Pentode and Tetrode Output Valves*

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SUMMARY.—An attempt has been made, by investigating the static and dynamic characteristics of screen-grid valves, to lay down the requirements that the static characteristic of such a valve must fulfil, in order to ensure a minimum of distortion in the output under all circumstances.

To meet these requirements it is necessary to suppress secondary emission and to make the deflection of the electron paths in the grids as small as possible. The passage of secondary electrons between two electrodes is subjected to closer examination, an enquiry being made into the possibility of preventing this passage of electrons by the use of two methods of suppression: a space charge and a suppressor grid. The optimum effect is obtained by the co-operation of both these expedients, the more potent of the two being the suppressor grid. By judicially planning the geometrical positions of the electrodes, deflection of the electron paths can be reduced to small magnitudes.

§ 1. External Load Circuit

IN determining the requirements, which should be fulfilled by the characteristics of screen-grid output valves in order to avoid distortion as much as possible, we must first consider the load circuit into which the valve is to deliver its energy.

It is usual to draw a straight line in a set of anode current/anode voltage characteristics, to represent the load where the valve delivers its energy to a resistance (line a in Fig. 1), in order to indicate how the anode current and voltage vary when an A.C. voltage is applied to the control grid. The slope of this line is a measure of the resistance used. This resistance is generally given such a value that, at full swing of the valve, the energy absorbed in the resistance is a maximum. The corresponding line for a given screen-grid output valve is generally one that passes approximately through the bend of the particular anode current/anode voltage curve which applies when the control grid voltage is nil. This resistance is approximately $R_a = \frac{V_a}{I_a}$, where V_a and I_a are the D.C. anode voltage and D.C. anode current respectively. Sometimes, for instance with tetrodes, a smaller resistance may be recommended, giving less distortion but at a lower efficiency. The loud speaker, to which the output valve is to deliver its energy, is usually connected via a transformer with such a ratio of turns that its input impedance tallies as closely as possible with this optimum resistance value. The impedance of a loud speaker, however, is not constant for all frequencies and even a good one shows very wide variations for

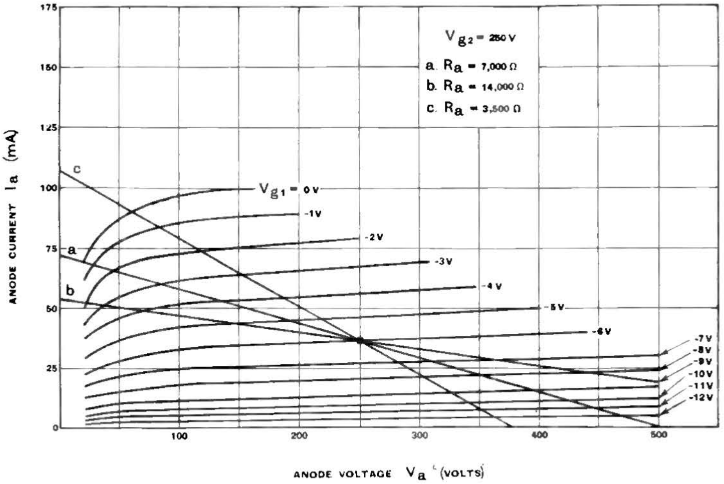

Fig. 1.—I_a — V_a *characteristic, using as parameter the control grid voltage* (V_{g1}). *Line a gives the dynamic characteristic in the case of a resistance load (resistance line) at maximum output. The resistance lines b and c apply respectively for large and small resistance values.*

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the different frequencies in the audible range; this is plainly shown by the curve a for such a loud speaker as given in Fig. 2(a). For higher frequencies the impedance increases considerably. The primary of the transformer is often shunted by a condenser, thus diminishing the impedance and hence also the sensitivity to high frequencies (curve a_1 in Fig. 2(a)).

Curves b and b_1 show the corresponding variation of impedance with frequency for a speaker with an additional damping ring which has been inserted to keep the impedance constant over a larger range of frequencies. Even then the impedance may still vary by a factor of about 4. For this reason it will not be sufficient to indicate the load by only one line on the current characteristics. We cannot, therefore, simply have one particular load characteristic extending as far as the sharp bend of the I_a/V_a characteristic at $V_{g1} = 0$ volt, thus giving a wide swing of the anode voltage. Output measurements with one matching resistance, as sometimes given in published data, are therefore incomplete and entail the risk of making too favourable an estimate, because in practice a frequency variation, with an accompanying impedance variation, causes a rapid decline of output for a given distortion. Hence, in order to have a proper criterion for the quality of an output valve, the dependence of distortion upon the value of the load impedance should be taken into account. Considering the phase angle of the load in the anode circuit, the angle may also be seen to be largely dependent upon frequency. In Fig. 2(b) we have plotted, for the same loud speakers as in Fig. 2(a), the phase angle of the loud speaker with a transformer and a condenser connected in parallel, as a function of frequency. On account of the phase shift between voltage and current, the dynamic anode current/anode voltage characteristic for one frequency will not be a straight line but an elliptical figure, covering a certain area of operation. If several frequencies are present at a time, the area covered will consequently be greater. We must therefore investigate what part of the characteristics will be covered and what influence the shape of these characteristics

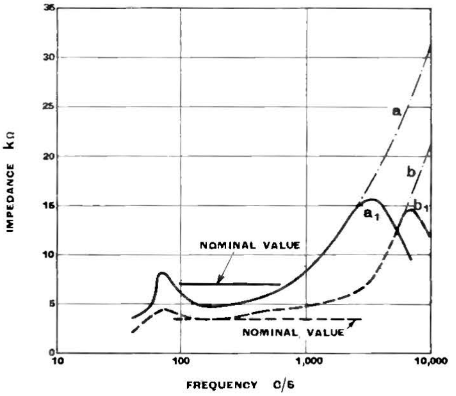


Fig. 2(*a*).—*Impedance characteristic of a loud speaker and its transformer as a function of frequency. a is the curve for a good moving-coil speaker ; a_1 the curve with a condenser of* 2,000 *μμF across the primary of the output transformer ; b and b_1 the curves for a speaker with a special damping ring.*

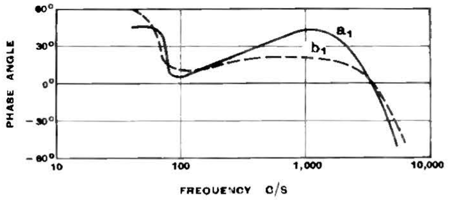


Fig. 2(*b*).—*Phase angle characteristic as a function of frequency for a load comprising the speaker and its transformer and a parallel condenser of* 2,000 *μμF.*

