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MODERN RECEIVING VALVES: DESIGN AND MANUFACTURE

BY

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[*Communication from the Research and Engineering Staffs of the M.O. Valve Co., Ltd., at the Works, Hammersmith, and (G.E.C.) Research Laboratories, Wembley, England*]

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SUMMARY

The authors discuss the main features in the geometrical design of the types of valve in common use to-day and the various factors, mechanical and chemical, which impose limitations in manufacture. The minimum tolerances to which it is possible to reproduce characteristics are indicated. The paper includes a brief historical survey of the recent improvements in thermionic emitters and gives details of the precautions necessary in the production of modern highly efficient oxide-coated cathodes and insulated heaters.

Pumping and activation processes are described, and the main factors affecting the life of a valve are discussed. The last section of the paper deals with some of the limitations encountered in the use of valves, such as hum, microphony, noise, and frequency limitation, and the methods of minimizing these factors are given. The authors conclude with some observations on possible future developments.

INTRODUCTION

During the past 10–15 years, the efforts of valve manufacturers have been directed towards increasing the efficiency of receiving valves by the development of special types for specific purposes, and towards the improvement of the characteristics of valves by modifications in the mechanical design, improvements in thermionic cathodes, and a close control of the properties of materials used for electrodes and insulators. A study of the causes and methods of reducing "noise" has also received considerable attention.

The fluctuating demand for valves of different types makes it difficult for the valve manufacturer to plan production in advance over long periods and so to ensure that continuity which is desirable in any mass production. Developments in radio-receiver design are continually calling for new types of valve and for modifications to existing valves, and the manufacturing plant must be sufficiently flexible to allow changes to be effected rapidly. In spite of this, however, the enormous increase in production and improvements in technique during the past 10 years have led to considerable reductions in manufacturing costs with the result that a modern complex valve, such as, for example, a triode hexode with an indirectly heated cathode, is sold at approximately the same price as was a simple triode with a filamentary cathode in 1924.

Until about 1924 the only type of valve in common use was the triode with a filamentary cathode. These valves were designed with high or low amplification factor and impedance according to the particular position in the receiver in which they were required to operate. Provided the cathode was capable of giving sufficient emission, and the grid current, with the grid at a negative potential with respect to the cathode, was not more than a few microamps., the valve was "good." Output valves were in general required to generate only a few milliwatts, sufficient to load a pair of headphones, although it is true that there were some high-priced valves capable of delivering several watts for loud-speaker use. Owing to the limitations inherent in loud-speakers at that time, and to the poor characteristics of intervalve transformers, the amount of distortion introduced by the valve itself was relatively unimportant.

In 1916 Siemens and Halske[*] patented a tetrode valve in which a fourth electrode in the form of a grid or "protective net" was interposed between the control grid and anode, and operated at a fixed positive potential with respect to the cathode. The object of this "protective net" was to prevent the field near the cathode from being influenced by changes in the potential of the anode.

In the Schottky tetrode[†] the fourth electrode did, in fact, provide slight electrostatic screening between anode and control grid, but it was not until after A. W. Hull[‡] had suggested the introduction of a close-mesh screen electrode in order to reduce the feed-back of alternating potentials on the anode to the grid, which resulted in serious interference between output and input circuits at high frequencies, that the screen-grid could be used for high-frequency amplification.

The introduction of a fourth electrode operating at a positive potential introduced secondary-emission difficulties hitherto absent from receiving valves. In 1926, the Philips Lamp Co. of Holland[§] described two methods of suppressing the secondary currents between anode and screen: (*a*) by removing the anode to a sufficient distance from the screen, and (*b*) by the introduction of an open-meshed grid in order to reduce the space potential between screen and anode. This second alternative, the Pentode valve, was used in the first instance only as a low-frequency output valve, but more recently high-frequency pentode valves—differing from output pentodes in the degree of screening between anode and control grid—have been used as high-frequency amplifiers and detectors.

In order to enable the output of a receiver to be adjusted to any desired level without distortion when

[*] See Reference (1).

[†] *Ibid.*, (2).

[‡] *Ibid.*, (3), (4).

[§] *Ibid.*, (5).

receiving strong or weak signals, screen-grid and high-frequency pentode valves having a variable mutual conductance (variable-mu) depending on the control-grid bias were later introduced.* There are several possible methods of obtaining the required characteristic, but the one now universally adopted is to vary the pitch of the control-grid winding or to introduce gaps in the winding so that over a small length of the cathode surface the grid has little effect on the field. The "tail" of the anode-current/grid-voltage characteristic is modified as shown in Fig. 1. The required shape of the variable-mu characteristic depends to some extent on the particular circuit in which the valve is to be used, and in practice a compromise must be effected between high control ratio and the maximum permissible anode current at zero grid bias and the maximum grid bias obtainable in the circuit. These conditions having been decided, the actual design of the grid is a matter of trial and experience.

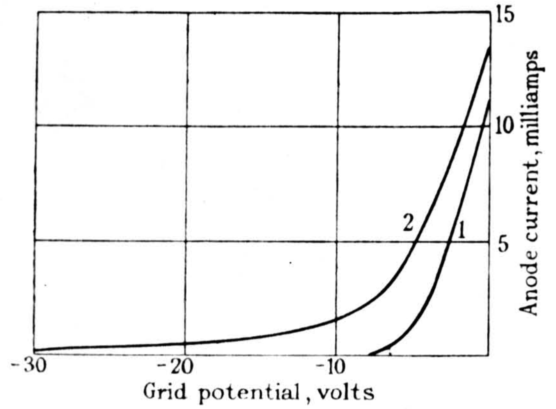

Fig. 1

Curve 1. Grid wound with uniform pitch.
Curve 2. Grid wound with gaps in grid winding.

Diode valves, which were until recently used only as power rectifiers for a.c. mains supply voltages, are now frequently employed as high-frequency detectors and, by a suitable arrangement of circuits, for automatically controlling the grid bias on variable-mu valves so that the output from the receiver can be kept at a substantially constant level. These applications have resulted in the introduction of further types, such as double diodes, double diode triodes, and double diode pentodes.

The rapidly increasing popularity of the super-heterodyne receiver, which is becoming even more extensively employed in short-wave reception, has led to the introduction of improved forms of frequency-changers by means of which it is possible to obtain a much greater conversion conductance and greater stability than was possible in earlier forms of valves. The most recent types include hexodes, heptodes, octodes, and double valves such as triode pentodes and triode hexodes.

It is not within the scope of this paper to describe the many circuits used in conjunction with various types of valves; the authors' object is rather to outline the main features in the design of the valves, and to indicate the limitations met in practice. For this purpose it is necessary to consider the types in more detail.

DIODES

(a) Power Rectifiers

The principal requirements in a power rectifier are a low impedance when the anode is at a positive potential with respect to the cathode, so that the voltage across the rectifier shall be small compared with that across the external circuit, and a high impedance when the voltage is reversed.

If we consider the simple case of a cathode of circular section surrounded by a cylindrical anode, the space-charge-limited anode current is*

$$i = \frac{K l V_a^{\frac{3}{2}}}{a\beta^2} \text{ (approx.)} \quad . \quad . \quad . \quad . \quad (1)$$

where l is the length of the system, and

$$\beta = \log\frac{a}{c} - \frac{2}{5}\left(\log\frac{a}{c}\right)^2 + \frac{11}{120}\left(\log\frac{a}{c}\right)^3 \quad . \quad . \quad (2)$$

a and c being the radii of anode and cathode respectively. V_a is the positive potential of the anode with respect to the cathode, and K is a constant.

It therefore follows that the impedance may be reduced by increasing l or decreasing $a\beta^2$. In directly-heated cathode valves (filamentary cathodes) the cathode length can be made large, and little difficulty is experienced in reducing the voltage-drop across the rectifier. It is, of course, important that, when the filament is in the form of a **V** or **W**, the limbs of the filament shall be sufficiently far apart to act independently of one another. In practice, this means that the distance between limbs shall be at least twice the distance between anode and filament. Directly-heated rectifiers, however, possess the disadvantage that the heating-up time is usually shorter than that of the indirectly heated valves in the set, with the result that the rectifier is open-circuited for a few seconds each time the receiver is switched on, and excessive voltages are developed across condensers. Indirectly-heated rectifiers are therefore necessary in some cases. In indirectly-heated valves, it is difficult to obtain a long cathode, and it is therefore necessary to make the cathode-anode clearance small. There is, however, a limitation (apart from the purely mechanical problem) in the value to which this distance can be reduced, since, as the anode surface is reduced, although the energy of the arriving electrons falls owing to the lower impedance, the temperature rises owing to radiation from the cathode. If the temperature of the anode becomes excessive, it will emit electrons when the anode voltage is reversed, since with oxide-coated cathodes some barium will have been deposited on the anode during activation of the cathode. Apart from the effect of this reverse current on the output of the rectifier, the cathode surface will rapidly be destroyed by bombardment of high-voltage electrons, and the valve become "soft." To keep the temperature of the anode as low as possible, its surface is usually carbonized by a heat treatment in a hydrocarbon atmosphere, thus increasing its thermal emissivity.

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* See Reference (6).

* See Reference (7).

Another method which has been employed to reduce the impedance is to include between the anode and cathode, and close to the cathode, an electrode in the form of a grid which is connected to the anode. In this way the system behaves as a diode with an effective anode diameter slightly greater than that of the grid. Most of the energy is, however, dissipated in the outer electrode, which may now be quite large.

In a recent publication* Aldous has shown that, in a rectifier feeding a resistance load shunted by an infinite capacitance, the following equations express quite accurately the values of the power dissipated in the anode (P), the output voltage (V), and the peak anode current ($I_{max.}$), as functions of the peak input voltage (E) and output current (I).

For a single-phase half-wave circuit,

$$\begin{aligned} P &= 1{\cdot}62\, K^{-\frac{1}{2}} E^{\frac{1}{4}} I^{\frac{3}{2}} \\ E - V &= 1{\cdot}94\, K^{-\frac{1}{2}} E^{\frac{1}{4}} I^{\frac{1}{2}} \\ I_{max.} &= 2{\cdot}71\, K^{\frac{1}{4}} E^{\frac{3}{8}} I^{\frac{3}{4}} \end{aligned}$$

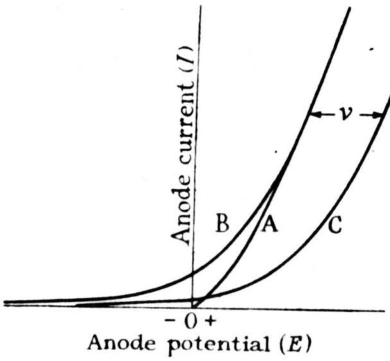

Fig. 2

Curve A. $I = kE^{\frac{3}{2}}$
Curve B. Effect of initial velocities of electrons.
Curve C. Effect of initial velocities and contact potential-difference between anode and cathode.

and, for a biphase half-wave circuit,

$$\begin{aligned} P &= 1{\cdot}14\, K^{-\frac{1}{2}} E^{\frac{1}{4}} I^{\frac{3}{2}} \\ E - V &= 1{\cdot}37\, K^{-\frac{1}{2}} E^{\frac{1}{4}} I^{\frac{1}{2}} \\ I_{max.} &= 1{\cdot}61\, K^{\frac{1}{4}} E^{\frac{3}{8}} I^{\frac{3}{4}} \end{aligned}$$

where K is the rectifier constant in the equation for the static characteristic of the rectifier, $i = KV_a^{\frac{3}{2}}$.

From these equations, the valve designer is able to estimate the cathode emission required and the minimum dimensions of the anode† for a given rectifier.

(b) Detector Diodes

In the approximate expressions given above, the initial velocities of the electrons and the contact potential-difference between cathode and anode were neglected. The effect of taking into account these factors is shown in Fig. 2. Curve A shows the three-halves power-law relationship of equation (1), curve B shows the effect of the initial velocities of electrons, and curve C the further effect of the contact potential-difference ν between cathode and anode. Expressions have been derived by Schottky,* Fry,† and Langmuir‡ for curve C, but these need not be considered here. It will be apparent that the value of ν is important in determining the characteristic of a detector diode which operates at very low values of anode potential. A change in the nature of the surface of the anode, an alteration in treatment of the cathode during pumping and activation, or the presence of gas, will affect the degree of contamination of the surface of the anode, and may change its contact potential by as much as 2 volts. A close control of all these factors is necessary to ensure reproducible results and stability during operation.

