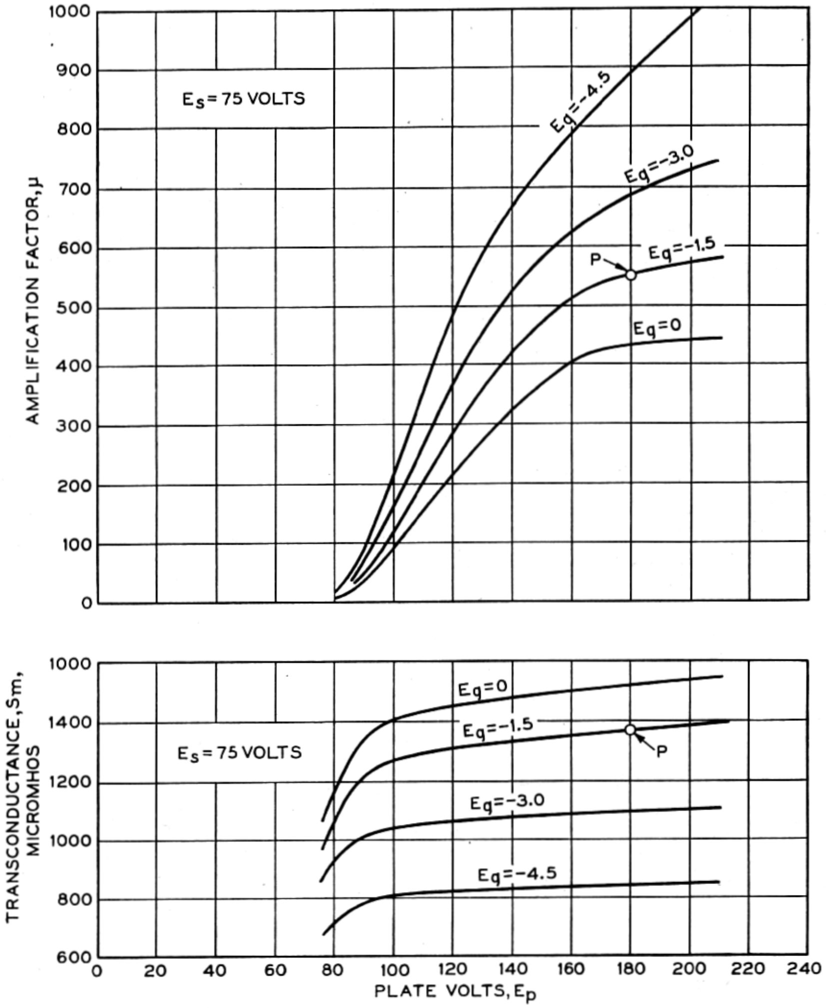

Fig. 5—Amplification factor and transconductance of a screen-grid tetrode as functions of the plate voltage.

is imposed by circuit coupling requirements and sometimes by restrictions on the permissible harmonic content in the power output. This limitation results in an amplification ratio that is much smaller than

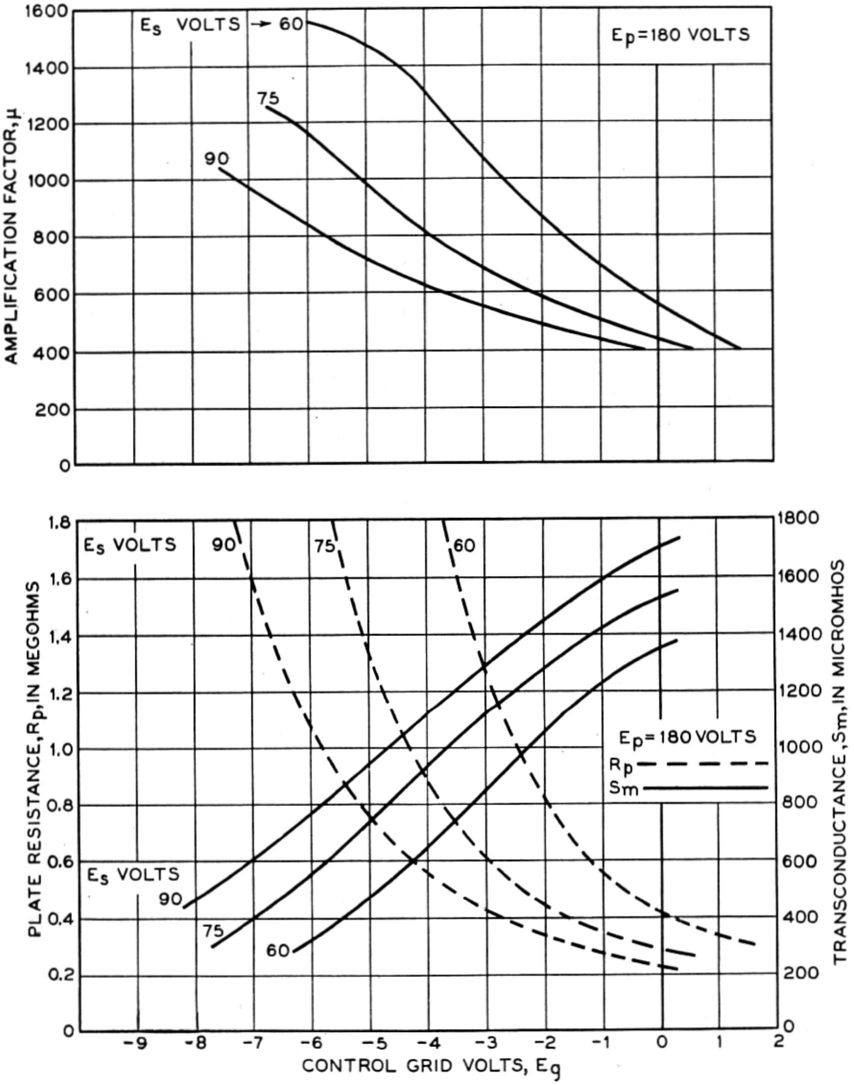

Fig. 6—Amplification factor, transconductance, and plate resistance of a screengrid-tetrode as functions of the control-grid voltage.

the amplification factor; but even so, a considerably higher amplification ratio usually can be obtained than with triodes. This is apparent from consideration of equation 16 which may be written in the form,

$$A_v = S_m \cdot \frac{R}{1 + \frac{R}{R_p}} \cdot \qquad (18)$$

Since in screen-grid tubes and pentodes, R/R_p is small, the voltage amplification is given approximately by

$$A_v = S_m \cdot R. \qquad (19)$$

Now, in a comparable triode the transconductance will have a value comparable with S_m, and it may be assumed that a load resistance could be used comparable with R. However, the ratio R/R_p for the triode is not small and may be greater than unity. Hence, from equation 18, the amplification obtained with the triode is correspondingly smaller.

It has been shown that the presence of the electrostatic screen in the screen-grid tetrode results in a high plate resistance and a high amplification factor, but that the ratio of μ to R_p (transconductance) remains normal. Such tubes yield high amplification and, with suitable associated circuits, are relatively free from feed-back; but they are limited in their range of operation because of the fold in the plate current-plate voltage characteristics resulting from secondary emission from the plate.

Power Pentodes

In order to deliver a large power output, a vacuum tube must be capable of large variations in plate current and plate voltage from their normal operating values. Both of these conditions are fulfilled by the power pentode. The arrangement of the electrodes, shown schematically in Fig. 7, corresponds to that in a screen-grid tube except that an additional grid, g_3, is inserted between the plate and screen grid, g_2. As in the screen-grid tube, the first grid, g_1, has a negative voltage applied to it and acts as the control element. The second grid, g_2, is maintained at a fixed positive potential, E_s, and provides the main driving field for the space current.

As in the screen-grid tube, the total space current is determined almost wholly by the geometrical dimensions and spacings of the cathode, g_1 and g_2, and by the voltages applied to these electrodes. Consequently, in the design of this portion of the structure, the same considerations apply as in the design of an ordinary triode to deliver large power output. By making the inner grid comparatively coarse and by designing the second grid to operate at comparatively high potentials, a structure having a low amplification factor is obtained which draws a large space current from the cathode at a control-grid bias sufficiently negative to permit relatively large swings of the control-grid voltage. In pentodes designed to operate at low frequencies, screening between the plate and control grid is unimportant; hence, the second grid can be comparatively coarse, thus permitting as large a portion as possible of the space current to pass through it to the plate.