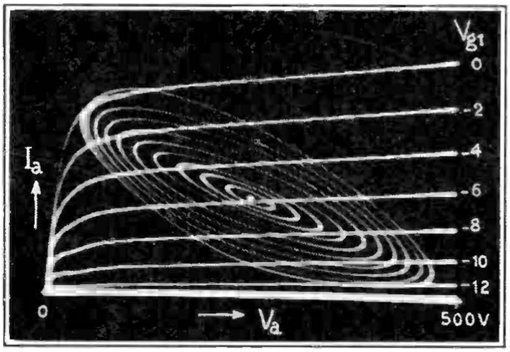
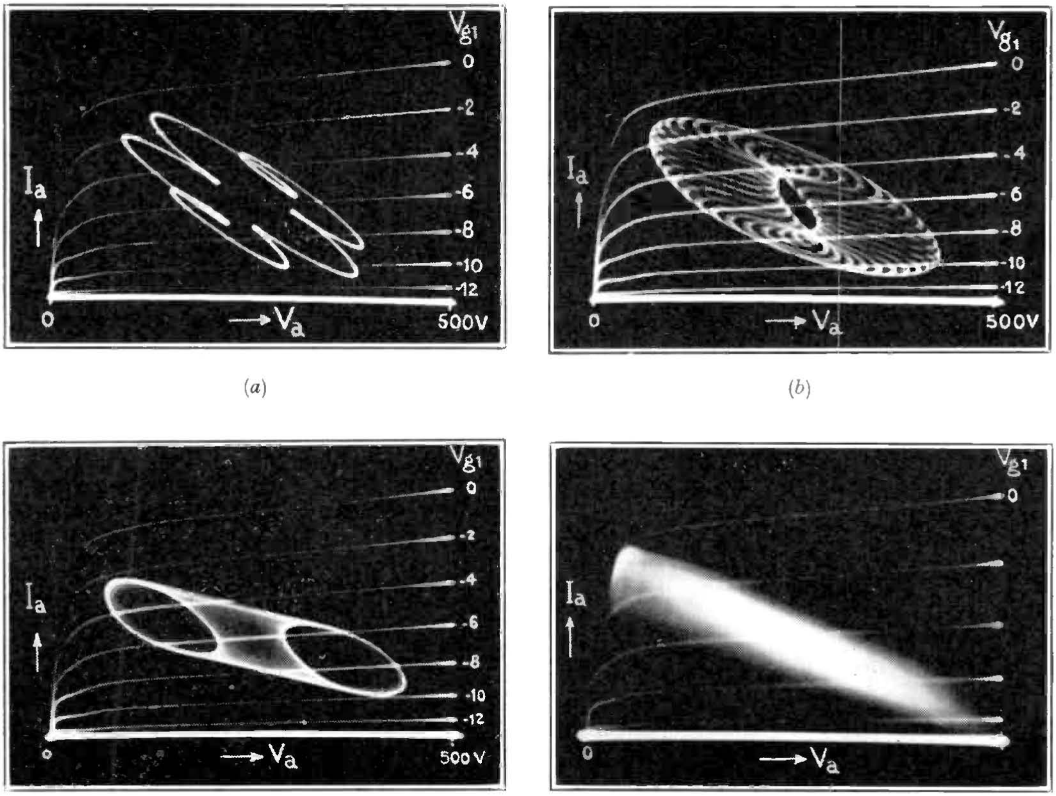


Fig. 3.—*Photograph, taken with the aid of a cathode-ray tube, of dynamic load characteristics for different A.C. grid voltages of a pentode output valve, on the graph of the $I_a - V_a$ characteristics. The elliptical shape of the dynamic curves is caused by the phase shift of the loud speaker. Distortion can be seen as deformation of the pure elliptical shape.*

has upon the distortion of the output and upon the maximum output which the valve can give.

§ 2. Dynamic Characteristics

Fig. 3 gives a photograph, obtained with the aid of a cathode-ray tube, which shows the dynamic load characteristics of a pentode output valve on the graph of the $I_a - V_a$ characteristics. These elliptical figures were obtained with a loud speaker serving as anode load. An A.C. voltage of a given frequency and of increasing amplitude was applied to the control grid of the output valve during operation. It is evident from this figure, in contrast to Fig. 1, that a particularly large area of the $I_a - V_a$ graph is traversed at the higher amplitudes.



(a) (b)

(c) (d)

Fig. 4.—*Photographs taken with the aid of a cathode-ray tube, of dynamic load characteristics on the graph of the $I_a - V_a$ characteristics.* (a) *On the control grid are two A.C. voltages whose frequencies differ by a factor* 6. (b) *Ditto, with frequencies differing by a factor* 30. (c) *Same as* (b), *but with phase-shift equal to nil at the highest frequency.* (d) *A music signal has been operating on the control grid for some time, so that on the photograph it can be seen how very wide is the region traversed by the dynamic characteristics. This considerable width does not show up to full advantage in the photograph owing to predominance of the small amplitudes.*

In practice, however, there is not only the one frequency present, but a complex wave form, containing a large number of frequencies simultaneously. In order to find out how far the swept area is influenced by such a complex waveform, we have given in Fig. 4 (a), (b), (c) and (d) by way of illustration four photographs of figures which are produced on the cathode-ray tube, when two A.C. voltages of different frequencies are simultaneously applied to the control grid. Fig. 4(a) was obtained with two voltages differing in frequency by a factor 6. On account of the fact that the loud speaker causes a phase-shift for both frequencies, the resulting dynamic figure is very broad and covers a large area. This is still more plainly shown by Fig 4(b), corresponding to a similar case in which the frequencies differed by a factor 30. As can be seen from Fig. 2(b), the phase-shift for a speaker transformer, which is shunted by a condenser, may become nil at a certain frequency. Fig. 4(c) gives the dynamic load characteristic for a case in which two voltages having different frequencies are simultaneously applied to the control grid, and in which no phase-shift is caused by the loud speaker for the higher of the two. Here, again, the figure clearly shows how the widening is brought about by joining together the straight lines and elliptical figures. In practice the voltage across the loud speaker during the reproduction of music will be made up of a large number of simultaneous voltages of differing frequencies which, at any considerable intensity, cover a large portion of the field of the $I_a - V_a$ curves as shown in Fig. 4(d). This photograph is the result of a long exposure during which music and speech signals had been applied to the control grid of the valve.