TRIODES

It is not possible to calculate with any great accuracy the characteristics of small receiving valves of given dimensions or, conversely, to determine the dimensions necessary to give any required characteristics. This is due to such factors as end effects, lack of axial symmetry of the electrode system imposed by mechanical considerations and, in most valves, the well-known phenomenon *Inselbildung*, which is due to the fact that the electric field in the neighbourhood of the cathode surface is not uniform along its length.

By making certain assumptions, however, formulae have been obtained by several workers for plane and cylindrical electrode systems (the former is, of course, a limiting case of the latter) and, although only approximate, these are useful in determining qualitatively the effects of the various electrode dimensions and operating conditions on the characteristics of the valve.

Vogdes and Elder§ deduced the following expression for the amplification factor (μ) of a triode in the form of a cylindrical system of electrodes, end effects being neglected:—

$$\mu = \frac{2\pi nb \log \dfrac{a}{b} - \log \cosh 2\pi n\rho}{\log \coth 2\pi n\rho} \quad . \quad . \quad (3)$$

where a is the radius of the anode, b is the radius of the grid, ρ is the radius of the grid wires, and n is the number of turns of the grid per cm. In practice, the second term of the numerator is negligible compared with the first term, and we have

$$\mu \simeq \frac{2\pi nb \log (a/b)}{\log \coth 2\pi n\rho} \quad . \quad . \quad . \quad . \quad (4)$$

The value of the space-charge-limited current (in amps.) flowing to grid and anode is given by the well-known expression‖

$$i = \frac{1{\cdot}47 \times 10^{-5} l}{b\beta^2} \left[\frac{V_a + \mu(V_g + v)}{1 + \mu} \right]^{\frac{3}{2}} \quad . \quad (5)$$

where l is the length of the cathode, V_a is the potential of the anode relative to the cathode, V_g is the potential of the grid relative to the cathode, v is a small voltage correction which takes into account the contact potential-

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* See Reference (8).

† The total power dissipated in the anode is, of course, $P + \alpha P_e$, where α is the proportion of the cathode power (P_e) absorbed by the anode and may be as high as 0·8.

* See Reference (9).

† *Ibid.*, (10).

‡ *Ibid.*, (11).

§ *Ibid.*, (12).

‖ *Ibid.*, (13).

difference between grid and cathode and the initial velocity of the electrons (a function of the cathode temperature), and

$$\beta = \log\frac{b}{c} - \frac{2}{5}\left(\log\frac{b}{c}\right)^2 + \frac{11}{120}\left(\log\frac{b}{c}\right)^3 - \dots$$

b and c being the radii of grid and cathode respectively.

When the grid is sufficiently negative to prevent electrons passing from cathode to grid, i is the anode current, and the mutual conductance g_m is given by

$$g_m = \frac{\partial i}{\partial V_g} = \frac{3}{2}\left\{\frac{1\cdot 47 \times 10^{-5} \times l\mu[V_a + \mu(V_g + v)]^{\frac{1}{2}}}{b\beta^2(1+\mu)^{\frac{3}{2}}}\right\} \quad (6)$$

and the anode impedance is

$$r_a = \frac{\mu}{g_m} = \frac{2b\beta^2(1+\mu)^{\frac{3}{2}}}{3 \times 1\cdot 47 \times 10^{-5} l[V_a + \mu(V_g + v)]^{\frac{1}{2}}} \quad (7)$$

It therefore follows that, for a given value of μ, the impedance may be reduced and mutual conductance increased by increasing the length of the cathode and/or reducing $b\beta^2$.

In directly-heated filament valves a high mutual conductance and low impedance may be obtained by employing a long filament system, the upper limit being determined by the emission per unit length of filament necessary to ensure that the anode current is space-charge-limited, and by other factors which will be considered in a later part of this paper. In indirectly-heated cathode valves, where it is not possible to employ long cathodes, the mutual conductance is increased by reducing the grid-cathode clearance.

In high-amplification-factor triodes, the upper limit of mutual conductance is set by the minimum value to which it is possible to reduce the grid-cathode clearance without risk of excessive variations in characteristics, due to accidental variations in this parameter, and by the degree to which it is possible to control the contact potential-difference between grid and cathode, μv being comparable with V_a [equations (5) and (6)].

In low-impedance triodes for output stages of a receiver, the limiting factors are different. The contact potential-difference between grid and cathode is relatively unimportant, since V_a is large compared with μv. There is a mechanical limitation to the minimum size of the grid wires (ρ) which can be employed, and minimum values to which it is permissible to reduce grid-cathode and anode-grid spacings without risk of grid emission and excessive anode temperature. Further, it is not possible to reduce n indefinitely, since as the ratio of grid pitch ($1/n$) to grid-cathode clearance increases *Inselbildung* becomes more serious, and affects the shape of the anode-current/anode-voltage curve at high anode voltages. This reduces the efficiency of the valve by limiting the maximum undistorted output obtainable. Fig. 3, in which the mutual conductance at constant anode current is plotted against grid pitch, shows the effect of *Inselbildung* in some experimental valves. As mentioned earlier, this phenomenon is present to some extent in nearly all receiving valves; but in low-impedance valves, where unfortunately its effect is most serious, it is most marked, and the manufacture of an indirectly-heated-cathode power output triode is only possible by the use of extremely fine wires for the grid together with a very small clearance between the grid and anode.

The maximum theoretical efficiency (ratio of output watts to anode dissipation) of an ideal triode, having zero impedance, would be 50 per cent. In practice, owing to the limitations mentioned above, the maximum efficiency obtained—even with directly-heated cathode valves—is only about 25 per cent. By using a pair of valves in push-pull it is possible to increase the efficiency since the second-harmonic distortions of the two valves neutralize one another, and lower-impedance valves together with low load impedance can be employed. An efficiency of 40 per cent can in this way be obtained. The efficiency can be still further improved by allowing the grid potentials of the valves to become positive over part of each cycle. From the point of view of the valve itself, the fact that an electron current is flowing to the grid introduces new problems in manufacture.

Greater precautions are necessary in pumping the valve to ensure that the grid is really gas-free, as, otherwise, this gas will be liberated by electron bombardment when the grid is positive and will " poison " the cathode. Further, since the grid is hotter than in a valve operating with no grid current, primary electrons may be emitted; and, although the input circuit of the valve is designed to deliver power to the grid circuits, a large increase in grid emission would be serious.

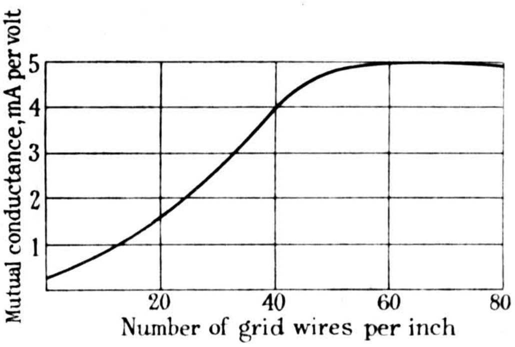

Fig. 3.—Effect of grid pitch on mutual conductance. Cathode diameter 2·1 mm., grid diameter 3·3 mm., $E_g = 0$, $I_a = 8\cdot 0$ mA.

TETRODES

Expressions giving the various characteristics of tetrodes (and pentodes) in terms of electrode dimensions and potentials have been calculated for simple electrode systems, but in practice these are of even less value to the valve designer than the equations for the triode, owing to the complex design of the electrodes and the effect of secondary emission. It will, however, be obvious that since the anode is screened from the grid, and therefore from the cathode, its dimensions and potential will have little effect on the anode current and mutual conductance of the valve compared with cathode, grid, and screen dimensions, and it is the design of these electrodes which is most important in determining the characteristics.

Tetrode valves may be divided into two classes: (*a*) high-frequency amplifier and detector valves, and (*b*) low-frequency output valves.

(a) Screen-Grid Valves

The principal requirement in these valves is that the screen shall reduce the capacitance between anode and control grid to a very low value (0·001–0·01 $\mu\mu$F). In practice, this is achieved by making the screen from sheet metal surrounding the grid as far as possible, with apertures covered by very fine mesh opposite the region of the cathode-grid system from which electrons are escaping. The screen is usually provided with one or more skirts which extend to the walls of the bulb, so that the screening can be completed outside the valve. The anode is designed to have as small a surface as is possible without unduly increasing the space charge between screen and anode. Two designs of screen-grid valve are shown in Fig. 4.

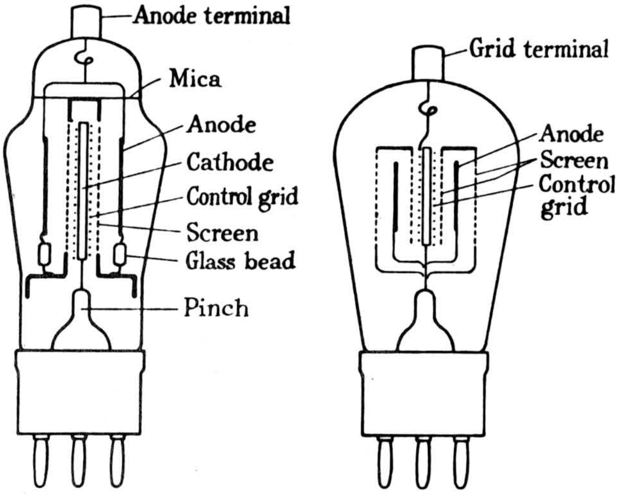

Fig. 4.—Screen-grid valves.

The general shape of the characteristic curves (Fig. 5) is well known. When the anode potential is lower than that of the screen, secondary electrons pass from anode to screen, thus reducing the anode current below, and increasing the screen current above, the values which they would have if secondary emission were absent. When the anode potential is above that of the screen, the secondary electrons flow from screen to anode, thus increasing the anode current and decreasing the screen current. With modern oxide-coated cathodes, screen and anode surface become contaminated with barium from the cathode (the actual layers having a complex BaO, O, Ba structure), which increases the secondary-emission coefficient considerably, and the phenomenon of a negative screen current (when the ratio of the number of secondary electrons flowing from screen to anode to the number of primary electrons from cathode to screen is greater than unity) is quite common. It will be noted that the higher the secondary emission from the screen, the higher the mutual conductance of the valve, which is in fact a secondary-electron multiplier. Unfortunately, the secondary emission is extremely difficult to control, and is dependent not only on the degree of contamination of the surface but also on its mechanical nature.

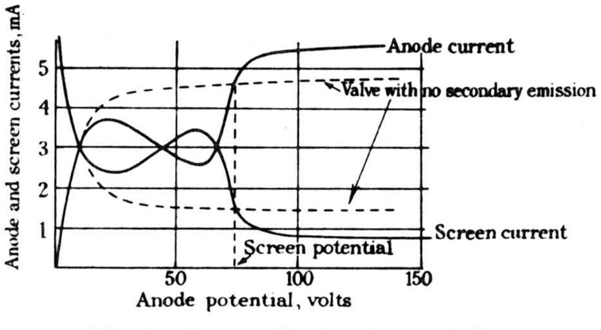

Fig. 5.—Screen-grid valve characteristics.

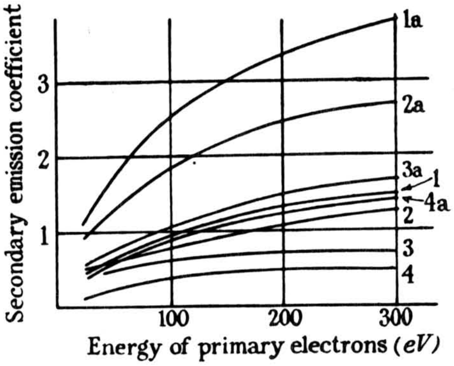

Fig. 6

1. Clean molybdenum.
1a. Barium on molybdenum.
2. Clean graphite (aquadag).
2a. Barium on graphite (aquadag).
3. Clean carbonized nickel.
3a. Barium on carbonized nickel.
4. Clean lampblack.
4a. Barium on lampblack.