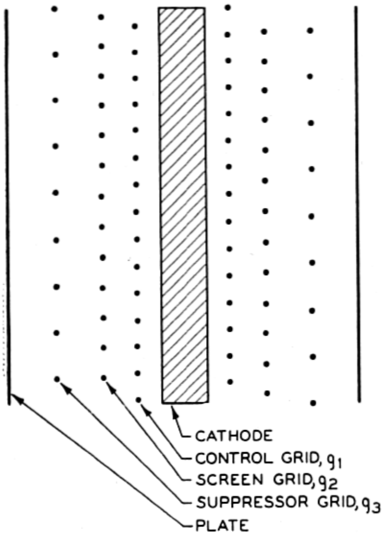

Fig. 7—Schematic diagram showing the arrangement of electrodes in a power pentode.

To permit the largest possible swings in plate voltage, it is necessary to remove the "fold" in the plate-current characteristics, caused by secondary electrons emitted from the plate. This is accomplished by the insertion of a third grid, g_3, between the plate and second grid, g_2. This grid, known as a suppressor grid, must be maintained at a lower potential than the lowest instantaneous potential reached by the plate, and is usually maintained at the cathode potential by connecting it to the cathode inside the tube. The suppressor grid exerts a retarding force on the primary electrons flowing toward it from the cathode, but, because of its coarse structure, all but a small fraction succeed in passing through it and are accelerated again, finally reaching the plate with the same velocity they would have if the suppressor grid were absent. On the other hand, secondary electrons emitted either by the plate or screen grid find themselves in a retarding field, which they are unable to traverse because of their low velocity, and are constrained to return to the electrode from which they came.

Plate current-plate voltage characteristics and screen current-plate voltage characteristics for a power pentode of the indirectly heated cathode type, are shown in Fig. 8. The secondary emission "fold" in the characteristics is almost completely eliminated by the suppressor grid.

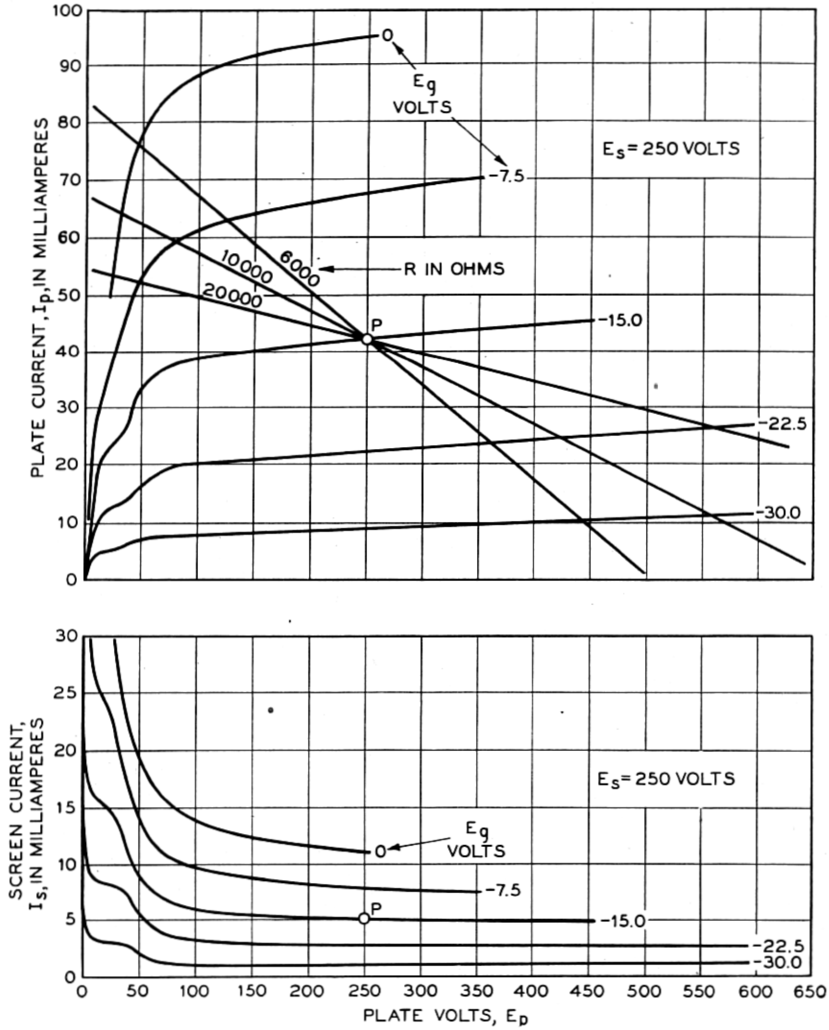

Fig. 8—Characteristics of a power pentode. Plate current, I_p, and screen current, I_s, as functions of the plate voltage with various values of the control-grid voltage, E_g, as parameters. Screen voltage, E_s = 250 volts throughout. Load lines are shown for resistance loads of 6000, 10,000, and 20,000 ohms.

The effectiveness of the suppressor grid is shown by the characteristics of Fig. 9. These curves were obtained from a tube of the same type as that for which the characteristics are shown in Fig. 8. One set of curves was obtained with the suppressor grid operating in the normal manner. The other curves were obtained with the suppressor grid tied to the screen grid and maintained at a positive potential of 250 volts. In this latter case, the number of secondary electrons escaping from the plate is practically the same as if the suppressor grid were removed from the tube. The presence of the suppressor grid not only permits the plate to swing to very much lower potentials than otherwise would be possible, but also permits the plate and screen to operate at the same potential, which is 250 volts in this case.

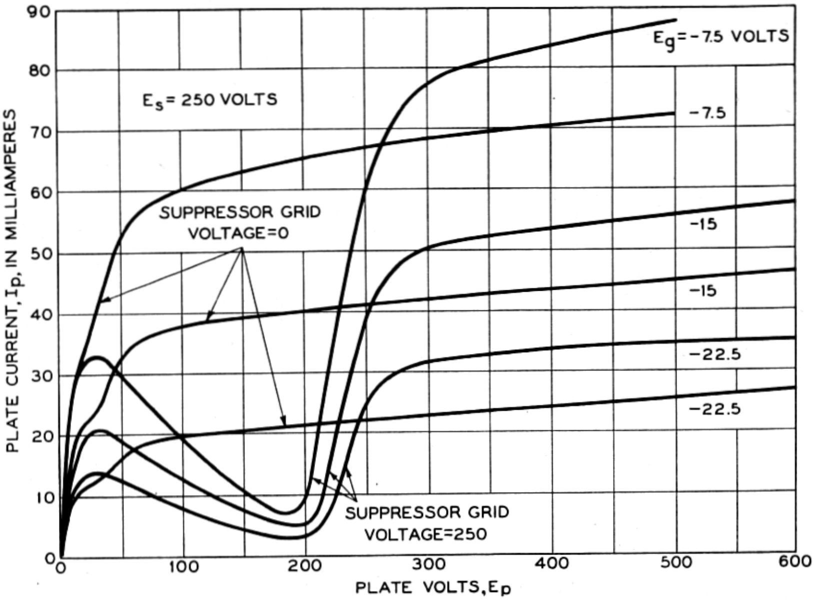

Fig. 9—Curves showing the effect of the suppressor grid in a power pentode.

The characteristics of Fig. 8 closely approach the form that would be expected from simple theory. As is usual with power pentodes, the plate-current curves are not quite as flat as those for screen-grid tubes. This is because of the more open character of the grids which permits the plate to have a slightly greater effect on the magnitude of the space current. This is evidenced also by the tendency of the curves to turn up at the higher plate voltages.

The normal operating point for this tube is at point *P* in Fig. 8, at which the plate and screen potentials are both 250 volts and the control grid potential is -15 volts. Under these conditions, the average characteristics are: $I_p = 42$ ma, $I_s = 5$ ma, $\mu = 156$, $R_p = 52{,}000$ ohms, and $S_m = 3000$ micromhos.