What can be learnt from these curves? It is obvious that, when designing a screen-grid output valve and judging its performance, we must consider almost the entire area of the $I_a - V_a$ characteristics. It is reasonable to assume, however, that the portion of the graph for low anode current and low anode voltage is hardly ever used. We will revert to this later on. Fig. 3 shows that for very small amplitudes the dynamic characteristic is an ellipse, whereas at larger amplitudes a certain deforma-tion of this figure is noticeable.

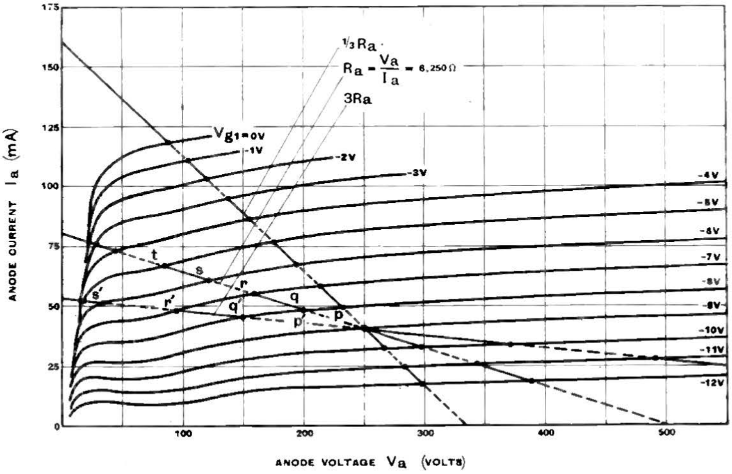


Fig. 5.—*$I_a - V_a$ characteristics for a "beam tetrode," using the control grid voltage as parameter. For normal load resistance* $\frac{V_a}{I_a} = R_a$, *$p = q = r = s = t$; hence litte distortion. For $3R_a$, p' and $r' \gg q'$ and s'; this means distortion.*

We can investigate thereasons for this with the aid of the $I_a - V_a$ characteristics. If these curves in the observed area were parallel straight lines which were equidistant for equal increments of the negative grid bias, no deformation of the ellipse would occur until the dynamic curves touched the horizontal or the vertical axis. It is, however, not possible to achieve characteristics of this form, for the simple reason that the relation between the anode current and the voltage of the control grid follows a 3/2 power law, so that the lines can never be equidistant.

Nevertheless, it will be a desirable characteristic from the point of view of distortion, if the $I_a - V_a$ curves are made as equidistant as possible; in other words, the $I_a - V_{g1}$ curve should be as straight as possible and show *as sharp a bottom bend as possible* (absence of "tail.") When using two valves in push-pull it is sometimes recommended that the $I_a - V_{g1}$ curve be a quadratic one, thus making the bottom bend less sharp, as the push-pull operation can then be used to neutralise the quadratic component of the distortion caused by the bottom bend. Such a valve could not be used alone, as it would give too much distortion, chiefly quadratic.

In order to judge distortion in the case of radio apparatus covering a bandwidth of 8 kilocycles, we must attribute approximately the same nuisance value to the 2nd and 3rd harmonics (see article on this subject by Ir. Heins van der Ven accepted for future publication in this journal).

If, for large anode currents, the valve has a low internal resistance, the $I_a - V_a$ curves will no longer run parallel but will show a fanlike distribution, as the internal resistance is, e.g. dependent upon the anode current. As this may cause distortion, it is desirable to have a *high internal resistance* (with respect to the loud speaker impedance). The variation of the internal resistance has then practically no influence. Should a low internal resistance be desired in certain cases, it will be better to obtain it by means of an inverse back-coupling.

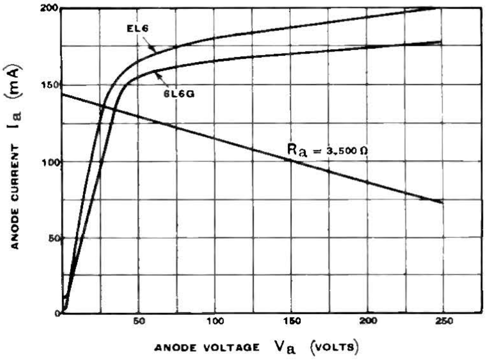


Fig. 6 (*a*).—*Anode current-anode voltage characteristics for a tetrode and for a pentode, with zero control grid voltage. Secondary emission in both valves is completely suppressed.*

Moreover, we wish to see straight lines for these $I_a - V_a$ characteristics. To achieve this result we must of course *completely suppress secondary emission in the region used*[1]*, as it may cause very great deviations. This point is all the more important because secondary emission may sometimes cause a deviation in the middle of the characteristic, so that deformation of the dynamic curve and hence distortion may occur even at low amplitudes. This is particularly the case if the $I_a - V_a$ curve, when distorted by secondary emission, is intersected by the dynamic curve at a small angle, i.e. when the load resistance is high.

We have drawn in Fig. 5 a set of $I_a - V_a$ curves for a beam tetrode, inserting the resistance lines for normal load R_a, for 1/3 R_a and for 3 R_a.

The various $I_a - V_a$ curves, plotted at a negative control grid voltage ascending by 1 volt for each curve, cut the resistance line into sections. No distortion occurs when these sections are equal.

It will be seen clearly that the normal R_a meets this requirement fairly well, the cut-off sections being $p = q = r = s = t$. For 3 R_a, however, p' and r' are greater than q' and s'. This represents distortion due to residual secondary emission.

With a smaller load resistance (1/3 R_a) there is less trouble in this respect.

In the tetrode it is practically impossible to suppress secondary emission over the whole region used. We can, however, achieve this in the pentode, as has been done in some of the newer types. Figs. 6 (a) and 6 (b) give an illustration of this. For low control grid voltage and consequently high anode currents (Fig. 6a), secondary emission in both valves has been completely suppressed. For high control grid voltage and low anode currents (Fig. 6b), secondary emission in the tetrode causes deflection of the characteristic up to much higher anode voltages.

In Fig. 7 the efficiency of a good pentode and tetrode has been plotted for different anode impedances, at constant phase angle with cos $\phi = 0.7$ and 5 per cent. distortion. The pentode gives a much better characteristic.