The secondary emission of clean and contaminated surfaces has been studied in the G.E.C. Laboratories, and Fig. 6 shows the effect of depositing barium from a barium-oxide cathode on various substances. The difference between colloidal graphite (aquadag) and lampblack is particularly interesting, the secondary emission of the former being approximately the same as for a metal, whereas the value for lampblack is only about one-third that of a metal. Screen-grid valves have been made with carbonized screens in an attempt to reduce the spread in characteristics between valves, and during life. Another method of reducing the

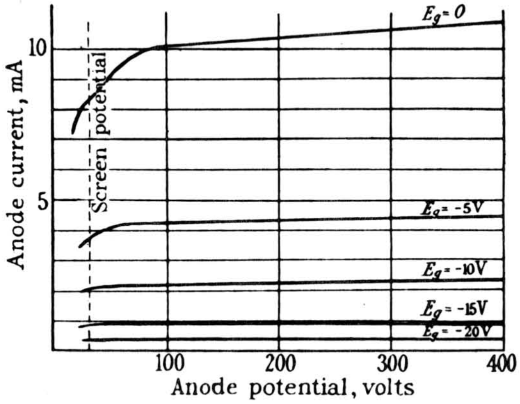

Fig. 7.—Variable-mu screen-grid valve designed for screen at 30 volts.

secondary emission is to lower the screen potential, the grid-screen clearance being reduced in order to maintain the characteristics. Anode-current curves of a screen-grid valve in which the screen was designed to operate at 30 volts are shown in Fig. 7.

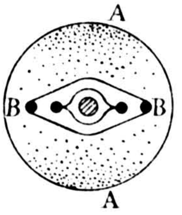

Fig. 8.—Space-charge distribution between screen and anode of tetrode (at low anode voltage).

(b) Low-Frequency Tetrodes

In low-frequency tetrode valves the capacitance between anode and grid is less important than in high-frequency valves, and the screen can be a much more open structure. The secondary emission from the screen is therefore less. For a tetrode to be an efficient output valve, the secondary emission between anode and screen must be suppressed. This can be done in either or both of two ways: (*a*) by so designing the anode, or by making the distance between anode and screen so large, that the space charge produces a potential minimum between anode and screen: and/or (*b*) by making the distance between screen and grid small, and the screen an open structure so that a potential minimum is produced outside the screen by the grid, which is always at a negative or zero potential. Most of the secondary electrons possess low initial velocities, so that provided the space-potential minimum is a few volts lower than that of the screen or anode (whichever has the lower potential) secondary electrons will return to the electrode from which they emanate. In practice, unless the distance between anode and screen is very large, since the electrodes are not axially symmetrical, the density of electrons in the neighbourhood of the support wires (see Fig. 8) is small even when the anode current is high, so that although there may be a potential minimum in the region A there is no potential minimum at B and secondary electrons can pass freely between anode and screen. Bull* has suggested a method of overcoming this difficulty by arranging the electrodes in the way indicated diagrammatically in Fig. 9. The anode AA is in the form of two segments of a cylinder, and BB are two additional electrodes operated at zero or negative potential to concentrate the electron stream between the boundaries enclosing the angle α. An alternative design which has been used in tetrodes designed to operate at relatively low anode and screen potentials is shown in Fig. 10, fins F being provided inside the anode. The potential varies from cathode to anode along the plane XX in the way indicated in Fig. 11, and most of the secondary electrons from the

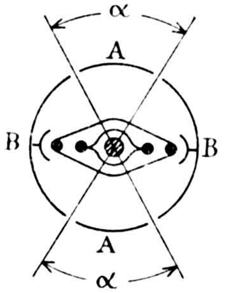

Fig. 9.—Tetrode with earthed plates to suppress secondary emission.

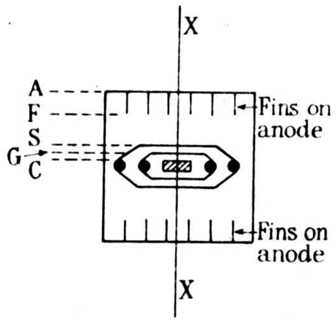

Fig. 10.—Tetrode with fins on anode to suppress secondary emission.

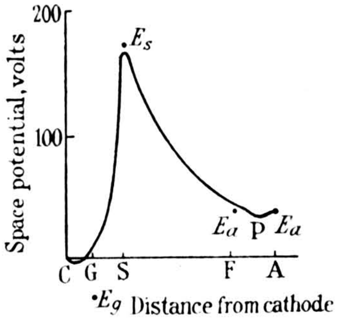

Fig. 11.—Potential distribution in tetrode with fins on anode (at low anode voltage).

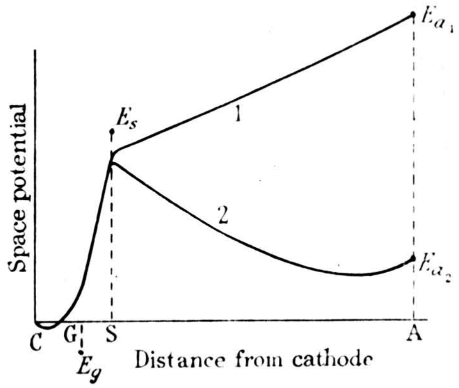

Fig. 12.—Potential distribution in tetrode with small clearance between grid and screen.

1. Anode potential higher than screen potential.
2. Anode potential lower than screen potential.

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* See Reference (14).

anode surface will be prevented from escaping by the potential minimum at P, or will be trapped by the fins.

It will be noticed that condition (*b*) mentioned above necessitates an increase in grid-anode capacitance, but this increase, if small, is not a serious disadvantage in output valves. The potential variation from cathode to anode is illustrated in Fig. 12; and the characteristics of a valve designed so that conditions (*a*) and (*b*) were satisfied are shown in Fig. 13.

The complete suppression of secondary emission in a tetrode is not an easy matter, particularly in valves designed to operate at high anode and screen potentials, and by far the most common method of suppressing the secondary electrons is by the inclusion of a suppressor grid—as in the pentode valve.

PENTODE VALVES

Pentode valves may be divided into two main classes: high-frequency valves, in which the screening between anode and grid is important; and low-frequency valves, in which the principal requirement is high output efficiency. The latter class will be considered first.

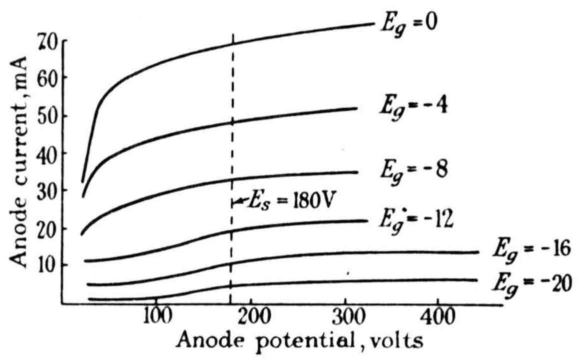

Fig. 13.—Characteristics of tetrode with large anode-screen and small grid-screen clearances.

(a) Output Pentodes

The general shape of the anode-current/anode-voltage curve of an output pentode is well known, and is shown in Fig. 14, the secondary emission " kink " in the curve which is characteristic of most tetrodes having been removed by the suppressor grid. The anode and suppressor-grid potentials have little effect on the field near the cathode surface, and therefore on the anode current and mutual conductance, which are functions of the cathode-grid-screen design and potentials in the same way as, in a triode, these characteristics depend on the cathode-grid-anode design and potentials. The amplification factor of the valve is, of course, the product of the amplification factors of the anode-grid, anode-screen, and anode-suppressor grid systems. The design of the suppressor grid, which can only be decided by trial for any particular valve, is most important in determining the shape of the " knee " of the curve. If the pitch of the suppressor-grid spiral is too small, the minimum space potential in the neighbourhood of the suppressor grid will have a slightly negative value relative to the cathode when the anode potential is low, and primary electrons will fail to reach the anode, with the result that the anode-current characteristic will be as shown in Fig. 15, curve (*a*). If, on the other hand, the pitch of the suppressor grid is too large, then at low anode potentials some of the secondary electrons will reach the screen, and the anode-current characteristic will be as in Fig. 15, curve (*b*). In either case it will be obvious that the maximum undistorted output will be limited, and, in designing the suppressor grid, its optimum dimensions must be determined by trial.

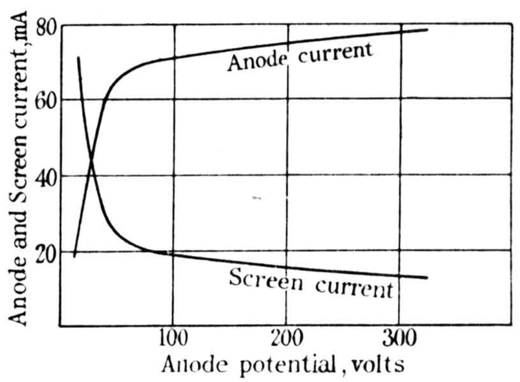

Fig. 14.—Characteristics of pentode.

The pitch of the screen-grid spiral also affects the shape of the characteristics, and here a compromise must be effected between an open structure which allows the potential of the anode to affect the field near the cathode, thus reducing the anode impedance and limiting the output [Fig. 15, curve (*c*)], and a close structure which will result in excessive screen current. The pitch of the screen-grid also affects the " knee " of the anode-current/anode-voltage curve in another way. The dispersion of the electron paths through the screen-grid depends on the pitch of this grid,* being smallest when the pitch is small. It will be obvious that, the smaller this dispersion, the lower will be the anode voltage necessary to draw all the electrons passing through the screen to the anode, and consequently the better the " knee " to the characteristic curve.

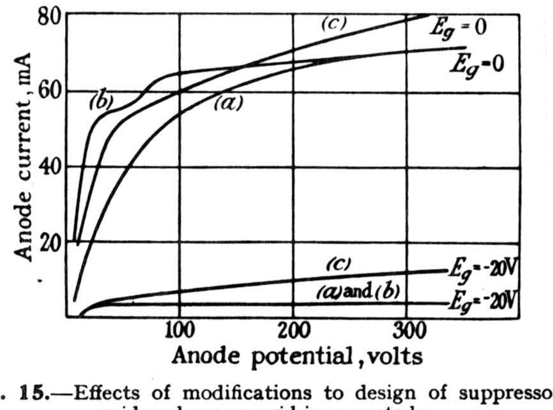

Fig. 15.—Effects of modifications to design of suppressor-grid and screen-grid in a pentode.

It might be expected at first sight that the limitations already mentioned in connection with indirectly-heated

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* See Reference (15).

cathode triodes would also be encountered in the design of output pentodes. This, however, is not so; for the μ value of the grid-screen system need not be very low, since the output efficiency is less dependent on this factor than it is on the anode impedance of a triode. Further, *Inselbildung*, which is a function of the anode potential in a triode, is independent of the anode potential in a pentode.

(b) High-Frequency Pentodes

The principal difference between high- and low-frequency pentodes is, as in the case of tetrodes, in the anode-grid capacitance. A high anode impedance is usually desirable in the high-frequency pentode, and this characteristic is fortunately complementary to a high degree of screening.

For convenience in manufacture, and also in order to keep the screen current as low as possible, the screen is usually made in the form of a close-wound grid, and the screening at the ends of the electrodes is completed by a skirt or skirts attached to the suppressor grid.

Although not usually designed for use with a control voltage on the suppressor grid, the high-frequency pentode can be used in this manner.* As the potential of the suppressor grid is made more negative, the anode current is reduced and screen current increased, and at the same time the anode impedance is reduced. With a suppressor grid having a very open pitch, however, the control on the anode current by this grid is poor, and it is natural that grids having a closer pitch should have been employed to improve this control. This led to the development of hexodes, heptodes, and octodes, which are designed specifically for the control of the anode current by two separate grids. These will now be described, and the action of the second control grid will be briefly considered.

HEXODES, HEPTODES, AND OCTODES

These may be divided into two classes, depending on the particular use for which they are designed rather than on a fundamental difference of principle.