Curves showing the amplification factor, μ, the plate resistance, R_p, and the transconductance, S_m, for several different values of grid bias, are shown in Fig. 10. They correspond in general form to those shown in Figs. 3 and 5 for the screen-grid tube. The maxima in some of the plate-resistance curves result from the fact that the corre-

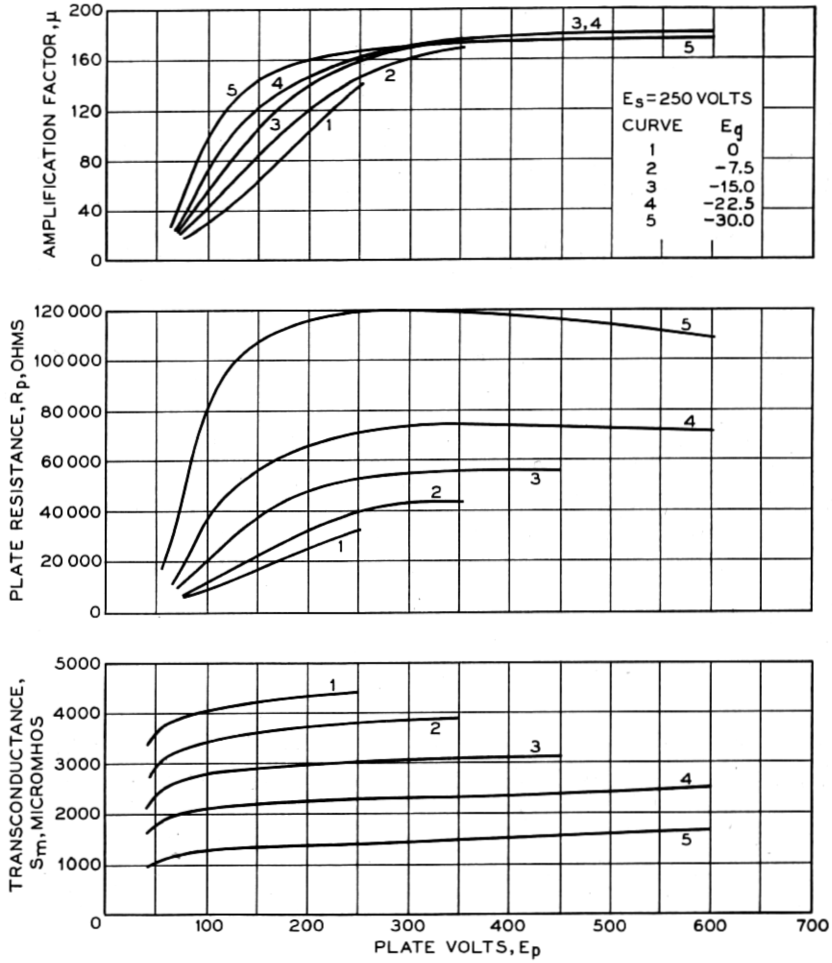

Fig. 10—Amplification factor, plate resistance, and transconductance of a power pentode as functions of the plate voltage, with various values of control-grid voltage as parameters. Screen voltage, E_s, is maintained constant at 250 volts.

sponding plate-current curves turn up at the higher plate potentials and thus have points of inflection.

In Fig. 11, the plate current is shown as a function of control-grid voltage for various values of the plate voltage, with the screen potential constant at 250 volts. The curves are very similar to corresponding ones for the screen-grid tube shown in Fig. 4. Here, curves are included at such low plate voltages that a large falling off in plate current occurs.

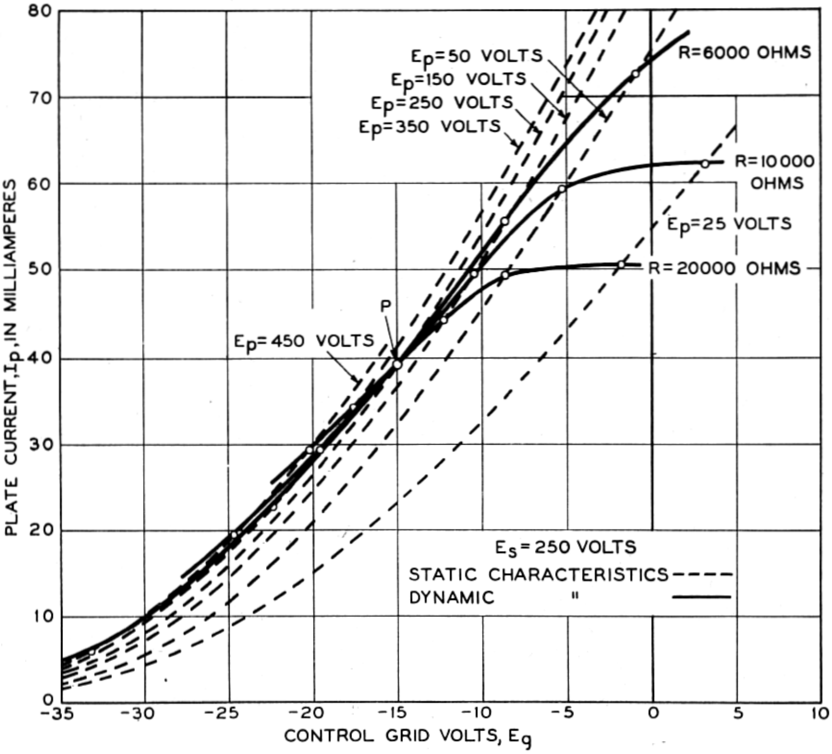

Fig. 11—Plate current-grid voltage characteristics of a power pentode, with dynamic characteristics for resistance loads of 6000, 10,000, and 20,000 ohms.

In Fig. 12, the output power in watts, and the second and third harmonics, expressed in decibels below the fundamental, are shown as functions of peak volts for a sinusoidal input applied to the grid. These data were obtained under the normal operating conditions previously given, and with the indicated load resistances. Since the curves are typical in form of those obtained in several types of multi-electrode tubes, it will be of interest to examine them in some detail.

Except at the higher inputs, the power output increases continuously with load resistance over the load range considered. This is to be expected, since the highest load resistance of 12,000 ohms is much smaller than the plate resistance of the tube, which is 52,000 ohms. For small inputs, the maximum power output would be obtained, as it is in triodes, when the load resistance is equal to the plate resistance of

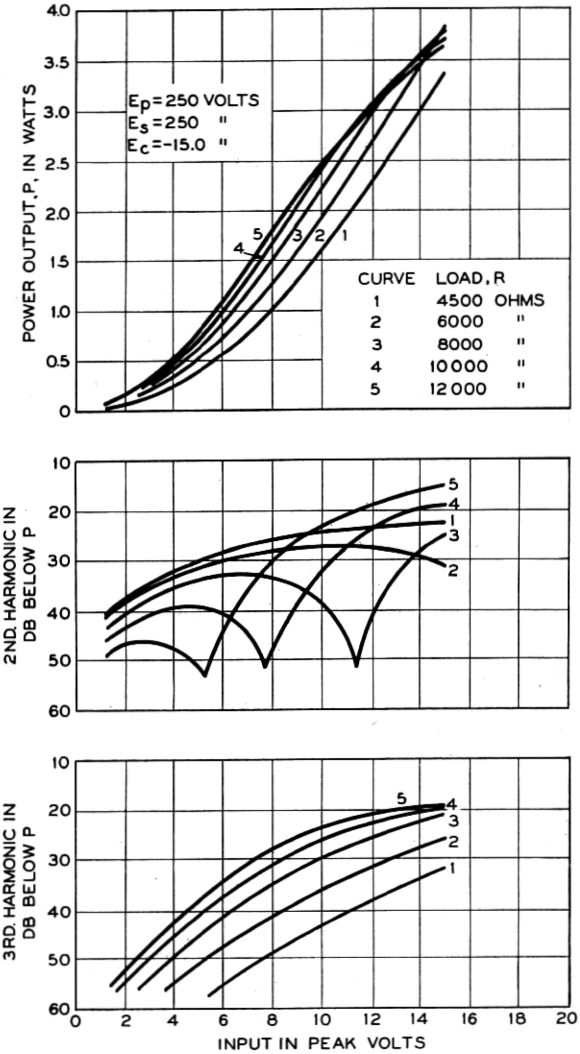

Fig. 12—Characteristics of a power pentode. Power output, P, in watts, second and third harmonics in decibels below the fundamental, as functions of the peak input when a sinusoidal voltage is applied to the control grid.

the tube. The decrease in power output with increasing load resistance, at the higher inputs, results from the progressive turning over of the dynamic characteristics as shown by the curves of Fig. 11.