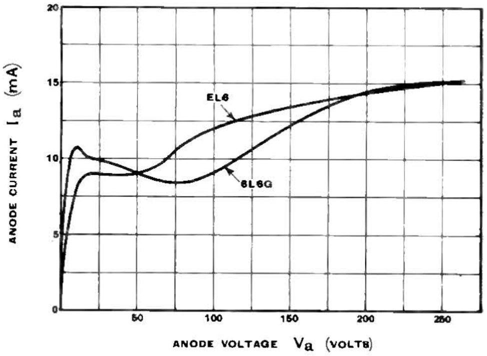


Fig. 6 (*b*).—*Ditto for the same valves with a control grid voltage, so that at* $V_a = 250$ *volts* I_a *is* 15 *mA. Secondary emission has been suppressed in the pentode at a much lower anode voltage.*

Audition tests have shown that the more suddenly the deflections in the dynamic curves take place, the more disturbing they

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* A bibliography will be published at the end of the concluding instalment.

are to the ear, owing to the occurrence of harmonics of a higher order. The sudden nature of the deflection as a result of positive control grid current is therefore the cause of this particularly annoying distortion. So we must do something to prevent it. The $I_a - V_{g1}$ characteristic should therefore cover a sufficiently wide field, so that the maximum output is not limited *by distortion due to control grid current* producing numerous higher harmonics, but only by the less troublesome distortion due to gradual curvature of the characteristic. Overloads will not then have such a disagreeable effect.

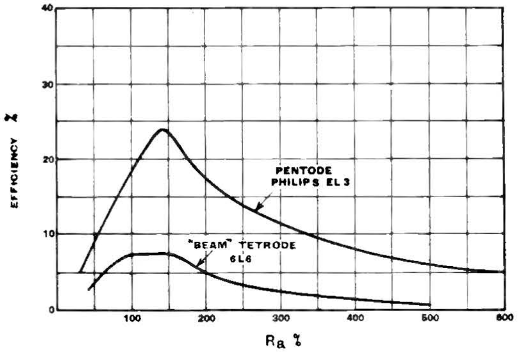

Fig. 7.—*Efficiency characteristic of a good pentode and of a beam tetrode, as a function of the load impedance for cos* $\phi = 0.7$ *and 5 per cent. distortion. The pentode gives a far more favourable curve.*

$R_a = 100\% =$ *Normal load impedance* $= V_a/I_a$.

At higher alternating voltage amplitudes in the anode circuit, the ultimate value of the output energy will in this case be limited by a compression, as it were, of the dynamic curves above and below. It is therefore essential to shift this limitation to as remote a position as possible. Moreover, the distortion caused by this compression of the dynamic curves must be reduced to a minimum. The lower side is limited, as we have seen, by the bottom bend of the $I_a = V_{g1}$ characteristic. The upper side is limited by the $I_a - V_a$ characteristic when the control grid voltage is equal to nil, as the positive control grid current begins at this point. If, by selecting a suitable value for the load impedance, we carry the amplitude a long way forward, it has finally to come as close as possible to the vertical axis.

By providing for a better distribution of current between the anode and screen-grid at low anode voltages we can *make the elbow of the* I_a *-* V_a *curves occur at low anode voltages.* In this respect, too, some of the new type pentodes are far ahead of their predecessors. The maximum efficiency has been increased and secondary emission suppressed over the entire field of operation. In order to achieve this the effect of a suppressor grid and of space charge had to be submitted to close examination, but it was necessary in the first place to learn more about the nature of secondary emission as it occurs in a screen-grid output valve, and the manner in which it is transmitted to another electrode. This will be dealt with in the next section.

§ 3. Secondary Emission

In order to be able to eliminate the unwanted deformation of the characteristic caused by secondary emission in a screen-grid output valve, it was first necessary to investigate the properties of this secondary emission and the manner in which it can be intercepted by another electrode.

(*a*) It is known that metals have a rather high secondary emission, whereas carbon, for instance, has a low secondary emission. Secondary emission is usually measured by the ratio between the total number of secondary electrons emitted and the number of primary electrons by which it was caused, so that $\delta = I_s/I_p$. This δ depends upon the primary voltage of the electrode from which the secondary emission emanates and the angle at which the primary electrons impinge on the electrode. This angle generally is 90°. Measured by this standard, *Ni* gives for δ a value of 1.2 at a primary voltage of 250 volts, *Cu* at this voltage gives 1.1, *Mo* 1.2, whereas a carbon-coated *Ni* plate yields a δ of 0.34[2,3,4,5,8]. It is therefore obviously desirable to use for the anode a material having a low δ, such as in the latter case.

It is a fact, however, that even with carbon or carbon-coated metals the secondary emission is still unduly high and liable to cause serious deviation of the characteristic. Increased secondary emission in a valve may also be caused by volatilising cathode material, for instance on the carbon coating, or by residual traces of gas [6,7,8].

When, as a result of the bombardment of primary electrons, secondary electrons are liberated, the latter will emerge in different directions,[9] [10] [11] and with different velocities.[4] [8] [12] [13]

(*b*) The fact that the mean velocity of the secondary electrons is lower than that of the primary electrons, places in our hands a means of suppressing the influence of secondary emission.

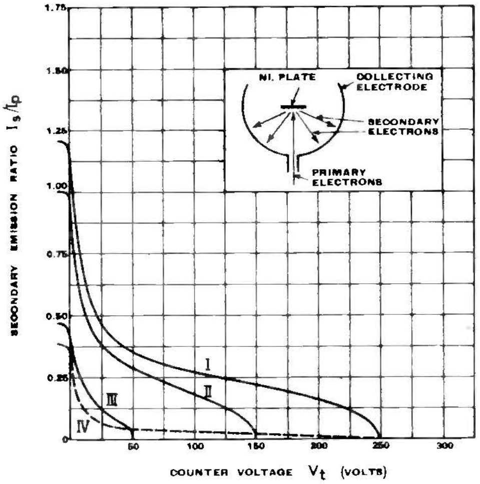

Fig. 8.—*The curves indicate how the ratio of the secondary electron current picked up on the sphere to the primary electron current, varies at different values of the potential difference (counter-voltage)* V_t *between sphere and plate. Curves I, II and III are for nickel, plotted respectively for a voltage of* 250, 150 *and* 50 *volts on the plate. IV gives the same curve for a carbon-coated plate at* 250 *volts. Inset: electrode arrangement for measurement of the ratio:* $\frac{\textit{secondary electron current}}{\textit{primary electron current}}$.

$$V_t = V_{plate} - V_{sphere}.$$

By means of a suppressor grid or a space charge between the anode and screen-grid we can create a region of lower potential which can be penetrated by the primary electrons travelling at a high velocity, but which holds back the secondary electrons travelling at a lower velocity. The depth of this region of minimum potential should therefore be determined on the basis of the velocity distribution of the secondary electrons. This velocity distribution is often measured with the help of a specially constructed valve in which the secondary electrons are picked up on a spherical electrode whose counter-potential with respect to the electrode from which the secondary emission originates can be controlled (see inset Fig. 8). We then obtain, for instance, Curves I, II and III in Fig. 8, which indicate the ratio I_s/I_p of the secondary emission picked up on the sphere, with respect to the primary emission current to a metal plate, for different voltages (250, 150 and 50 volts respectively) on this plate and for different values of the potential difference V_t between the sphere and the plate.