The first class, including hexodes and certain heptodes, consists essentially of a high-frequency pentode in which the pitch of the third grid is reduced in order to obtain a good control of the electron stream, and to which a screen is added between this grid and the anode to overcome the variation in anode impedance mentioned above. The heptodes in this class have, in addition, a suppressor grid between this second screen and the anode. The main use of these valves is for frequency-changing in superheterodyne receivers, the signal voltage being applied to the inner control grid (which usually has a variable-mu characteristic) and the oscillator voltage (derived from a separate source) being applied to the outer control grid.

The design of the cathode, control grid, and screen section is essentially the same as in a high-frequency pentode. The action of the second control grid, however, is different from that of the grid of a triode. Whereas in the triode space charge is an essential intermediary in the relationship between anode current and grid potential, it is the potential distribution in the plane of the outer control grid which mainly determines this relationship in the case of the hexode (or heptode). The electrons leave the inner screen with a high velocity, and whether or not a particular electron or group of electrons will reach the anode (and outer screen) or return to the inner screen depends on the position of the electron paths relative to the second control-grid wires, the space-potential distribution in the neighbourhood of this grid, the deflection of the electron paths by the inner screen, and the initial velocity of the electrons as they leave the cathode. The calculation of the dimensions of the second control grid from theoretical considerations is not in practice possible, but a general picture of the action of the grid can be obtained from Fig. 16, which represents the potential distribution (*a*) between the two screens of a hexode, and also (*b*) in the plane of the second control grid. The maximum anode current will be obtained with approximately zero potential on the control grid, space charge being small; and the anode current, when this grid is at a negative potential, will depend on the effective potential in the grid plane. This latter is given by Schottky's formula,* namely

$$V_{eff.} = \frac{DV_a + V_g + RV_s}{1 + D + R}$$

where D is the *Durchgriff*† of the outer electrodes (anode, outer screen, and suppressor grid, in a heptode) through the grid, and R is the *Ruckgriff*† of the inner electrodes through the grid. It is clear, therefore, that close spacing between these electrodes and high voltages tend to lower the control of the second control grid.

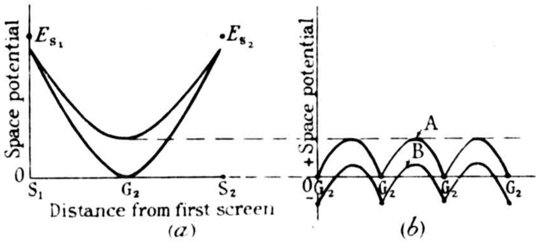

Fig. 16.—Potential distribution in hexode.

(*a*) Potential distribution between the two screens.
(*b*) Potential distribution in plane of second control grid.
A. Control-grid potential zero.
B. Control-grid potential negative.

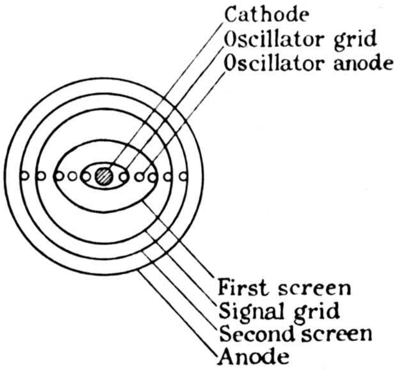

Fig. 17.—Electrode arrangement in heptode.

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* See Reference (16).

* See Reference (2).

† "Durchgriff" and "Ruckgriff" are the reciprocals of the amplification factors of the grid-outer screen and grid-inner screen systems respectively.

The second class of heptodes, together with octodes, differ from the above chiefly in that they contain an additional electrode at a positive potential between the inner control grid and screen, the inner triode system being used as an oscillator to modulate the electron stream. The outer control grid in these valves, which usually has a variable-mu characteristic, is used for the signal input. The control action of the additional electrode (triode anode) on the electron stream must be less than that of the inner grid, as otherwise the resultant modulation of the electron stream will be low (in the limiting case, if the control of the oscillator electrodes were equal, equal and opposite voltages would leave the electron stream constant). For this reason, and also to reduce the interaction between the second control grid and the oscillator, the oscillator anode is usually in the form of two wires parallel to the cathode which may even be placed between the support wires of the inner grid and screen (Fig. 17). In this case, the oscillator anode current is mainly the result of secondary emission from the screen.

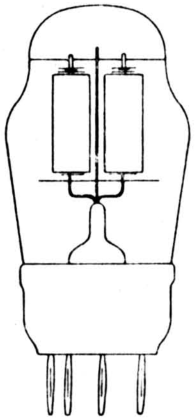


Fig. 18.—Double pentode.

MULTIPLE VALVES

The design and manufacture of multiple valves does not introduce any fundamentally new principles, such valves being made mainly for the convenience of set manufacturers, and it will only be necessary to refer to these types briefly.

Double output valves (triodes and pentodes) for push-pull operation with or without positive grid drive merely consist of two separate valve-assemblies mounted side by side on a single pinch (Fig. 18). Precautions are necessary in the design of these types to ensure that there is no mutual control between the two electrode systems, such as would occur if the anodes were made of mesh or if electrons escaped from the ends of the electrodes, and that the temperatures of the electrodes do not become excessive owing to heat radiated from one system to the other.

In double diode triodes, the anodes of diodes, which only require a small total emission to satisfy their characteristics, are usually mounted at the end of the cathode nearer the pinch, and the grid of the triode, screened from the diode anodes, is connected to a cap at the top of the bulb (Fig. 19).

The triode hexode, which is used as a combined oscillator and frequency-changer, is made in a similar manner, the triode being assembled on the lower end, and the hexode on the upper end, of a common cathode. The hexode signal-control grid (nearest the cathode) is connected to the top cap, and the triode grid is connected internally to the second control grid of the hexode (Fig. 20).

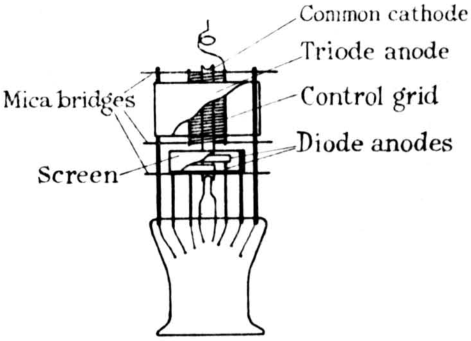


Fig. 19.—Double diode triode.

FACTORS AFFECTING CHARACTERISTICS

In addition to the development of special types of valves and to improvements in the characteristics, a continuous effort has been and is being made by valve manufacturers towards reducing, in any given valve type, deviations from the mean value of the characteristics; since with greater uniformity in the product the set manufacturer is able to use more efficient circuits. It may, at first sight, seem rather surprising to the user of valves that the spread in characteristics from valve to valve is, even with the utmost precautions in manufacture, quite large: ± 20 per cent and in some cases ± 40 per cent on such characteristics as anode current and mutual conductance being the smallest limits to which it is at present possible to work economically.

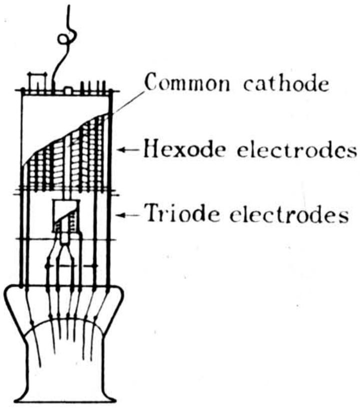


Fig. 20.—Triode hexode.

From the remarks made earlier in the paper it will be seen that the factors which affect the characteristics of a valve are the mechanical dimensions and chemical properties of the surfaces of the electrodes. With the small distances between electrodes which are employed to obtain the high efficiency of the modern valve, and lack of continuity in the production of any given type, uniformity in these two factors becomes increasingly difficult.

(a) Mechanical Variations

A fairly accurate idea of the effects of small variations in the mechanical dimensions of the various electrodes can be obtained from a consideration of the approximate expressions given earlier in this paper and elsewhere for the characteristics of the valve. Thus, to take the simplest case of a triode, the effect of variations in the parameters a, b, c, ρ, n, l, on the characteristics μ, i, g, R can be obtained from equations (4), (5), (6), and (7) by logarithmic differentiation of these functions with respect to the various parameters. The expressions, which are readily deduced, are rather complex, and the authors will therefore content themselves with giving in Table 1 one of the results of calculations which have been made for a particular high-impedance triode. This table gives the coefficients B in the expression

$$\frac{\delta A}{A} = B\frac{\delta C}{C}$$

where A is one of the characteristics μ, i, g, R; and C is one of the parameters a, b, c, ρ, n, l.

Table 1

Triode valve: $a = 0\cdot617$ cm., $b = 0\cdot187$ cm., $c = 0\cdot099$ cm., $\rho = 0\cdot0055$ cm., $n = 15\cdot75$ per cm., $l = 3\cdot5$ cm., $V_a = 100$ volts, $V_g = 0$, $v = 0\cdot83$ volt.

	$\delta a/a$	$\delta b/b$	$\delta c/c$	$\delta\rho/\rho$	$\delta n/n$	$\delta l/l$
$\delta\mu/\mu$	0·84	0·16	0	1·23	2·23	0
$\delta i/i$	−0·90	−3·59	2·42	−1·32	−2·38	1
$\delta g/g$	−0·28	−3·47	2·42	−0·40	−0·73	1
$\delta R/R$	1·12	3·63	−2·42	1·64	2·96	−1

It will be seen that an error of 1 per cent in the radius of the cathode, for example (representing an absolute error of 0·001 cm.), will introduce an error of 2·42 per cent in the value of the anode current, mutual conductance, and impedance. If small errors in more than one parameter exist, then the effects are, of course, additive; so that if a, b, ρ, n are 1 per cent too large and c and l 1 per cent too small, the total deviation in anode current from its correct value will be as much as 11 per cent. In practice, the tolerances to which it is possible to manufacture components on a large scale economically for a valve such as that cited in Table 1 are: cathode diameter ± 1 per cent (including coating), grid diameter ± 1 per cent, grid pitch (mean) ± 1 per cent, grid-wire diameter ± $1\frac{1}{2}$ per cent, anode diameter ± 2 per cent; and although it is extremely improbable that all the maximum permissible errors will occur at the same time in any given valve, a total variation in characteristics of ± 5 to ± 10 per cent, due to mechanical variations alone, will exist in quite an appreciable percentage of valves. It will readily be seen that any improvement in the mutual conductance effected by reducing the grid diameter will increase the values of the coefficient B in the expression

$$\frac{\delta A}{A} = B\frac{\delta C}{C}$$

and make the task of manufacturing a uniform product more difficult. Mechanical shock or strain in the materials which might result in slight distortion of the electrodes will also seriously affect the characteristics.

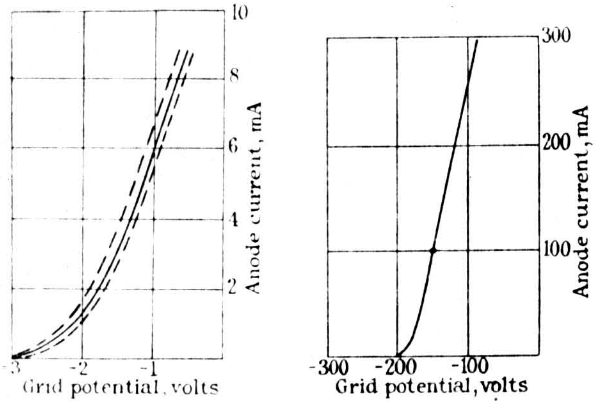
In valves having more than three electrodes, the possibility of variations in characteristics will be greater, although in these cases also the dimensions of the cathode and control grid are generally the most important factors.