The second harmonic decreases continuously with increasing load resistance at small inputs. At large inputs, it decreases at first, then increases with increasing resistance. At very low resistances, the second harmonic increases continuously with input. At higher load resistances, it rises to a broad maximum, then falls to a very sharp minimum, after which it again rises rapidly with increasing input. The explanation of these phenomena will be given later.

The third harmonic increases continuously both with increasing input and with increasing load resistance. At load resistances that are small compared with the plate resistance of the tube, it rises to a higher level than the second, over a certain range of input. Relatively high levels of third harmonic are characteristic of pentodes, screen-grid tubes, and also of some other types of multi-electrode tubes. For example, from the curves of Fig. 12, with a load resistance of 6000 ohms and an input of 15 peak volts, the power output is 3.8 watts with the volume level of the second and third harmonics 31 db and 26 db, respectively, below that of the fundamental. At an input of 10 peak volts, the volume level of the second harmonic rises to 27 db and of the third harmonic falls to 36 db below that of the fundamental.

These results are quite different from those obtained with triodes where the third harmonic is, in general, 10 db or more below the second. Furthermore, in triodes, both the second and third harmonics decrease continuously, as a rule, with increasing load resistance. There are exceptions to this, however, where the third harmonic curves show minimum points or cusps, similar to those shown by the second harmonic curves for pentodes.

The reason for the relatively large harmonic content in the output of pentodes is apparent from consideration of the load lines drawn through the operating point P in Fig. 8. At the lower values of plate voltage, the load lines cut across the rapidly descending portions of the plate-current characteristics. This effect is more marked and begins at more negative values of grid bias as the load resistance increases and the slope of the load lines becomes correspondingly less. The effect of this is to produce current variations through the external load resistance that are not proportional to the variations in grid voltage, thus resulting in distortion of the output.

The character of the distortion is made clearer by reference to the dynamic characteristics of Fig. 11, for resistance loads of 6000, 10,000, and 20,000 ohms. All the curves show a flattening out at the top which increases progressively with load resistance. It readily is shown that such dynamic characteristics, having points of inflection at which the curvature changes sign, give rise to peculiarities in the harmonic output.

If such a characteristic be expressed by a power series in terms of grid-voltage variations from the operating point P, there usually is found a relatively large contribution by third and higher odd-power terms the coefficients of which are predominantly negative in sign. Since odd-power terms yield odd harmonics, this accounts for the relatively high levels of third harmonic at input voltages sufficiently large that the flat portion of the characteristic is traversed. However, positive and negative signs are about evenly divided among the coefficients of the even-power terms, which yield even harmonics. At some value of the input voltage, which varies with the load resistance, the contributions to the second harmonic by positive and negative terms are approximately equal, resulting in a very small value of this harmonic. This accounts for the cusps in the second harmonic curves of Fig. 12. For inputs less than the value at the cusp, the contribution of positive terms (largely the second-power term) prevails over that of negative terms, while at higher inputs the reverse is true. Consequently, there is a reversal in the phase of the second harmonic at the cusp.

If the point of inflection were at the operating point P in Fig. 11 and, if the dynamic characteristic were symmetrical about P, then only odd-power terms would appear in the equation of the curve. Consequently, in this special case, even harmonics would vanish from the output and only odd harmonics would remain.

Plate-circuit efficiency of pentodes is higher than that usually found in triodes. The underlying physical reasons for this difference are as follows: In the triode, the plate simultaneously performs two functions. First, it is the element in the output circuit whose fluctuating potential is impressed across the load resistance. Second, assuming that the grid potential is not positive at any time, the plate is the only positive electrode providing the necessary driving force for the space current. These two functions militate against each other to a certain extent, for, as is evident from consideration of the dynamic characteristic of either a triode or a pentode, the plate voltage reaches its minimum value at the instant when the plate current reaches its maximum value. This minimum voltage, which must be sufficiently large to draw the peak current through the tube, is a very substantial fraction of the operating plate voltage, particularly when the latter is comparatively low.

In pentodes and in some other multi-electrode tubes, the positive grid, maintained at a constant voltage, provides the necessary driving force for the space current, thus relieving the plate from performing this function. Consequently, the plate is free to swing to lower voltages than otherwise would be possible, which results in a corresponding increase in efficiency.

In Table I, similar data are shown for typical pentodes and triodes.

TABLE I

COMPARATIVE DATA FOR TYPICAL TRIODES AND PENTODES

	Triodes			Pentodes		
	A	*B*	*C*	*D*	*E*	*F*
Plate voltage, E_p	200	250	325	180	250	250
Screen voltage, E_s				180	250	250
Grid voltage, E_g	−45	−50	−68	−18	−16.5	−15
Plate current, I_p, ma	45	34	60	14.5	34	42
Screen current, I_s, ma				2.8	6.5	5
Transconductance, S_m, micromhos	2,810	2,175	5,200	1,050	2,200	3,000
Amplification factor, μ	2.9	3.5	3.8	105	220	156
Plate resistance, R_p, ohms	1,030	1,610	730	100,000	100,000	52,000
Load resistance, R, ohms	2,060	3,900	2,750	12,000	7,000	6,000
Input, peak volts	45	50	68	18	16.5	15
Power output, watts	1.9	1.9	7.8	1.2	3.0	3.8
Second harmonic, %	7.4	5.7	5.0	5.0	2.3	2.8
Third harmonic, %	0.7	1.2	1.1	7.5	6.6	5.0
Total harmonic, effective %	7.45	5.9	5.1	9.0	7.0	5.7
Plate efficiency, %	21	22	40	46	35	36
Plate-grid capacitance, $\mu\mu$f	12	7.2	20	1.2	0.8	0.2
Plate-ground capacitance, $\mu\mu$f	3.2	3.0	5.5	7.8	8.5	15
Grid-ground capacitance, $\mu\mu$f	6.8	4.5	9	6.4	8.4	9

While the triodes and pentodes are not directly comparable with each other, the data are indicative of the differences between the two types of tubes. The chief differences between pentodes and triodes may be summarized as follows: (1) Pentodes yield higher gain and require correspondingly lower input voltages to drive them. (2) Pentodes have much higher amplification factors and plate resistances than triodes. The latter constitutes a handicap in coupling the tube to its circuit, particularly if transformer coupling is employed. (3) Pentodes yield high power output, generally at higher plate efficiency than triodes. (4) The harmonic content in the output of pentodes is high, the third harmonic being particularly high compared with its level in triodes. This requires that pentodes work into load impedances that are very low compared with the plate resistance. Ratios of R to R_p of 1/3 to 1/10 are common. (5) The plate-grid capacitance is much lower and the plate-ground capacitance is somewhat higher in pentodes than in comparable triodes.

Space-Charge-Grid Pentodes

One limitation in the three-electrode tube and in the multi-electrode tubes considered thus far in this paper, is the resistance offered by space charge to the flow of space current. Tubes having so-called space-charge grids overcome this limitation to some extent by having a positive grid close to the cathode, which partially neutralizes the negative field very near the cathode surface due to space charge. A comparatively large current is drawn from the cathode by the space-charge grid. A portion of this current (usually about half of it) is collected by this grid, while the remaining portion passes through it and is acted on by the remaining elements of the tube.

The arrangement of the electrodes in a space-charge-grid pentode is shown in Fig. 13. The space-charge grid, g_1, is maintained at a relatively low positive potential with respect to the cathode, usually in the range from 10 to 20 volts. The second grid, g_2, is the control grid and is maintained at a negative potential with respect to the cathode.

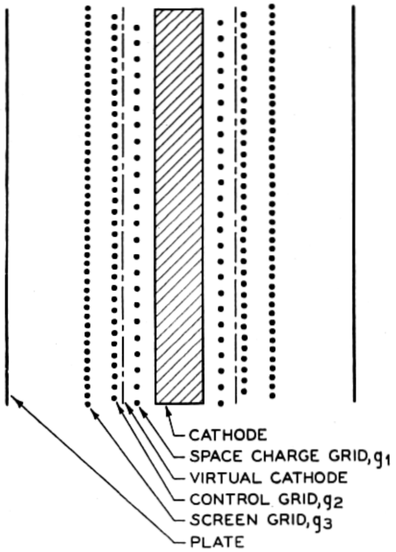

Fig. 13—Schematic diagram showing the arrangement of electrodes in a space-charge-grid pentode.