Curve IV gives the ratio I_s/I_p for a carbon-coated plate on 250 V, the secondary emission of which is considerably lower. It can be seen that although these different curves have a similar trend, the number of rapid electrons (" reflected electrons ") in the case of nickel is proportionately smaller the higher the voltage, whilst for carbon the number is always smaller than for nickel.

Though the low-velocity electrons are predominant in number, suppression of these alone would still permit considerable disturbance due to the number of secondary electrons.

For the case indicated by the above curves, the electrons which emerge at a certain velocity have been measured independently of the direction in which they emerge. Although measurements of the distribution of the direction in which the electrons emerge have only occasionally been carried out and whilst our own investigation is not yet completed, it may be taken for granted for a first approximation that the distribution in different directions in the space in which the secondary electrons

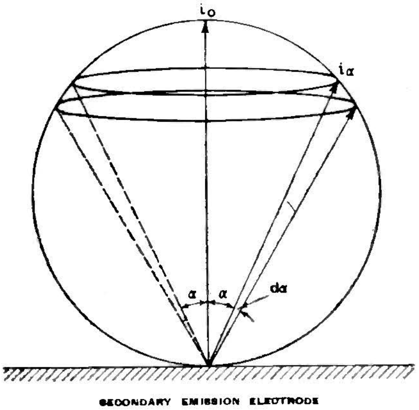

Fig. 9.

emerge is governed by Lambert's law of cosines. Assuming this law to apply, we can infer from it the trend of the curve $I_s/I_p = f(V_t)$ for other electrode arrangements. Whether a secondary electron will or will not arrive at the screen-grid is determined by the component of the velocity in the direction of the screen-grid. If secondary electrons are emerging in all directions, the mean velocity perpendicular to the screen-grid in the parallel electrode example will be lower than that shown by Fig. 8.

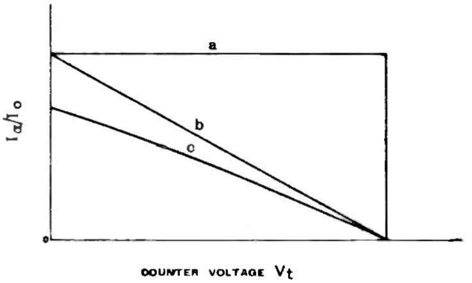

Fig. 10.—*Curve a gives the characteristic of the ratio* $\frac{\textit{secondary electron current}}{\textit{primary electron current}}$ *for the spherical electrode arrangement, as a function of the counter-voltage, on the assumption that all the secondary electrons have the same velocity v. Curve b, ditto for the parallel electrode example, and Curve c for a cylindrical arrangement as used in practice.*

If we imagine the spherical pick-up electrode to be replaced, for instance, by a flat electrode parallel to the electrode which is being bombarded, conditions will agree more closely with the state of affairs in a screen-grid valve with a flat electrode arrangement. Now an electron emerging at a certain velocity v corresponding to a voltage V_0, at an angle α with the normal, cannot reach the opposite electrode unless its velocity is so great that the counter-voltage V_t can be overcome. This counter-voltage V_t must be equal to or less than $V_0 \cos^2 \alpha$ [14]. Lambert's law of cosines indicates, for a given quantity of emerging electrons, the spatial distribution of electrons emerging at different angles with the normal ($i\alpha = i_0 \cos \alpha$). In that case the total emergent secondary emission current, I_0, is equal to πi_0. We will assume that a certain portion of this, the current I_a, emerges at a smaller angle than α and can just reach the anode. This current, in the space above the secondary emission cathode, is limited by a spatial angle ω equal to an inverted cone with apical angle 2α (Fig. 9). Now $i_a d\omega = 2\pi i_a \sin \alpha d\alpha$, so that there is present in the cone a current

$$I_a = I_0 \int_0^\alpha 2 \sin \alpha \cos \alpha \, d\alpha = I_0 \sin^2 \alpha,$$

from which we find:

$$\frac{I_a}{I_0} + \frac{V_t}{V_0} = 1$$

If there were only secondary emission electrons of one velocity v, a spherical arrangement of the pick-up electrode would thus give us line *a* in Fig. 10. From a certain voltage onward, all the electrons can in this case reach the sphere. For flat arrangements of the electrodes, the above relation gives us line *b*. It will now be obvious that, for an arrangement consisting of concentric cylindrical electrodes, this line will sag and so intersect the vertical axis at a lower position (line *c*). We know, however, that electrons of different emergent velocities will occur in practical cases.

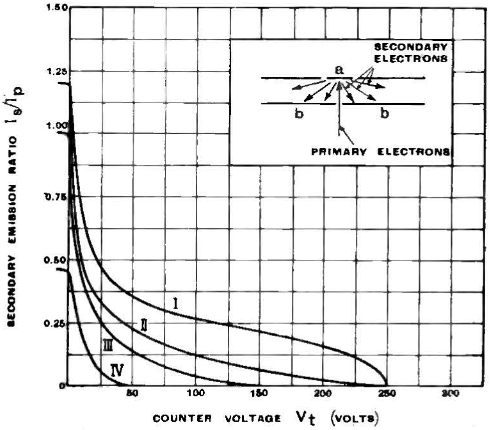

Fig. 11 (*a*).—*Curves II, III and IV give the characteristic of the ratio* $\frac{\textit{secondary electron current}}{\textit{primary electron current}}$ *as a function of the counter-voltage for a flat parallel arrangement of the Ni plate a and the pick-up electrode b, with a voltage on the plate of* 250, 150 *and* 50 *volts respectively. For the sake of comparison, Curve I is inserted for* 250 *volts and a spherical arrangement. Inset: drawing of the electrode arrangement.*

$$V_t = V_{plate\ a} - V_{collecting\ electrode\ b}.$$

Figs. 11 (a) and 11 (b) show how the counter-voltage curves appear in the parallel electrode example, for a nickel plate and for a carbon-coated plate. These curves are obtained graphically from the curves for the spherical arrangement using Lambert's law of cosines. By way of comparison we have inserted in each figure the curve for a primary voltage of 250 volts as given by the spherical pick-up electrode.