(b) Chemical Variations

The factors, other than mechanical, which affect the characteristics are the degree of activation of the cathode along its length, depending on the temperature distribution (which is discussed in another part of this paper), the contact potential difference-between cathode and grid, and secondary emission in tetrodes and other types in which no auxiliary grid is used to suppress secondary currents. The effect of variations in grid-cathode contact-potential is, as already stated, most serious in valves with high amplification factor and high mutual conductance, and is indeed the biggest single cause of variation in characteristics in these types. For example, in a valve designed to operate with an anode current of 6 mA with a mutual conductance of 6 mA per volt a change of 0·1 volt in the grid-cathode contact potential-difference will result in a deviation of 10 per cent in the anode current, and over 3 per cent in the mutual conductance. In low-amplification-factor valves in which the ratio of mutual conductance to anode current is small, the effect of variations in grid-cathode contact potential-difference is, of course, much smaller and may be negligible; as, for example, in a valve such as a 100-watt output valve operating at 100 mA anode current with a mutual conductance of 3·9 (Fig. 21).

As has been mentioned earlier, the contact potential-difference between anode and cathode in a detector diode, or cathode and grid of a triode, tetrode, pentode, etc., is determined by the materials used for the electrodes, the physical nature of the surface, and the contamination (metallic or gaseous) on the surface. Even when a close control is exercised on all the materials and operations during manufacture, it is not possible economically to control the variations in grid contact-potential to within closer limits than ± 0·2 volt of a mean value. A particular difficulty arises in the case of such valves as double diode triodes where for certain circuit requirements it is necessary to keep the contact potential-difference between cathode and diode anodes approximately equal to that between cathode and triode grid, so that the diode anode current shall start at the same negative bias value as that at which grid current starts. The difficulty arises owing to the fact that the grid-wire material is usually different from the diode-anode material, and also that the evaporation of barium from the ends of the cathode on to the diode anodes is less rapid than from the centre of the cathode on to the grid. Special care is necessary in devising activating processes which will satisfy the above requirement without de-activating the cathode, and it is often necessary to subject such valves to very long ageing treatment in order to establish stable characteristics.

The control of secondary emission is equally difficult, and depends on the same factors as does contact potential. It has in fact been shown in the G.E.C. Laboratories* that the secondary emission from a contaminated surface is closely related to its contact potential and work function. Variations of ± 50 per cent in the value of secondary current from the screen to the anode of a screen-grid valve are quite common, and will introduce deviations from the mean value of anode current of 15 to 20 per cent, while the value of the screen current may vary between positive and negative values.



(*a*) (*b*)

Fig. 21

(*a*) High-impedance triode, showing large effect of contact-potential variation.

(*b*) Low-impedance triode, showing negligible effect of contact-potential variation.

(c) Negative Grid Current and Input Impedance

The main causes of negative grid current when the grid is at a negative potential with respect to the cathode are: (i) Leakage across insulators. (ii) Positive-ion current to the grid due to poor vacuum. (iii) Electron current from the grid (grid emission). The maximum permissible value of the total grid current due to these causes varies, according to the purpose for which the valve is used and according to the value of the resistances which may be included in the grid circuit, between 10^{-8} and 5×10^{-6} amp.

(i) Leakage.

Little difficulty is experienced in obtaining electrode spacing insulators having a sufficiently high resistance (of the order 10^{10} ohms) even with the small distances between electrode support wires; but films of metal (e.g. barium) deposited on the insulator surfaces during pumping and subsequently, may reduce the insulation considerably. When mica is used, it is usual to roughen the surface by covering it with a thin layer of magnesium oxide, so that the metallic deposits do not form continuous films between electrodes. Another possible source of leakage between electrodes is the glass pinch, if its temperature rises and electrolysis occurs. The material used for valve pinches is usually a lead glass having high insulating properties (Fig. 22), and in practice leakage currents are negligible if the temperature is below 200° C. In power output valves and power rectifiers, special precautions may be necessary to ensure that this temperature is not exceeded. Most of the heat received by the pinch is conducted to it along the electrode support wires, and the substitution of wires of a metal with low thermal conductivity, such as nickel-chromium or nickel-iron alloys instead of nickel, reduces the temperature of the pinch considerably. To give one example, in an output pentode in which the temperature of the pinch was regarded as being dangerously high (205° C.) with nickel support wires to the anode, the substitution of nichrome wires reduced its temperature to 158° C. In the "ring seal," shown in Fig. 23, which has been used for several types of small valves, the glass is at a very low temperature, and the lead-in wires are separated from one another by greater distances than are possible in the usual type of flat pinch. Leakage currents through the glass are therefore negligible.

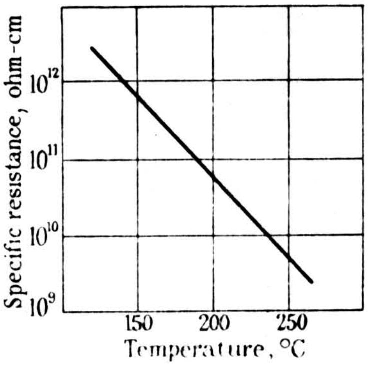


Fig. 22.—Specific resistance of glass used for valve pinches.

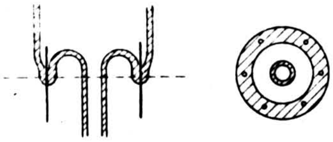


Fig. 23.—Glass ring seal.

(ii) Positive-ion current.

The gas pressure which will produce a given positive-ion current to the grid of a valve depends on the nature of the gas, the magnitude of the electron currents, the potentials of the electrodes, and the electrode design, and is therefore different for different types of valve. Valves in which the control grid is not adjacent to the cathode, such as the heptode oscillator-detector, are more sensitive to gas than triodes, tetrodes, and pentodes.

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* See Reference (17).

Measurements made on representative types of valves have shown that the maximum permissible pressure which may exist without causing excessive grid current is of the order 10^{-5} mm. of mercury. Although the pumps used for exhausting valves in mass production are not capable of reducing the pressure to less than 10^{-3} to 10^{-4} mm. of mercury, the average pressure in modern valves using efficient getters (such as barium) is about 10^{-7} mm. or in some cases as low as 10^{-8} mm. of mercury.

(iii) Grid emission.

In power output valves and in indirectly-heated cathode valves, in which the grid-cathode clearance is small, electron emission from the grid is difficult to prevent. Many attempts have been made to reduce grid emission by treatment of the surface of the grid wires, such as plating with copper or silver. These metals can dissolve barium deposited on them, leaving a low barium concentration on the surface, which has a relatively high work function. Experiments have shown, however, that little difficulty would be experienced if barium metal alone were deposited on the clean grid surface, and that it would be possible for a grid contaminated in this way to operate at a temperature as high as 400° C. without risk of excessive emission. Barium oxide on the grid surface, however, may cause serious grid emission at temperatures as low as 320° C., and the main difficulty arises owing to the fact that the grid surface may oxidize during pumping when the barium-strontium carbonates are being decomposed, and a barium-on-barium-oxide layer then results from the subsequent deposition of barium on the oxidized grid surface. Although plating the grid with silver or copper is effective in reducing the average value of grid emission in any type of valve, it is not a certain cure, and the authors have found that in large-scale production a small percentage of valves with excessive grid current is produced. Further, the volatilization of the metal or the oxide of the metal deposited on the grid often " poisons " the cathode emission.

The only sure method at present known of preventing emission from the grid of a valve is to keep the grid temperature below 320° C., and to do this when the grid wires may be less than 0·5 mm. from a cathode at 770° C. is not easy. Grid support wires made of a metal with high thermal conductivity, e.g. copper, are employed in some types of valves, often with radiating fins welded to the end of the grid (a modification which unfortunately increases the grid capacitance and makes screening more difficult). The thermal conductivity of the grid-winding wire material is also an important factor in this connection, as in the fine wires used there may be a considerable temperature gradient between the part of the grid nearest the cathode and the support wires. Some alloys which valve manufacturers would like to use (owing to their mechanical properties and low cost) have a very much lower thermal conductivity than molybdenum, and for this reason cannot be employed in grids adjacent to the cathode. The substitution of such alloys would increase the temperature of the hottest part of the grid by as much as 30 deg. C. and seriously increase the risk of grid emission.

Anodes and screens with carbonized surfaces or made from mesh instead of sheet metal are also used to prevent the grid from becoming overheated by radiation reflected from their inside surface. The temperature reduction effected in this way may be as much as 100 deg. C., and there are in fact few indirectly-heated valves made to-day in which this precaution is not necessary.

In addition to the three main causes of grid current mentioned above, there are several other contributory causes such as positive-ion emission from the cathode, and photo-emission from the grid. The values of these currents are, however, extremely small, and their elimination is only of importance in valves designed for special purposes, such as electrometer triodes and tetrodes, in which grid currents as low as 10^{-17} amp. are obtained.*

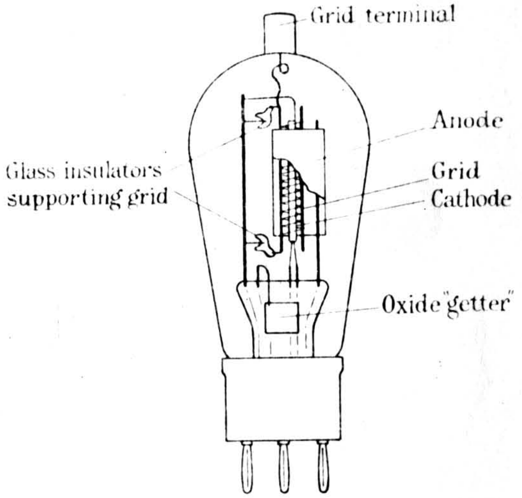

Fig. 24.—Triode for valve voltmeter.

During the past few years, the improvements in the efficiency of tuned circuits have necessitated a corresponding improvement in the high-frequency impedance between the grid and other electrodes of valves for use at radio frequencies. Circuits with an impedance of 0·5 megohm at 1 000–1 500 kilocycles per sec. are now quite common, and in order that the valve shall not seriously load such a circuit, its impedance must exceed 3 megohms. The valve base and socket are here the main limiting factors, and it is now becoming more usual to design valves for radio-frequency purposes with the grid lead taken to a cap on the top of the valve rather than to a pin in the base. When a still higher grid impedance is required, as in the case of valves for use as valve voltmeters at radio frequencies, specially-designed insulators for the grid are substituted for the usual mica bridge. A high-frequency voltmeter valve which has an impedance of more than 20 megohms at 1 200 kc is shown in Fig. 24.

(d) Bulb Charges

One other factor which may seriously affect the characteristics of a valve must be mentioned. This is secondary emission from the walls of the glass envelope.

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* See References (18), (19).

It is well known that an insulated electrode in a thermionic valve can under certain conditions assume either of two stable potentials. If the electrode is initially at cathode potential or at any positive potential below that at which the number of secondary electrons emitted per primary is unity, then the electrode will collect electrons from the cathode until its potential has fallen to a small negative value $-V_1$ at which equilibrium is established between the rate of arrival of electrons having initial velocities greater than $\sqrt{(2V_1e/m)}$ (e and m being the charge and mass of the electron) and the leakage current between the cathode and free electrode. If, on the other hand, the initial positive potential of the free electrode is greater than the value V_c at which the ratio of secondary to primary electrons is unity, and the anode potential V_a is also higher than V_c, then the free electrode will assume a final equilibrium potential V_2 at which the secondary current from the free electrode to the anode is equal to the primary current from the cathode to the free electrode. The value of V_2 will depend on the secondary-emission coefficient at V_2 and the space charge in the neighbourhood of the free electrode.

Fig. 25.—Output wave-form showing " buzz " effect.

The internal surface of a glass bulb, particularly if this is coated with a film of an electropositive metal such as barium, behaves in exactly the same way, and the characteristics of the valve will be modified according to whether the surface is at the potential $-V_1$ or $+V_2$ since the potential distribution in the space inside the envelope will be different in the two cases.

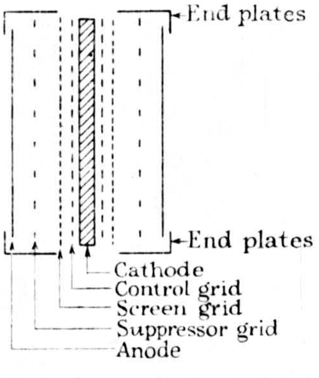

Fig. 26.—A method of preventing secondary emission from bulb.