Ideally, at some cylindrical surface between these two grids (assuming the structure to be cylindrical) the electrons are retarded to nearly zero velocity forming a second space-charge region which may be regarded as a virtual cathode. Since this space-charge sheath is larger in area than the original cathode and is very close to the control grid, it results in very large values of transconductance. Practically, the ideal condition is not fully realized, largely because velocity components other than radial are imparted to the electrons in passing through the space-charge grid. Consequently, these electrons reach any given cylindrical surface outside the space-charge grid with rather widely varying radial components of velocity. This, as will be seen later, places a rather serious limitation on the performance of such tubes.

The arrangement and functioning of the other electrodes in Fig. 13, outward from the virtual cathode, correspond with that of the screen-grid tetrode. The screen grid, g_3, is maintained at a fixed positive potential necessary to accelerate the electrons from the region of the virtual cathode. The plate must be maintained at a potential higher than that of the screen for the same reason as in the screen-grid tetrode. It will be shown that the characteristics of this pentode correspond roughly with those of the screen-grid tube previously discussed.

If g_3 were omitted, the structure outside the virtual cathode would correspond to that of a triode and the characteristics in the resulting tetrode would correspond roughly to those of a triode. In Fig. 14, characteristics are shown for a pentode of this type, the cathode and general dimensions of which are the same as those of the power pentode, the characteristics of which were shown previously. The plate-current and screen-current curves are seen to correspond very closely with those previously shown for a screen-grid tube. The characteristics exhibit the same "folds" due to secondary electrons, although this portion of the characteristics is not shown. The net or space-charge-grid current, I_n, increases as the plate current decreases with increasing negative control-grid voltage. This is to be expected since, as the control grid becomes more negative and reduces the current passing through it to the plate, the excess current returns to the net rather than to the cathode as in the screen-grid tube.

If values of the amplification factor, plate resistance, and transconductance are plotted as functions of the plate voltage, families of curves are obtained similar in all respects to those for a screen-grid tube as shown in Figs. 3 and 5. These characteristics are not shown for this tube.

In Fig. 15, plate-current, screen-current, and net-current characteristics are shown as functions of the control-grid voltage with different values of the screen voltage as parameters. As in the case of the screen-grid tube, only a slight displacement of the characteristics results from variation of the plate voltage. It is of interest to note the high values of net current, particularly as the plate current drops toward zero with increasing negative grid bias. For example, if the operating point is chosen at *P* in Fig. 15, with a screen potential of 90 volts and a grid potential of − 2 volts, the plate current, screen current, and net current are 24, 0.5, and 23 ma, respectively, making a total space current of 47.5 ma drawn from the cathode, nearly half of which is collected by the space-charge grid.

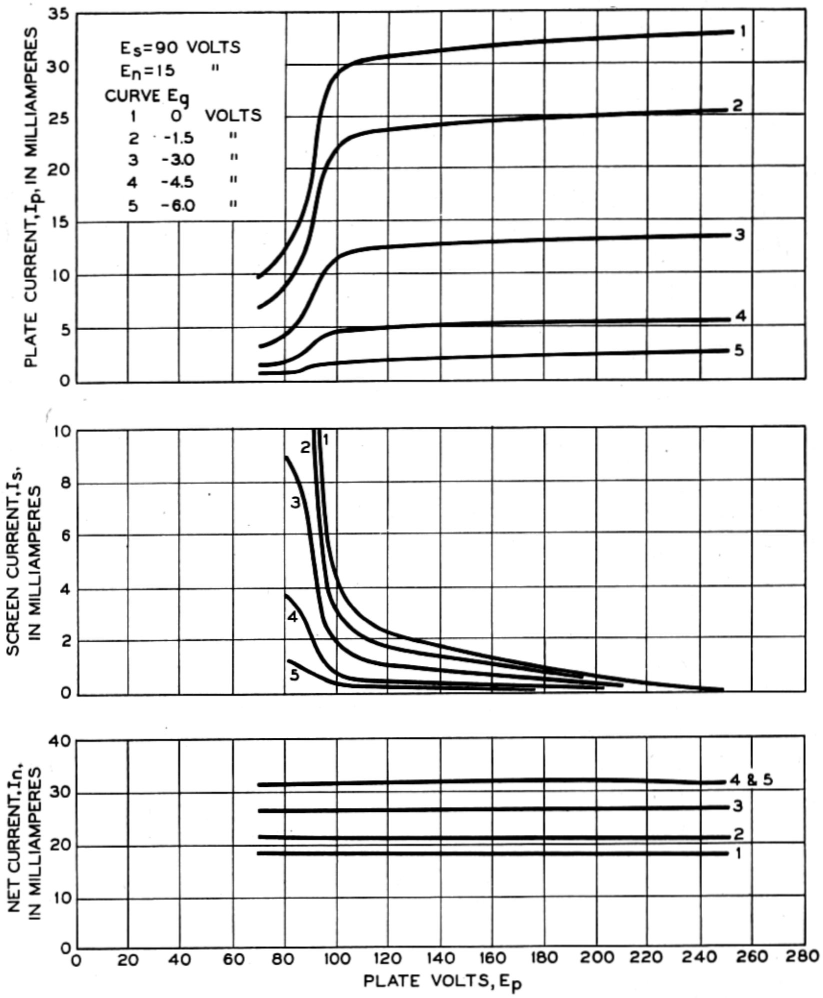

Fig. 14—Characteristics of a space-charge-grid pentode. Plate current, I_p, screen current, I_s, and net (space-charge-grid) current, I_n, as functions of the plate voltage with the indicated values of control-grid voltage as parameters. Screen-grid voltage, E_s = 90 volts. Net (space-charge-grid) voltage, E_n = 15 volts.

Another point of interest in Fig. 15 is the flattening out of the plate-current characteristics at the higher values of plate current, in a manner very similar to that exhibited by triodes of low cathode emission. In fact, this phenomenon is caused by the partial exhaustion of the space charge in the region of the virtual cathode. This is a fundamental characteristic of space-charge-grid tubes, caused largely by the imperfect character of the virtual cathode, which results from electrons entering the space-charge region with widely varying normal components of velocity. It constitutes a serious limitation on the practicable range of operation of such tubes, since it prevents the plate potential from swinging over a sufficiently large range to obtain a large power output without resulting in prohibitive distortion.

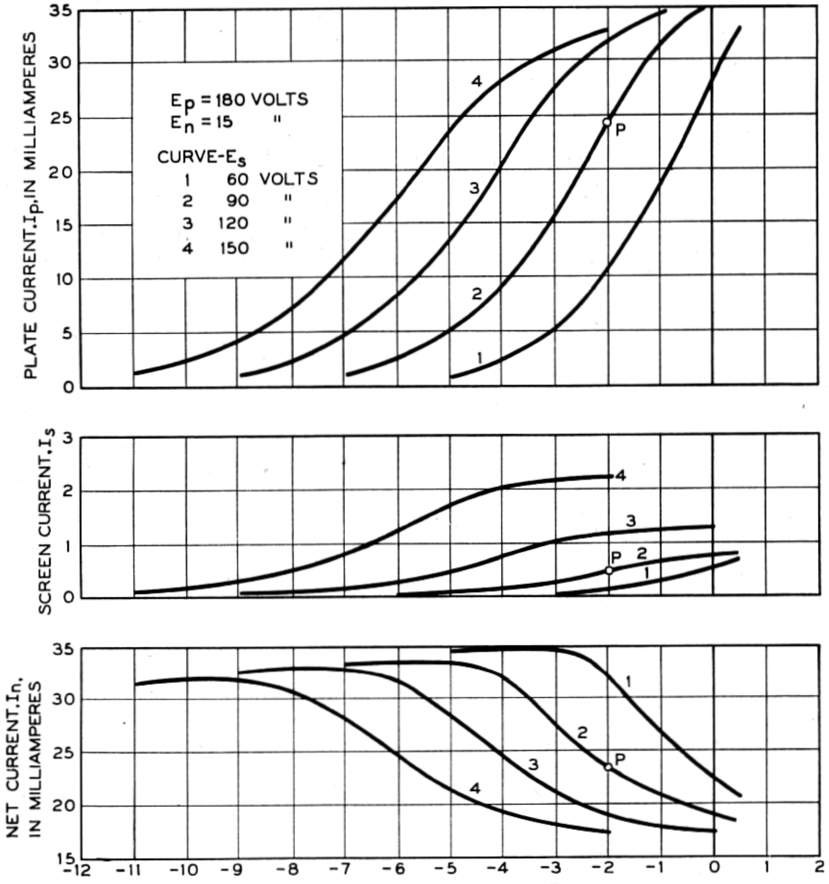

Fig. 15—Characteristics of a space-charge-grid pentode. Plate current, screen current, and net current as functions of the control-grid voltage, E_g, with the indicated values of screen voltage as parameters. Plate voltage, E_p = 180 volts. Net voltage, E_n = 15 volts.