Now what conclusions can we draw from this and what conditions will a counter-voltage formed by a suppressor grid or space charge in a screen-grid output valve be required to fulfil?

(1) Although the secondary emission characteristics of carbon may, for instance, be greatly modified by residual traces of gas or by volatilising cathode material, it is a well-known fact that the choice of anode material plays an important part.

(2) The passage of secondary electrons may also be influenced by the geometrical form of the electrodes (e.g. flat or spherical arrangement), which in turn affects the dimensioning of the suppressor grid or space charge.

(3) The screen-grid output valve cannot be rendered entirely free from secondary or reflected electrons. It is not possible to state in general terms, how much secondary emission is permissible for a given valve at every anode voltage and current, because on the one hand the quality standards of different valves show a wide limit of diversity, and on the other hand the disturbing effect due to secondary emission is manifested differently at different voltages and currents. We shall revert to this question later on. If, however, by way of example, we were prepared to permit the same percentage of secondary electrons with respect to the primary electrons, for a constant current and a variable voltage in all cases, it will be seen from Figs. 11 (a) and 11 (b) that although a fall of the anode voltage will result in a fall of the counter-voltage, the ratio of the counter-voltage to the anode voltage is bound to increase, because at lower anode voltages the proportion of the number of secondary electrons with high velocities increases. It is also evident that the value of 10 to 20 volts which is often stated[15 16] as being the required value for the counter-voltage, will be quite insufficient to nullify the effect of secondary emission under all circumstances.

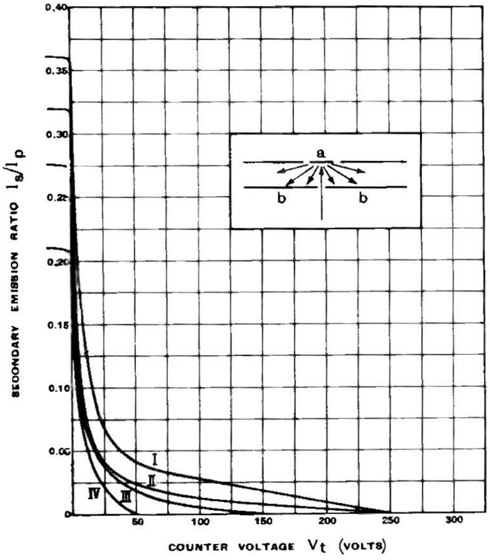

Fig. 11 (*b*).—*Same as* 11*a, but for a carbon-coated Ni plate a. For the sake of comparison, Curve I is inserted for* 250 *volts and a spherical arrangement.*

$$V_t = V_{plate\ a} - V_{collecting\ electrode\ b.}$$

In a screen-grid output valve, in which means for suppression of secondary emission are included, the counter-voltage will therefore acquire much greater values than 10-20 V, for instance, at a higher anode voltage. We will make a close examination of these means of suppression.

The two expedients, already mentioned, are generally adopted in practice for the suppression of secondary emission in screen-grid valves, viz., a suppressor grid and a space charge. We will now investigate the nature of these two expedients and examine how, in connection with the above, they will suppress secondary emission. Both expedients are already described in the original pentode patent[1]. The suppressor grid was adopted first and is still in use, because, as we shall see later, it possesses valuable properties. The space charge, too, has been employed in beam power output valves [15], the space charge being used in combination with the electrostatic effect of "beam plates," which, in a similar manner to the suppressor grid, create a minimum of electrostatic potential and thus supplement the action of the space charge. Space charge has, moreover, been turned to account in improved new type pentodes. We will now investigate what counter-voltage the space charge can cause for the purpose of suppressing secondary emission.

§ 4. Space Charge

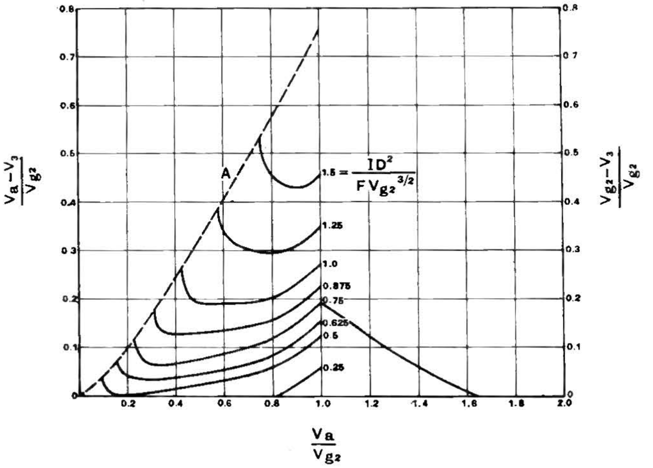

Fig. 12.—*Characteristic of the counter-voltage, due to space charge, between the screen-grid and anode in a tetrode, as a function of the anode voltage. The counter-voltage is the difference between the voltage on the electrode whose potential is lowest, and the lowest potential* V_3 *in the space. The parameter is* $\frac{ID^2}{FV_{g2}^{3/2}}$ *which, for a specific case with constant D, F and* V_{g2}, *is equal to the current passing between the screen-grid and the anode.*

Using Poisson's equation $\frac{d^2V}{dx^2} = 4\pi\rho$ for an ideal tetrode, Calpine and others[17] [18] [19] [20] [21] [22] investigated the potential minimum which is created by a space charge between the anode and screen-grid. It was assumed that the current I emerges as a beam of uniform density from the screen-grid into the space between the screen-grid and anode, the electron velocities in the direction of the anode being equal. The screen-grid and anode are situated in parallel planes. The following relation is then obtained between the voltages at the screen-grid (V_{g2}), at the anode (V_a) and at the point of minimum potential (V_3)[18]:

$$\frac{ID^2}{FV_{g2}^{3/2}} = K\left[\sqrt{1 + 3\left(\frac{V_3}{V_{g2}}\right)^{1/2} - 4\left(\frac{V_3}{V_{g2}}\right)^{3/2}} + \sqrt{\left(\frac{V_a}{V_{g2}}\right)^{3/2} + 3\left(\frac{V_3}{V_{g2}}\right)^{1/2}\frac{V_a}{V_{g2}} - 4\left(\frac{V_3}{V_{g2}}\right)^{3/2}}\right]^2$$

where F is the area of cross-section of the beam, D the distance between the anode and screen-grid, K a constant and equal to $\frac{1}{9\pi}\sqrt{\frac{2e}{m}}$. For the suppression of secondary emission it is important to examine the characteristic curve corresponding to the difference between the anode voltage and the voltage at the potential minimum, as this difference constitutes the counter-voltage by means of which secondary emission is to be repelled. Having inserted numerical values in the above formula, we plotted a graphical representation of this difference $V_a - V_3$ for various anode voltages and currents, as we wished to know the value of this counter-voltage for all points on the anode voltage/anode current characteristic.