The effect was observed in screen-grid valves several years ago, when it was found that the anode impedance fell to one-third its normal value if the bulb was raised initially to a high positive potential, or if the bulb surface became momentarily charged by electrostatic induction on applying a positive potential to the anode. The initial flow of electrons passing through the screen reached the bulb, secondary electrons were emitted, and a high bulb potential was maintained which reduced the valve impedance. Valves in which the envelope had been metallized externally did not exhibit the phenomenon since the metallic coating at earth potential prevented the inside surface of the bulb from acquiring a high positive potential.

More recently, a curious distortion of the output-current wave-form (Fig. 25) has been observed in some output pentode valves. This is known as the " buzz " or " S " effect, and is due to the induction of charges on the bulb which then emits secondary electrons when the anode potential swings above a critical value. In a power valve, it is not possible to metallize the outside surface of the bulb, as this would increase the temperature of the bulb and electrodes considerably, and shorten the life of the valve. One method of overcoming the difficulty is to arrange earthed screens at the ends of the electrode system, as shown in Fig. 26, so that no electrons from the cathode can reach the bulb. A simpler method which is effective in most cases is to coat the inside of the bulb with a material such as lampblack which has a low secondary-emission coefficient.

Table 2

	Valve type		
	Triode	Output pentode	Output pentode (air-cooled anode)
	°C.	°C.	°C.
Heater ..	1 150	1 150	1 150
Cathode ..	770	770	770
No. 1 grid ..	300	315	325
No. 2 grid ..	—	410	417
No. 3 grid ..	—	260	275
Anode ..	420	445	145

PROPERTIES OF MATERIALS, AND MANUFACTURE OF COMPONENTS

From what has already been said, it will be evident that a very close control must be kept of the mechanical properties of materials used for components. The manufacturer is limited in his choice of metals from which to make electrodes to those which possess high melting-points, and which have low vapour pressures even at temperatures as high as 1 000°–1 100° C., the temperature reached by the electrodes during pumping.

The operating temperatures of the electrodes vary according to the type of valve; Table 2, giving the results of measurements taken under operating conditions for a high-impedance triode and two output pentodes, is typical.

Nickel is usually employed as the anode material and for electrode support wires, but is not sufficiently rigid for the winding wires of grids. The diameter of these must, for reasons already stated, be as small as possible, and molybdenum, alloys containing molybdenum, or —for some purposes—nickel-manganese alloys, are used. All these metals are readily obtained free from undesirable impurities, are easily worked, and do not tarnish on exposure to the atmosphere, which in a valve factory may be extremely hot and humid. Iron is sometimes used as an anode material for screen-grid valves in which the anode is in the form of two plates, since it can be heated, during pumping, by hysteresis due to the magnetic field of the eddy-current heating coil.

Electrodes such as anodes and screens which are made wholly or in part from sheet metal are pressed into the required shape, and precautions must be taken to prevent distortion due to strain in the metal when it is heated in the valve.

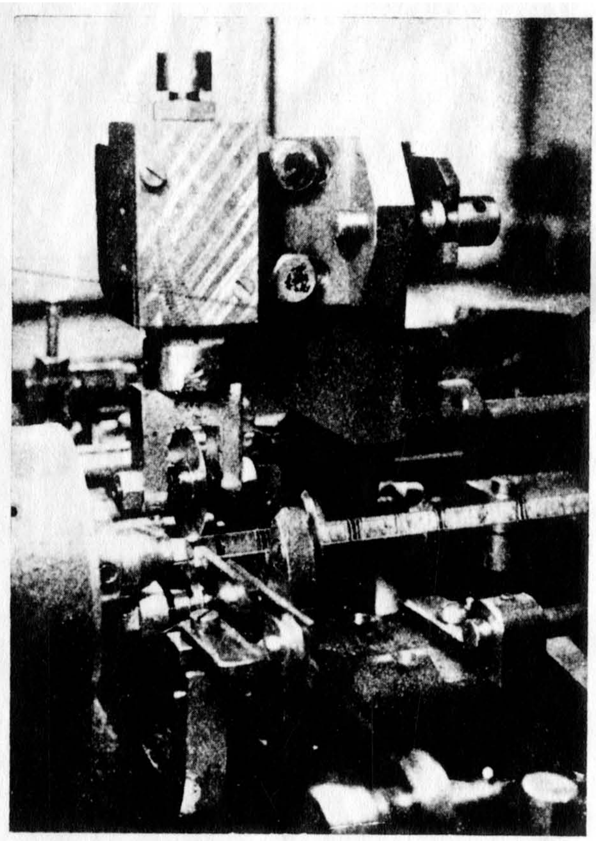

Fig. 27.—Grid-winding machine.

The manufacture of grids, which at one time was an extremely laborious process, is now carried out on special machines capable of winding as many as 200–1 000 grids per hour, depending on the grid pitch. Fig. 27 shows a photograph of part of one of these machines. Fig. 28 shows rather more clearly the action of the machine. The support wires S are fed into grooves on the rotating mandrel M, and the winding wire G is wound into notches cut in the support wires by the fixed cutting-wheel C. The winding wire is fixed in position in the notches by a swaging wheel H which hammers the metal of the support wire over the winding wire. The earlier practice of welding is thus eliminated. The grids are wound in lengths of about 60 cm. and subsequently cut into the required lengths, and if necessary stretched or pressed to their final shape. By the operation of a cam on the machine a gap or gaps can be introduced in the winding of grids which are required to give a variable-mu characteristic.

We have already indicated the degree of accuracy required in grid dimensions to ensure uniform characteristics. The importance of uniform mechanical properties of the wire used for winding grids, which are of course always slightly larger than the mandrels on which they are finally pressed or stretched, will be appreciated. The strain introduced during final shaping must be small, as otherwise distortion will occur on heating.

Equally important as the mechanical properties are the " gas properties " of the electrode materials. Here the term " gas properties " is intended to include not only the amount of gas which may be included in the metal (either " volume " or " surface " gas) but also the capacity of the metal to re-adsorb gas on its surface. This last factor is in some cases even more important than the first. An exhaustive study of the sources of gas in receiving valves has shown that the carbon dioxide adsorbed by the electrodes during decomposition of the barium-strontium carbonates on the cathode is far more difficult to remove than the residual gas existing in the metal, and that the nature of the surface of the electrodes has an enormous effect on this adsorption. Table 3 gives the relative adsorption of CO_2 on different surfaces during the decomposition of the cathode carbonates.

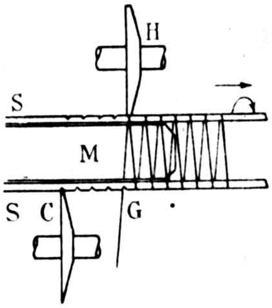

Fig. 28.—Grid-winding machine.

The " volume gas " in a metal may be permanently removed by heat treatment *in vacuo* or in hydrogen,* and Fig. 29 shows the effect on the " volume " gas in nickel of heat treatment at 1 000° C. The degree to which " volume " gas is removed in practice depends on the purpose for which the metal is being used. In support wires of grids, where the ratio of volume to surface is relatively large, it is important to reduce the volume-gas content to a low level, and a long degassing treatment of the wire, either during manufacture or subsequently, is necessary. On the other hand, in the case of sheet metal used for anodes and screens, where the ratio of surface to volume of metal is large, the volume gas is relatively unimportant, but the surface of the metal should be as smooth and bright as possible. From this point of view it is unfortunate that the valve manufacturer is compelled, for reasons stated elsewhere in this paper, to use anodes with carbonized surfaces (see Table 3).

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* See Reference (20).

The treatment of the thoriated tungsten filament was generally as follows:—

The electrode system was outgassed on the pump by high-frequency treatment, and by bombardment from the filament run under ordinary tungsten conditions. The valve was then sealed off, and the filament flashed near the melting point for a minute or so. This treatment cleaned the wire surface, and at the same time reduced some of the thorium oxide to thorium. The filament was then run at 2 200° K. At this temperature thorium diffused to the surface, and there formed the active layer. The operating temperature for these filaments was 1 900° K.

The thorium layer on the surface, being chemically very active, was easily " poisoned " by the presence of oxygen or water vapour. This danger could be avoided if the pumping time were prolonged. An alternative solution was to carbonize the filament. A small amount of a hydrocarbon vapour was admitted to the hot filament, and the hydrocarbon combined with the tungsten to form tungsten carbide. The usual method was to burn the filament in the vapour until its resistance had increased by 7 per cent. The thorium was produced by running the filament off the pump at 2 400° K. for several minutes. The carbide produced thorium by its reducing action on the thoria. The filament was then run at 2 200° K. in order to stabilize the emission. Furthermore, the filament was protected against " poisoning " by the presence of the carbide, which was preferentially attacked by gas and water vapour. The gaseous products of the attack were adsorbed on the walls of the glass bulb.

The main objection to the carbonizing process was the fact that the filament was rendered very brittle by the carbide, and valve losses in transport were very heavy. The solution to this trouble was the stranded filament. It was made very much as a 7-strand cable is made, i.e. six wires were twisted round a central wire of similar diameter. During carbonizing, only the exposed surfaces of each wire were carbonized, and the central wire remained unaffected. This filament was therefore much more robust.

The operating temperature for maximum efficiency is determined by the temperature necessary to maintain the optimum covering of thorium atoms, and this is too low to stop the cathode cleaning-up evolved gas. To counter this defect, a " getter," i.e. a layer of some substance that will adsorb gas, is deposited on the inside of the glass envelope. The early getter was phosphorus, which was originally used in lamps for removal of water vapour. Later getters were alkali or alkaline-earth metals. The action of getters is discussed more fully later in the paper.

(ii) Caesium-on-oxygen-on-tungsten (**W-O-Cs**).

The discovery that the work function of a metal was reduced when a layer of atoms of another electropositive metal was present on its surface led to much work on this form of emitter.[*] Generally, the more electropositive the contaminating metal is, the more the work function is reduced. A still greater reduction in work function is obtained when the contaminating film consists first of a layer of electronegative atoms such as oxygen, and then the layer of electropositive atoms. The most efficient form of this sandwich type of surface yet developed is caesium-on-oxygen-on-tungsten. The tungsten surface is prepared as follows: The tungsten is first oxidized. It is next heated in vacuum until only a monatomic film of oxygen remains, and caesium is then evaporated on to the surface from a suitable source. The final cathode is again heated in vacuum at a suitable temperature in order to obtain the maximum activity.

Despite the high emission efficiency of this type of emitter, it has never been successfully developed commercially. The properties of caesium valves have been extensively studied in the G.E.C. Laboratories, and the following facts have been established. The emission varies with temperature as shown in Fig. 30, and the operating temperature for maximum life is about 810° K. This low temperature is necessary because the degree of covering of the tungsten surface is a function of the vapour pressure of the caesium, and of the temperature of the cathode. The vapour pressure in turn is affected by the bulb temperature. The emission density is very low, so that an extremely large cathode area is necessary and microphonic problems in filamentary types become in consequence much more serious. The cathode can only be operated with very low anode voltage (≯ 120 volts), because positive ions will readily remove the caesium atoms by a bombardment process. Judged from a manufacturing standpoint, a very high degree of skill is required to make this form of cathode, and it has so far proved unsatisfactory for commercial development.

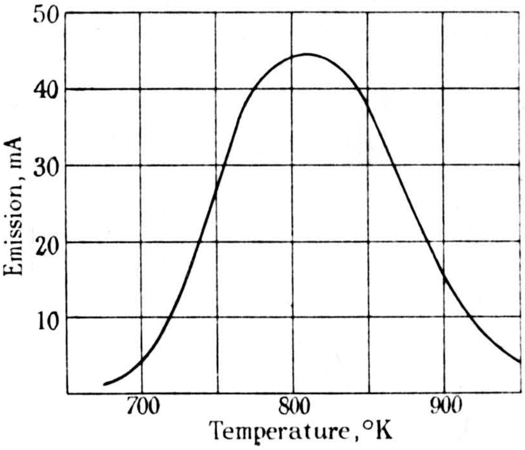

Fig. 30.—Emission from W-O-Cs.

(c) Oxide Emitters

(i) The alkaline-earth oxides.