In Fig. 16, the amplification factor, plate resistance, and transconductance are shown as functions of control-grid voltage, with the same parameters as were used in obtaining the curves of Fig. 15. Of particular interest in these curves, are the unusually high values of transconductance for a tube of this size. For example, at the selected operating point *P* it is 9200 micromhos. Also of interest is the peaked character of the transconductance curves. Since transconductance is defined by the slope of the plate current-grid voltage curves, which for this tube have points of inflection in them, maximum points must occur

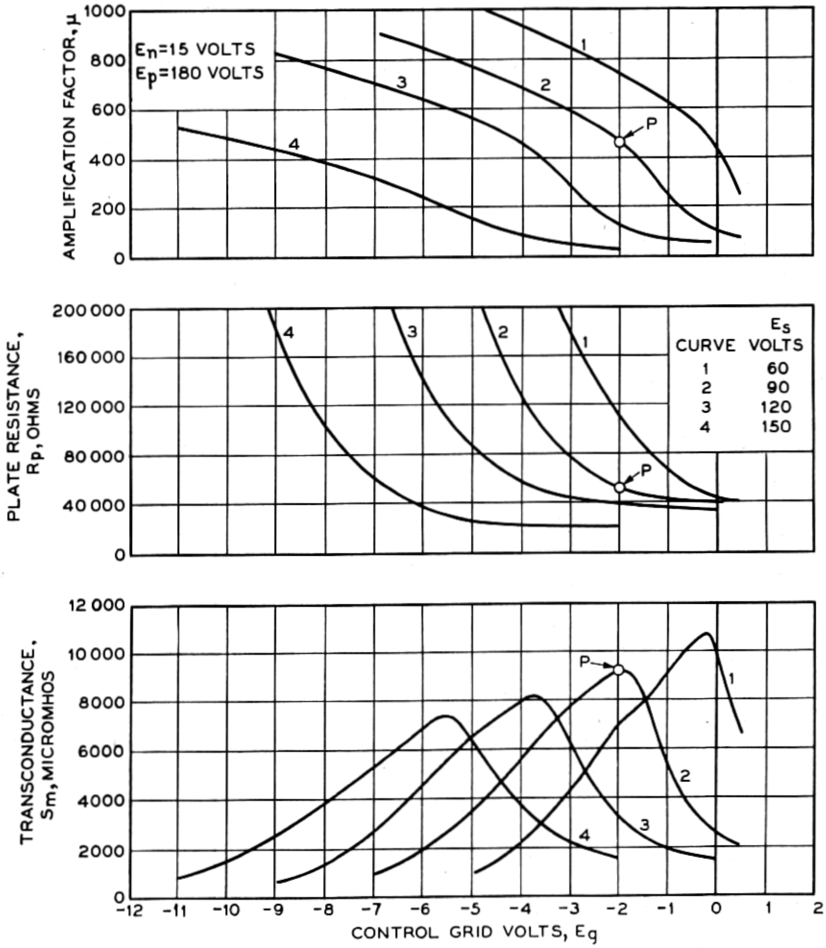

Fig. 16—Amplification factor, plate resistance, and transconductance of a space-charge-grid pentode as functions of the control-grid voltage.

in the transconductance curves. The rapid falling off in transconductance on either side of the maxima, with change in grid voltage, also indicates that a large amount of distortion would result if the tubes were operated with large swings in grid potential.

Space-charge-grid pentodes are capable, then, of yielding very high amplification because of their extraordinarily high transconductance; but, practically, they are limited to use as voltage amplifiers for fairly small inputs, since operation over the wide range necessary for large power output results in prohibitive distortion. These statements apply also to space-charge-grid tetrodes. These tubes have the advantage over ordinary triodes, however, of yielding high values of transconductance at comparatively low voltages applied to the plate.

Co-Planar-Grid Tubes *

Thus far only multi-electrode tubes have been considered in which the electrodes are arranged in concentric order one about another. In the case of the power pentode it has been shown that this arrangement results in characteristics yielding comparatively high output power at high amplification and efficiency but with relatively large percentages of harmonics. It has also been pointed out that the high plate-circuit efficiency is largely due to the presence of a positive grid held at a fixed potential, which permits larger plate voltage swings than would otherwise be possible.

It is evident also from the underlying physical principles that in such a structure, with three concentric grids between the plate and cathode, even though the lateral spacings are fairly wide, enough shielding is interposed between the plate and cathode to make the plate resistance high. The question then arises: Is there any possible way of obtaining the advantages of a positive grid in tubes designed to operate at comparatively low plate voltages without the accompanying high plate resistance of the pentode structure?

This objective is accomplished reasonably well by a four-electrode structure in which the positive grid is placed in the same plane as the control grid. The arrangement of the electrodes in such a structure, which will be referred to as a co-planar-grid tube, is shown schematically in Fig. 17. The lateral wires of the two grids are asymmetrically arranged, the positive and negative lateral wires being arranged in pairs close together. The object of this arrangement may be described roughly as follows: By such an arrangement, when the control grid is very negative, the field about each negative wire very largely neutral-

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* This section, "Co-Planar Grid Tubes," is an addition to the material published in *Electrical Engineering*.

izes the field due to its positive companion so that the latter becomes ineffective in drawing electrons away from the cathode. As the negative grid approaches zero potential it uncovers the positive grid electrically so that the latter becomes highly effective in drawing a large space current from the cathode at the moment when the peak current is drawn to the plate. This would not be so effectively accomplished if the lateral wires were symmetrically arranged.

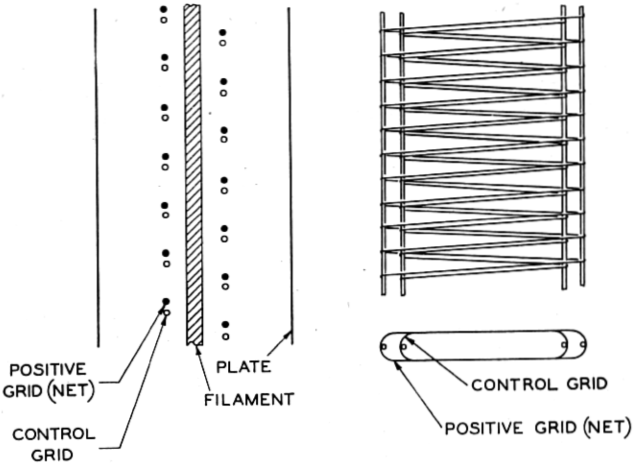

Fig. 17—Schematic diagram showing the arrangement of electrodes in a co-planar-grid tube.

In Fig. 18, characteristic curves are shown for a co-planar-grid tube designed to operate at a plate potential of 130 volts and at a plate current of 35 milliamperes. Each of the three groups of curves shows the plate current as a function of the control-grid voltage for plate voltages of 100, 130 and 160 volts, and with the positive-grid voltage maintained constant at the indicated value. It is evident from these curves that the primary effect of increasing the potential of the positive grid, or net, is to translate the group of plate-current curves to the left. By so doing it is obvious that larger control-grid swings are possible, at any given operating plate current, without the potential of the control-grid becoming positive at any time. This results in a comparatively large power output, to obtain which large grid swings are essential.

The lower curve in Fig. 18 shows that a nearly linear relation exists between the positive and negative increments in voltage that must be applied to the positive and negative grids, respectively, to maintain a constant operating current, in this case 35 milliamperes.