The resulting graph is shown in Fig. 12, in which the characteristic for $\frac{V_a - V_3}{V_{g2}}$ has been plotted as a function of $\frac{V_a}{V_{g2}}$ at various values of $\frac{ID^2}{FV_{g2}^{3/2}}$.

These curves are bounded on the left by line A, which indicates the limit of the gradual trend of V_3; as $\frac{V_a}{V_{g2}}$ decreases, the potential minimum suddenly acquires zero value and electrons return to the screen-grid. Such a point is described as a virtual cathode. On the right, all the lines but one are interrupted at a point $\frac{V_a}{V_{g2}} = 1$. The region $\frac{V_a}{V_{g2}} < 1$ is in fact the most important, because the secondary emission of the anode—which draws far more current—will be many times greater than that of the screen-grid and hence be more likely to cause disturbing effects. To illustrate the trend of space charge in the region $\frac{V_a}{V_{g2}} > 1$, we have extended one of the curves. We shall thus concern ourselves chiefly with the region in which $\frac{V_a}{V_{g2}}$ lies between 0 and 1.

From the above figure a number of general conclusions might be drawn concerning the application of this counter-voltage $V_a - V_3$ in the screen-grid output valve, bearing in mind, however, that the above curves refer to an ideal case. In practice a slight deviation may occur as a result of the space charge of the secondary electrons. The fact that this deviation is rather small, will be explained next.

We suppose the anode emits an infinite number of secondary electrons which have a velocity so high that they are repelled exactly before the potential minimum and return to the anode. This minimum will then be situated very close to the anode.

The primary electron current I_2 which is necessary to form this potential minimum may be calculated and compared with the primary current I_1 which forms this potential minimum in the absence of secondary emission. In practice the value of the primary current will be between I_1 and I_2. As the secondary emission ratio of the usually carbon-coated anode is low, the practical value lies near I_1. If $V_{g2} = 250$ V, $V_a = 50$ V; $V_3 = 40$ V and the distance anode-screen-grid is 5 mm, $I_1 = 47.4$ mA/cm² and $I_2 = 33.3$ mA/cm². Besides that, the velocity components of the electrons in the beam in the direction of the anode have different values, mainly due to deflection occurring at the screen-grid. If this velocity component is small, the electrons will remain for a longer period in the space between the screen-grid and anode and will thus intensify the space charge. However, as long as no electrons are returning, the potential characteristic will not deviate greatly on this account, and the general trend will be maintained. On the other hand, the point at which electrons return and a virtual cathode is formed, will necessarily undergo a deviation, since electrons of lower velocity return first. Fig. 12 shows that even at a low value of the quotient $\frac{ID^2}{FV_{g2}^{3/2}}$, the potential characteristic for the case $\frac{V_a}{V_{g2}} < 1$ sags, as it were, and the counter-voltage (exactly: counter voltage proportion) $\frac{V_a - V_3}{V_{g2}}$ then has a positive value; for higher or lower values of this ratio $\frac{V_a}{V_{g2}}$, the counter-voltage may rapidly decrease to nil. At very low values of $\frac{V_a}{V_{g2}}$ and higher values of the quotient $\frac{ID^2}{FV_{g2}^{3/2}}$ the virtual cathode can be formed and the screen-grid current rapidly increases at the expense of the anode current. Before this happens the counter-voltage has acquired a minimum value and may even vanish. The potential curves have been plotted in Fig. 13 for different anode voltages and we can clearly follow the course of the sag (counter-voltage). This minimum value is most critical at the point at which the passage of secondary electrons to the screen-grid will occur first, and the position of this point differs considerably from the point at which, in a normal tetrode with little space charge, the characteristic shows the maximum deviation due to secondary emission, viz. at $V_{g2} = V_a$. We can best illustrate this by a set of curves (Fig. 14) plotted for a special valve. The electrode structure is shown diagrammatically in the inset. Only the current flowing to one small anode was measured, thereby avoiding "side effects" which may be caused when secondary

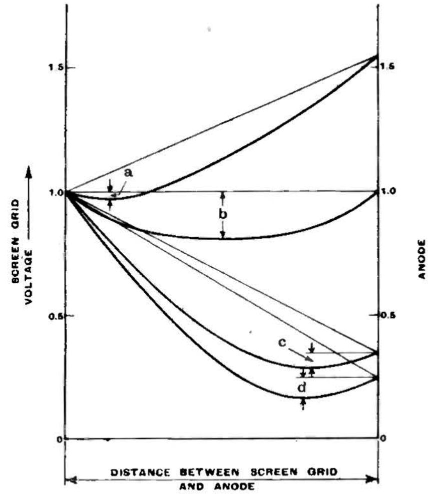

Fig. 13.—*Characteristic of potential between screen-grid and anode for a flat electrode arrangement, at different voltages, in a case where* $\frac{ID^2}{FV_{g2}^{3/2}} = 0.75$. *The dip in the potential characteristic is due to space charge.*

electrons emerging obliquely along the sides of the electron beam succeed in reaching the screen-grid. The current was controlled by varying the negative potential on the 1st grid. From the occurrence of secondary emission, indicated by the dip in the anode current characteristic, we can follow the course of the counter-voltage caused by sagging of the potential characteristic. With increase of current, secondary emission will only become possible in the region of low anode voltages, where it will finally vanish also when the minimum value of the counter-voltage is sufficient (curve for $V_{g1} = -6$ volts). On further increase of current the characteristic shows a rounding-off at lower anode voltages, and the elbow at which the electrons return to the screen-grid is shifted to higher voltages.