As early as 1904, Wehnelt[*] showed that the emission from a metal wire coated with calcium oxide was very high when compared with the emission from the metal itself. It was not until 1920, however, that this form of emitting cathode was used commercially by the Western Electric Co.[†]

The demand for highly efficient cathodes which were

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[*] See References (24), (25), (26), (27).

[*] See Reference (28).

[†] See discussion.

Plate 1

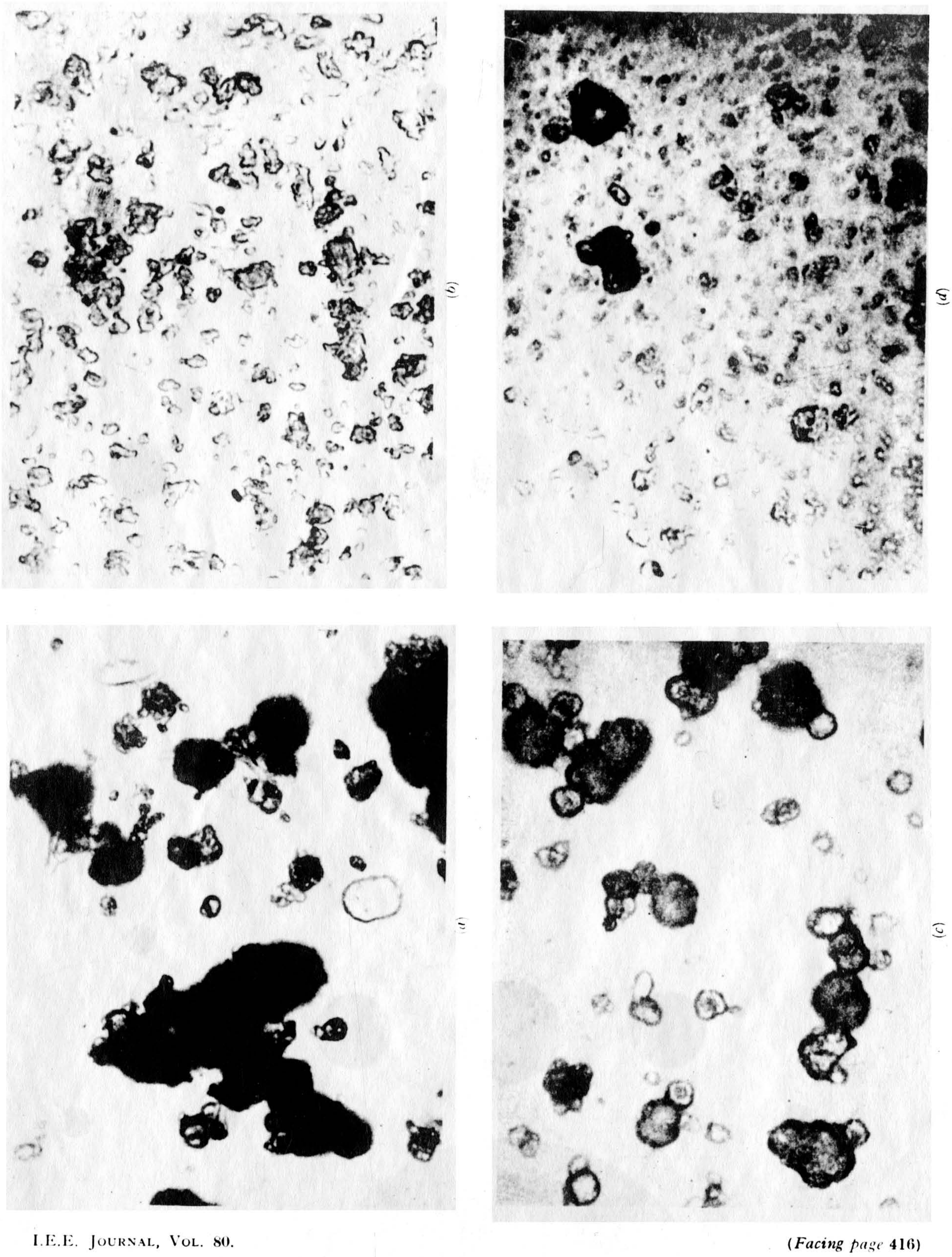

Fig. 32.—Effect of method of precipitation on particle size of double carbonate. (Magnification 1 000.)

(*a*) Precipitation using $NH_4OH + (NH_4)_2CO_3$.
(*b*) Precipitation using Na_2CO_3.
(*c*) Precipitation using $CO_2 + NH_4OH$.
(*d*) Precipitation using $CO_2 + NaOH$.

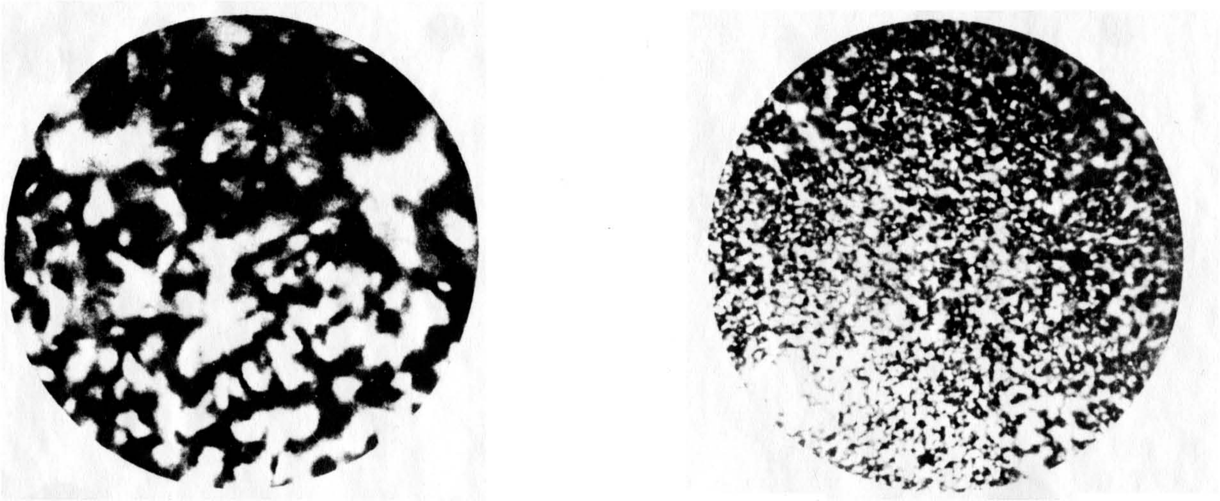

Fig. 33. Electron microscope photographs. Magnification 200

(*a*) Carbonate coating shown in Fig. 32(*a*)

(*b*) Carbonate coating shown in Fig. 32(*b*)

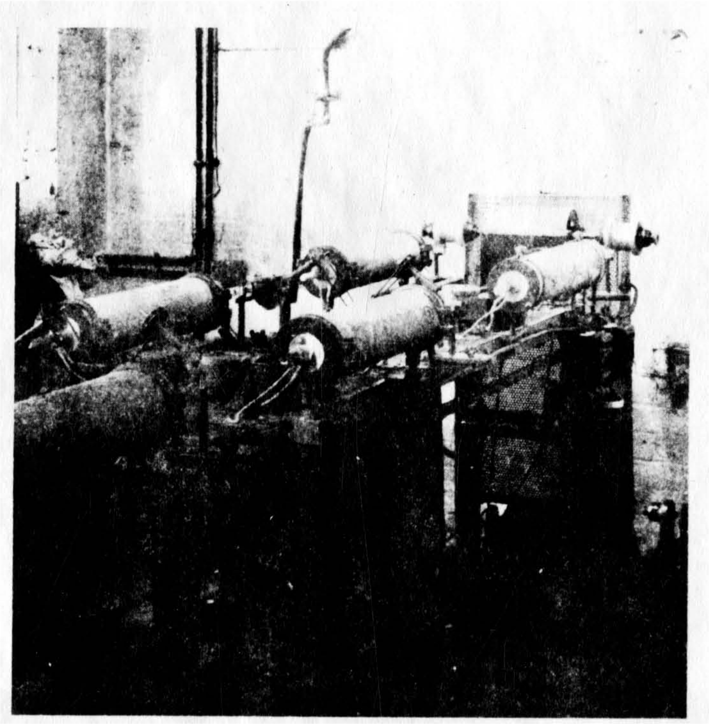

Fig. 35. Filament coating plant

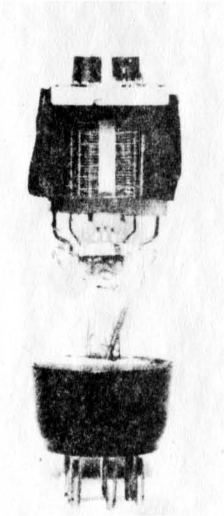

Fig. 43. [illegible]

[illegible]

inexpensive to operate, focused commercial attention on the oxide emitters. A considerable improvement in the standard of high-vacuum technique had to be achieved, however, before general commercial manufacture could be contemplated. We have seen that, as the emitter becomes more efficient, the degree of vacuum becomes increasingly important, because of the "poisoning" effect of gas on the emitter. The oxide cathodes are generally produced in the evacuated bulb, and a large quantity of gas has to be removed from the valve before any activation of the cathodes can be attempted. Two processes have been in general use. In Europe, the process was to plate a tungsten wire with a thin film of copper. The copper was oxidized, and the alkaline earth, usually barium, was obtained by decomposition of the alkaline-earth azide. The barium metal combined with the copper oxide to form barium oxide.

This process, the vapour process, was introduced by the Philips Lamp Co., of Holland. The process had one distinct advantage: the large quantities of barium liberated during the distillation acted as a very efficient getter, both on the pump and during life.

In America, the oxide was formed by coating a wire with a paste of the carbonate or hydroxide. This paste, when raised to a suitable temperature in a vacuum, decomposed to form the oxide. The gas evolved had to be pumped away, and getters were employed during pumping in order to maintain a high vacuum.

Table 4

Emitter	Efficiency	Emission density	Operating temperature	Work function
	mA per watt	mA per cm.^{2}	°K.	volts
W ..	1 to 5	274	2 500	4·52
W-Th ..	20 to 25	3 000	1 900	2·77
W-O-Cs ..	700	126	810	0·7
BaO, SrO CaO	150 to 250	250	1 040 to 1 100	0·95

The vapour process lost favour when the necessity for indirectly-heated cathode valves arose. The distillation of barium introduced leakage between electrodes, and this leakage resulted in very noisy valves. To-day practically all makers of receiving valves employ the paste oxide type of cathode.

Table 4 summarizes the properties of types of emitters mentioned, and gives the results obtained over a number of years in the organization with which the authors are associated.

(ii) Mechanism of the emission.

The theory generally accepted* is that the alkaline-earth oxide coating behaves as an electronic semi-conductor. It conducts because of the presence of the right kind of impurity atoms, in this case barium atoms. The barium atoms are produced from the oxide, and it is these barium atoms which supply the conducting electrons. These electrons are finally emitted into vacuum because of the presence of a monatomic film of barium on the surface of the oxide. If certain assumptions are made, it can be shown that the Richardson equation

$$I = A\theta^2 e^{-(\phi-\mu)/k\theta} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

holds for these oxides. μ, the inner potential, is given by

$$\mu = \tfrac{1}{2}(W_1 + W_2) + k\theta \log \frac{\alpha N_0^{\frac{1}{2}}}{(\beta\theta)^{\frac{3}{4}}} \quad . \quad . \quad . \quad (9$$

where W_1 and W_2 are energy levels in the oxide, α and β are constants, and N_0 is the number of barium atoms per cm.^{3}; so that the work function depends on the concentration of barium atoms.

(iii) Chemical composition and physical state of practical oxide coatings.

The usual oxide coating consists of barium and strontium oxides present in equimolecular proportions or equal parts by weight. The oxides are usually obtained by decomposition of the carbonates in vacuum. It has been established that under ideal vacuum conditions, a mixture of the two oxides has a higher emission than either of the single oxides. The maximum emission is obtained when, for a given chemical composition, the oxides are present as a homogeneous solid solution. In Fig. 31 the relation between emission and chemical composition of the double oxide is shown. The theoretical reasons for the necessity for the double oxide are discussed elsewhere.* The emission also appears to be a function of the particle size of the double oxide. Thus, the three main features of the cathode coating are: (1) it should be a homogeneous solid solution of barium and strontium oxides. (2) It should have the correct oxide composition after final treatment in the valve. (3) The mixed oxide particles should be as small as possible.