In Fig. 19, a more extended family of characteristics is shown for a positive-net potential of 65 volts. Across these static characteristics a dynamic load characteristic is drawn for a resistance load of 3400 ohms, which matches the plate resistance of the tube at the operating point

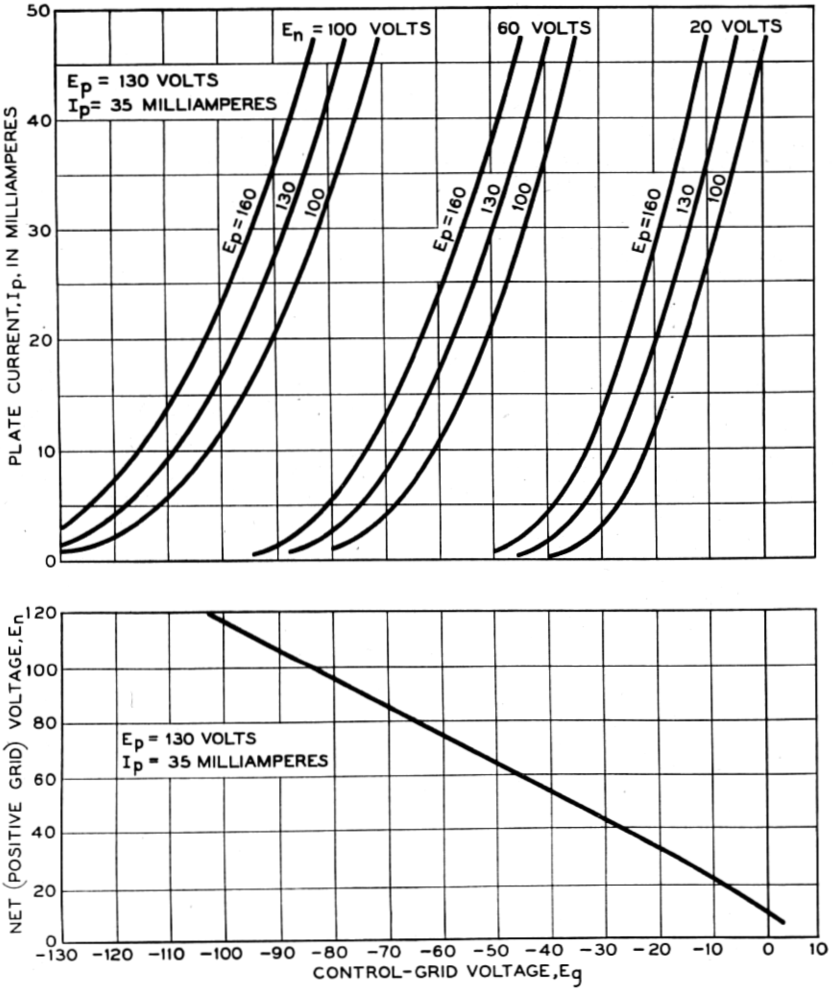

Fig. 18—Plate current-control grid voltage characteristics of a co-planar-grid tube with various values of plate voltage and net (positive-grid) voltage as parameters.

P. At this point $E_p = 130$ volts, $E_n = +65$ volts, $E_g = -51$ volts, $I_p = 35$ milliamperes, and $\mu = 5.3$. The turning over of the dynamic characteristic at the top is due to the increasing fraction of the total space current collected by the positive net. The magnitude of the net current in this region is shown by the family of curves in the lower part of Fig. 19.

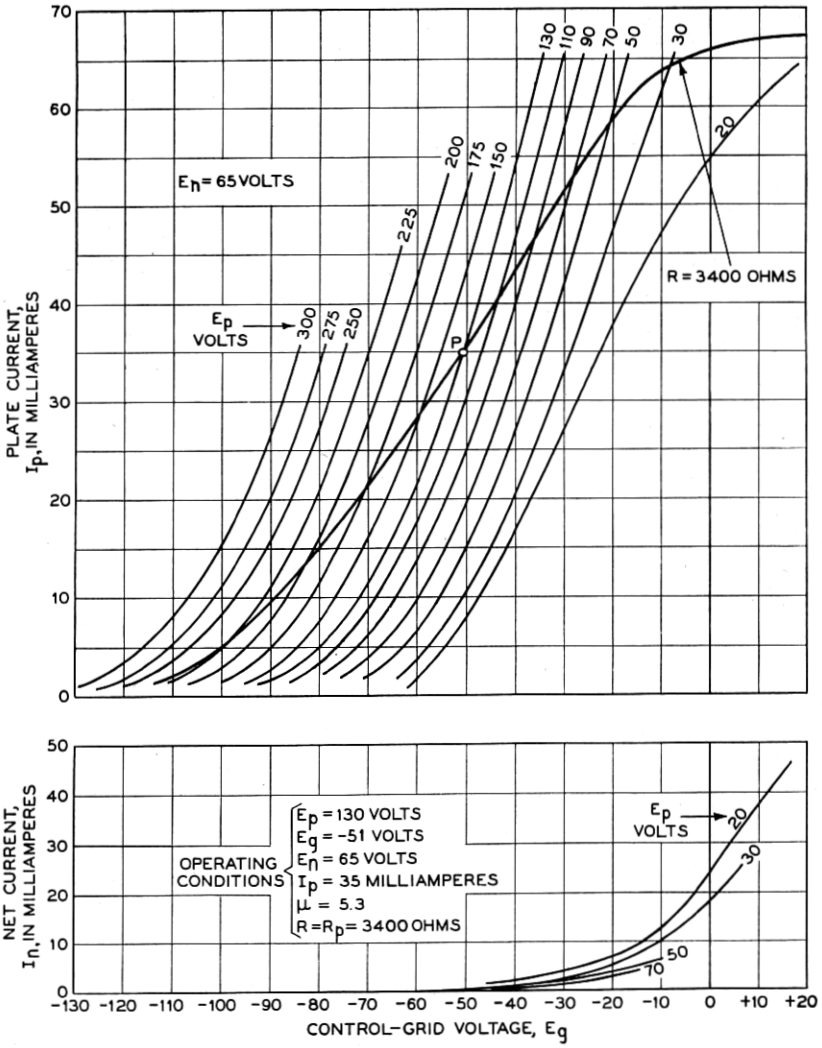

Fig. 19—Plate current-grid voltage and net current-grid voltage characteristics of a co-planar-grid tube. The net (positive-grid) potential is maintained constant at 65 volts. A dynamic characteristic is shown for a resistance load of 3400 ohms.

In Fig. 20, curves are shown giving the power output, and second and third harmonics expressed in decibels below the fundamental, as functions of the peak input when a sinusoidal voltage is applied to the control grid. The curves were obtained with the indicated values of load resistance, and with the indicated bias voltages applied to the grids. In each case the grid voltages were adjusted to give a plate current of 35 milliamperes. The curves are very similar in form to

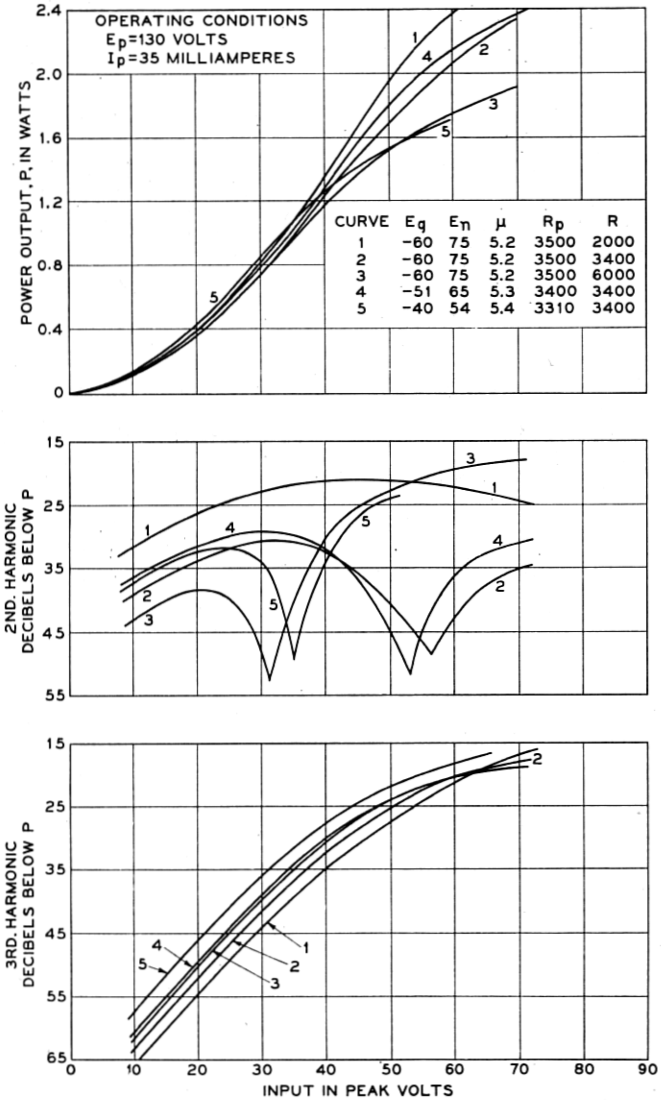

Fig. 20—Co-planar grid tube.