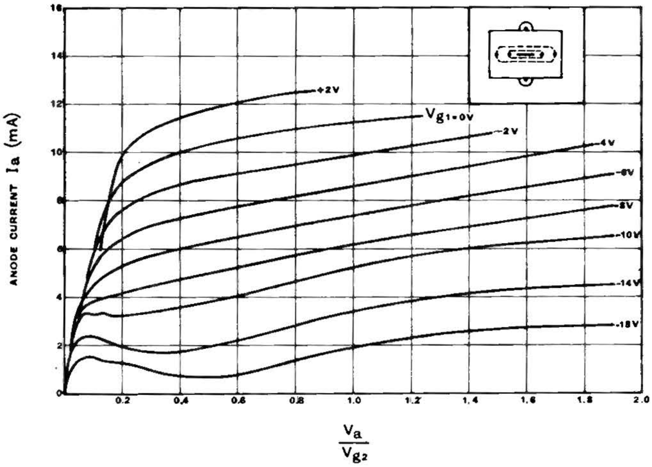

Fig. 14.—I_a — V_a *characteristics of a tetrode of special construction. At a negative control grid voltage of 6 volts, the counter-voltage due to space charge is practically sufficient to suppress secondary emission. In the curves for a higher control grid voltage and hence for a lower current, secondary emission is manifested at increasingly high values of the anode voltage. Inset: drawing of the electrode arrangement.*

How can these considerations be utilised in practice? In the design of a tetrode output valve, the V_{g2} and V_a and the maximum value of I_a are pre-determined. According to the material selected for the anode and the corresponding counter-potential necessary for the suppression of secondary emission, we assign to $\frac{D^2}{F}$ a value that will yield a sufficient counter-voltage over the entire graph. And although the square of the distance appears in this ratio, it is not altogether correct to speak of a "critical distance" as is sometimes done[23], since other factors such as current, voltage and current density might equally well be termed critical factors. For an output valve it is not sufficient, as we have already seen (§ 2), to ensure that one of the anode current characteristics (e.g. the Fig. 14 curve for $V_{g1} = -6$ volts) is undeformed by secondary emission. It can be seen from Figs. 12 and 14 that even a small drop in current may again precipitate this unwanted phenomenon. If we wish the secondary emission to be eliminated over a large part of the anode current/anode voltage characteristics, we must ensure a sufficient counter-voltage for curves with a much lower current value than I_{max}. The drawback remains, however, that secondary emission is not suppressed for very small currents. On the other hand, if we do obtain a sufficient counter-voltage with small currents, the drawback is that with larger currents the virtual cathode is formed at increasingly high anode voltages. The elbow of the characteristic then shifts to the right in the figure and the maximum output drops. In practice we must therefore accept a compromise. Another practical difficulty is that in most valves the current density on either side of the cathode is not exactly the same, owing to slight differences which are always inherent in the structure of the electrodes. It sometimes happens that one of the two halves carries twice as much current as the other half.

In the type of valve known as the "beam tetrode" an attempt has been made to overcome all these difficulties by the use of "beam plates" which intercept the secondary electrons circulating around the beam when the current has a high density and the potential characteristic shows a pronounced sag,[15] [16], whereas in the case of small currents and high anode voltages the beam plates create a minimum of electrostatic potential, thus acting in a similar manner to a suppressor grid. The beam plates thus being a kind of suppressor grid with a high pitch, their action at different points in the electron beam is very unequal and hence this expedient does not effectively do away with the above drawbacks. The name "beam plates" is misleading, as it suggests that the plates assist in forming the electron beam. Actually, however, the electron beam in beam tetrodes is governed by the shape of the cathode and grids. The plates would therefore be more appropriately described as "suppressor plates," as their action in restraining the secondary electrons can best be compared with that of a suppressor grid.

Conclusion : Space charge *alone* is not a suitable means of suppressing secondary emission in output tetrodes. Either the secondary emission is insufficiently suppressed, or the elbow of the characteristic is shifted too far towards the higher anode voltages and efficiency thus becomes too low.

A serviceable solution is achieved by the use of additional plates which repel the secondary electrons in a similar manner to the suppressor grid and which also supplement the action of the space charge. The above drawbacks are, however, still present to a certain extent, as the suppressor grid effect is never absolutely complete. An advantage of this construction[15] is that very few electrons can be deflected by these "beam plates" in such a manner that they return to the screen-grid. This used to happen in older type pentodes as a result of less accurate dimensioning of the suppressor grid, thereby creating in the $I_a - V_a$ characteristic an elbow which was too round and which occurred when the anode voltage was too high. We will investigate this in our next Section and see how this trouble has been avoided in the new type pentodes.

(To be concluded.)

Theory and Application of Electron Tubes

By Herbert J. Reich, Ph.D. Pp. 670 and 512 illustrations. Published by McGraw Hill Publishing Co., Aldwych, London, W.C.2. Price 30s.

So many text books on electron tubes have been written during the past few years that a con-considerable amount of overlapping is inevitable. Dr. Reich covers an extremely wide field and most of the applications of electron tubes which he discusses are dealt with in a clear and thorough manner. The first few chapters of his book are, however, a little disappointing, and a more accurate presentation of the fundamental principles could have been given without making the book any longer, if necessary by omitting some of the manufacturing details. The description of the action of the control grid, for example, on pages 30 and 40 is likely to leave the student with a false picture of the mechanism of the control of the space current. Valves of the hexode and heptode type have now been in extensive use for several years, and have already found applications outside the field of radio communication ; but, so far, no adequate analysis of their operation and characteristics has been given in any text book. Dr. Reich ignores them completely. Secondary emission is only briefly referred to, in spite of the author's statement that "the phenomenon of secondary emission is an important one in all types of electron tubes." A more serious omission is, however, the absence of any discussion or quantitative data on the important subject of "noise," either in tubes or in circuits. Chapter 4 deals with the analysis of vacuum tube circuits in a lucid manner which will be easily understood by the student approaching the subject for the first time and forms a sound foundation for the succeeding sections which deal very thoroughly with modulation and detection, amplifiers and oscillators. The chapter on electrical conduction in gases is included as an introduction to a description of Glow- and Arc-Discharge Tubes and their many applications which are dealt with in a manner which indicates a familiarity with the subject based on first-hand knowledge. The well condensed chapter on Light-Sensitive Tubes includes circuits for photometric measurements, and a brief description of the Zworykin type of secondary emission multiplier is given. Rather more than a mere reference might, however, have been made to the multipliers designed by Farnsworth and others. There is a useful chapter on Power Supplies, and the final chapter, which is devoted to Electron Tube Instruments, is an excellent summary of the various applications of electron tubes in this important field.

The subject matter of the book is well arranged (although the subject index would have been better without so many cross-references) and the book should be of considerable value not only to students, but also to a large number of engineers in whose fields of activity thermionic, photoelectric and gas-discharge tubes have become such important tools. The radio engineer, too, will find much useful information, although, as the author remarks, "the design of radio transmitters and receivers, which are adequately treated in books on radio engineering, has not been taken up." The bibliography contains a useful list of references on all the subjects covered ; but it is a pity that so many important papers published outside America have not been mentioned.

G. W. W.