Power output, P, in watts, second and third harmonics in db below the fundamental, as functions of peak input when a sinusoidal voltage is applied to the control grid.

those for the power pentode shown in Fig. 12. For the co-planar-grid tube, as for the pentode, the third harmonic is comparatively high and increases with the load resistance, while the second harmonic curves exhibit minima. This is to be expected from the form of the dynamic characteristic which is very similar to that of similar curves for the pentode previously discussed. For example, consider the curves marked 2 in Fig. 20, obtained with $E_p = 130$ volts, $E_n = 75$ volts and $E_g = -60$ volts. The output power under these conditions, with an input of 50 peak volts, is 1.68 watts with the second and third harmonics 40 db and 25 db, respectively, below the fundamental. At an input of 30 peak volts, the level of the second harmonic rises to 29 db and that of the third harmonic falls to 41 db below that of the fundamental.

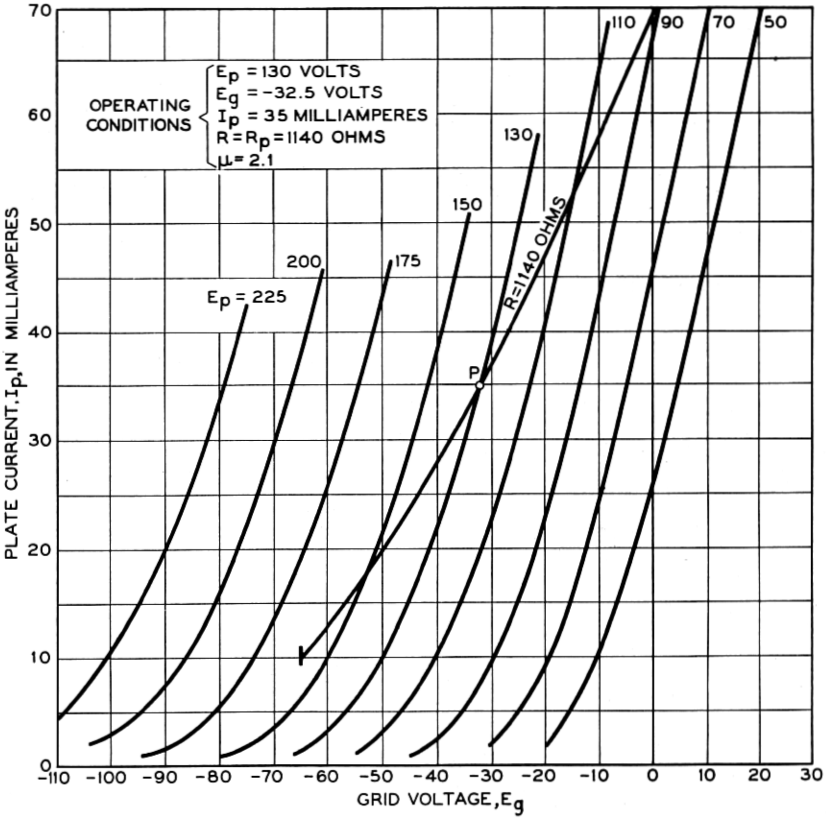

Fig. 21—Plate current-grid voltage characteristics of a triode with a dynamic characteristic shown for a resistance load, $R = R_p = 1140$ ohms.

It is of interest to compare the characteristics of this co-planar-grid tube with those of a three-electrode tube designed also to operate at a plate potential of 130 volts and at a plate current of 35 milliamperes. The plate current-grid voltage characteristics of such a triode are shown in Fig. 21. The dynamic characteristic is for a load resistance of 1140 ohms which matches the plate resistance of the tube at the operating point *P*. At zero grid bias on the dynamic characteristic, the plate potential is 92 volts, a drop of only 38 volts from the operating potential of 130 volts. In the co-planar-grid tube the dynamic characteristic cuts the axis of zero grid bias at a plate potential of 27 volts, a drop of 103 volts from the operating plate potential. The larger plate-voltage variation in the co-planar-grid tube results in higher efficiency than in the triode. The reasons for this difference are identical with those previously discussed in the case of the power pentode.

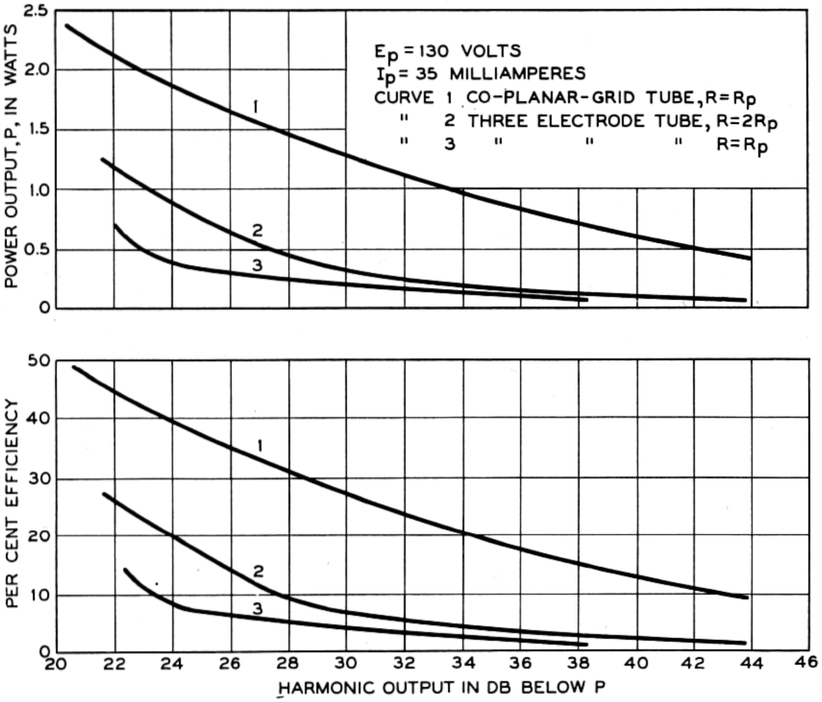

Fig. 22—Curves showing the output power and plate efficiency of a triode and a co-planar-grid tube with varying effective values of second and third harmonics expressed in db below the fundamental.

In Fig. 22, curves are shown comparing the power output and plate-circuit efficiency of the triode and co-planar-grid tube at varying harmonic levels expressed in db below the fundamental. Curves are shown for the triode with the load resistance, R, equal to the plate resistance, R_p, and also with $R = 2R_p$. In both tubes the plate voltage is maintained at 130 volts, and the plate current at 35 milliamperes.

With the harmonics 26 db below the fundamental (5 per cent) and with $R = 2R_p$, the output from the triode is 0.65 watt. At the same harmonic level the output from the co-planar-grid tube is 1.65 watts with a resistance load matching its plate resistance. The efficiencies are 14 per cent and 35 per cent respectively.

The most significant differences between the co-planar-grid tube and the power pentode are as follows: (1) The former has a much lower plate resistance which simplifies coupling the tube to its output circuit and is particularly advantageous in applications where it is desirable to operate the tube into an impedance matching its plate resistance. (2) The pentode yields higher amplification and, consequently, requires a correspondingly smaller input voltage to drive it. (3) The plate-circuit efficiency is not greatly different except at low plate voltages where the co-planar-grid tube is somewhat more efficient.

It should be borne in mind in considering the efficiency of output power tubes used at audio frequencies, that the usual criterion of available power is the harmonic content. As has been shown, fundamental physical factors tend to make the harmonics, particularly the odd harmonics, relatively high in pentodes and co-planar-grid tubes. On the other hand, the recent trend in the design of triodes has been toward tubes of very low plate resistance, which operate into comparatively large load resistances. This tends to decrease the harmonics on the one hand and increase the efficiency on the other. The net result has been that triodes of more recent design, particularly those operating at 250 volts or higher, are not far below the pentode or co-planar-grid tube in efficiency.