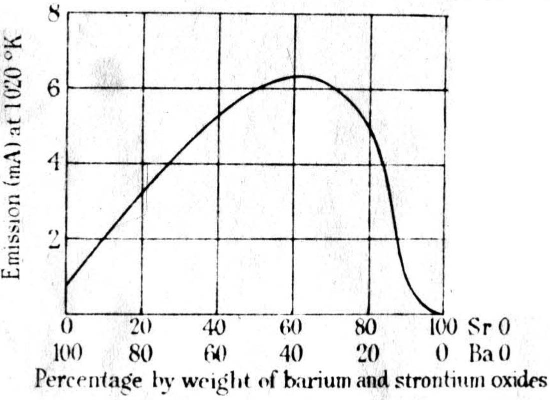

Fig. 31.—Emission from solid solution of barium and strontium oxides.

Condition (1) is achieved by correct preparation of the original carbonates. If the carbonates are in solid solution, then they invariably give a double oxide when decomposed in a vacuum. The double carbonate is obtained by simultaneous precipitation from a hot alkaline solution of the nitrates.

Condition (2) is achieved by using the correct amount of each nitrate, and by ensuring that the nitrates solution is alkaline. Otherwise preferential precipi-

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* See Reference (22).

* See References (29), (30).

tation of the strontium carbonate occurs, and the resulting carbonate may have two or more phases of varying chemical composition. On heating the double carbonates in vacuum, the temperature must be controlled, or else a change in chemical composition of the resulting oxide may occur. This point will be amplified under the heading " Pumping Technique."

Condition (3) depends on the way in which the precipitation from the nitrates solution is carried out. The exact nature of the precipitating agent, the alkaline agent used, temperature, speed of precipitation, and the solution strengths employed, are all important factors. Although there is not space to describe the various methods, the photomicrographs in Fig. 32 (Plate 1, facing page 416) illustrate the range of particle sizes that can be obtained. Recently, E. Patai and Z. Tomaschek* have described a method for obtaining carbonate particles of colloidal dimensions.

The authors are now studying the effects of the carbonate particle size by means of the electron microscope. Although the results obtained are not yet conclusive, it may be of interest to show just how two coated surfaces which differ only in the particle sizes of the original carbonates exhibit very different emission characteristics. In Fig. 33 (Plate 2) are shown the electron photomicrographs of two cathodes, one coated with the coarse-particle double carbonate and the other with the fine-particle double carbonate shown in Fig. 32. It will be seen that while the emission density is very much the same for both, the total emitting area is very much greater in the case of the fine-particle carbonate. The photographs are reproduced here so that the importance of particle size can be visually appreciated.

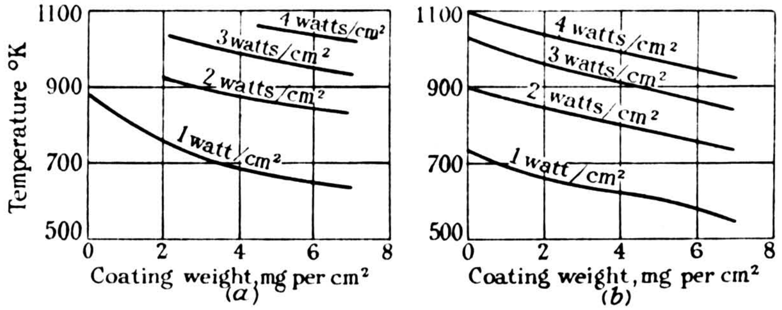

Fig. 34.—Effect of coating weight on temperature of coated copper and nickel cathodes.

(a) Copper cathode.
(b) Nickel cathode.

(iv) The core material.

The essential features of the core material are that it shall be mechanically strong, easily worked, have a high melting-point and low thermal emissivity, and be inexpensive.

Nickel, copper, silver, gold, platinum, and various alloys of these metals are all possible core materials. Tungsten cannot be used, because shaped indirectly-heated cathodes are extremely difficult to make. Platinum and gold are too expensive, and silver is too volatile. Therefore, nickel or copper, both of which are cheap, might be used. Copper has one advantage over nickel; its thermal emissivity is much lower, and since, in practice, the temperature of the coated cathode is dependent on the thermal emissivity of the core and the thickness of coating, a coated copper cathode will require less power to maintain it at a given temperature than a similarly coated nickel cathode.

Curves showing the temperatures of coated copper and coated nickel at the same watts input per cm^2 are given in Fig. 34. It will be seen that the temperature of the coated cathode depends on the coating thickness, and that at a given temperature a copper cathode requires about 25 per cent less power than a nickel cathode.

The chief disadvantages of copper are: (1) Its lower melting-point (1 080° C., as against 1 450° C. for nickel). (2) Its greater volatility (evaporation takes place at temperatures as low as 730° C.). It is therefore necessary to activate a copper cathode at a lower temperature than that employed for nickel (1 100° C.), and to operate the cathode at a maximum temperature of 730° C. At higher temperatures, any evaporation which takes place will give rise to electrical leaks and noisy valves. For these reasons, nickel is to be preferred as a core material, and it is the core metal normally used by all valve makers.

It has been shown* that, in order to obtain the best thermionic results, certain metallic impurities, which will act as reducing agents to the oxide coating, are desirable in the nickel. These impurities increase the barium concentration by their reducing action, and so assist in improving the thermionic emission. Suitable metals are aluminium, magnesium, titanium, the rare-earth metals, and silicon. The actual amount and nature of impurity added is governed by the ease of manufacture of the nickel alloy, and by the following considerations: (1) Effect on thermal emissivity of the nickel (generally increased). (2) Effect on electrical resistance of the nickel (generally increased). (3) Effect on mechanical strength of the nickel (generally increased).

In the case of indirectly-heated cathodes (1) is the chief consideration. For directly-heated cathodes, some adjustment can be made to diameter and length which will offset the effects of (1) and (2). In practice, the authors have found that, for directly-heated filaments, a nickel + 2 per cent aluminium alloy is satisfactory. For indirectly-heated cathodes, the presence of up to 0·1 per cent of magnesium is best.

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* See Reference (31).

* See Reference (32).

Attempts have been made to introduce barium directly into the core. Alloys of nickel and barium which contain more than a trace of barium are extremely difficult to make, and nickel-barium alloy cathodes have not yet been used commercially.

(v) Coating processes.

For directly-heated cathodes, in the form of a wire or strip the cathodes are made by drawing the wire through a series of baths and ovens. The apparatus is illustrated in Fig. 35 (Plate 2). The baths contain a water suspension of the carbonates together with about 12 per cent of barium or strontium nitrate, which acts as a binder. After passing through a bath, the wire passes through the oven at 750° C. The atmosphere is generally one of CO_2 in order to avoid any decomposition of the carbonates, and the authors have found that oxidation of the core due to nitrate decomposition can be avoided by the use of suitable mixed gases. This is important, as core oxidation slows up the cathode activation. In the oven the coating is sintered on (the nitrates decompose to form carbonates) and the final coating consists of a homogeneous double carbonate. This coating and sintering process is repeated until the required weight of coating is obtained.

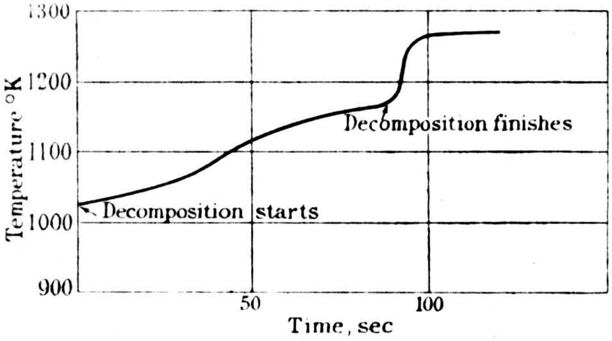

Fig. 36.—Cathode temperature-changes during degassing at 5·9 watts per cm.².

For indirectly-heated cathodes, a suspension of carbonates in an organic solvent is made and sprayed on to the nickel base. The degree of adhesion of the coating to the core metal is governed by the nature of the diluent used and by the actual spraying conditions. The following factors are also important—stable viscosity of the spraying suspension, temperature of spraying, fineness of the carbonate particles.

The carbonates are decomposed to oxides by heating them on the pump. The carbonates begin to decompose at 750° C. An important factor in manufacture is that the time of decomposition should be kept as short as possible. In order to avoid evaporation of the coating, however, the temperature of the coated cathode must never exceed 1 100° C.

An additional complication is that the thermal emissivity of the coating falls when it changes from carbonates to oxides, so that a rise in temperature occurs although the watts supplied remain the same. A curve showing temperature-changes and time of decomposition of the carbonate is given in Fig. 36.

HEATERS

(a) Core Material

In indirectly-heated types, the cathode is normally a hollow tube of circular, oval, or rectangular section, which is heated by means of a filament inside the cathode, but insulated from it. The core material is generally tungsten. Since the heater wire normally runs at a temperature several hundred degrees above that of the cathode surface, it is essential that the wire should have a high melting-point. One of the disadvantages of tungsten, however, is that it is prone to brittleness at high temperatures. The brittleness, caused by crystal growth, can be avoided if 0·02 per cent alumina is added to the tungsten. This prevents temperature recrystallization below 2 000° C.

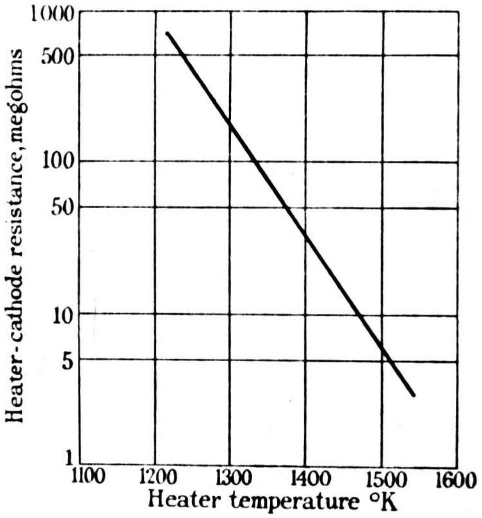

Fig. 37.—Electrical resistance of alumina coating.

Another form of core wire now being used consists of a molybdenum-tungsten alloy. This alloy was first introduced in America, and the advantages are that the alloy retains the ductility associated with the molybdenum, and yet has a melting-point well above that of molybdenum, and a vapour pressure which is negligible below 1 750° C.

(b) Insulating Material

The insulating material consists of a refractory such as alumina which is sprayed on to the heater. The heater-cathode insulation, which must be as high as possible for circuit reasons, depends on: (1) The temperature of the heater. (2) The nature of the insulator used.

(1) A curve, showing variation in the heater-cathode insulation with temperature, for alumina-coated tungsten, is shown in Fig. 37. It is essential to design the heater to run at as low a temperature as is possible.

(2) The current/voltage curve for a typical alumina coating is shown in Fig. 38. It will be seen that a higher current flows when the cathode is positive with respect to the heater, and that it saturates. There is reason to believe that the alumina behaves as an impurity semi-conductor, although it is difficult to

determine whether the leakage current is carried mainly electronically or electrolytically. There appears to be no doubt, however, that the purer the alumina the higher the insulation. The chief impurity in alumina is sodium, present as sodium aluminate, and this must be removed as far as possible by chemical means. The following treatments are usually given to the alumina:—

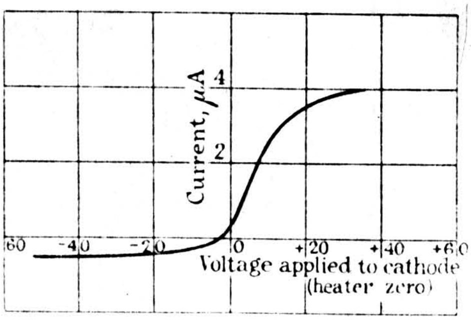

Fig. 38.—Current/voltage characteristics of alumina coating.

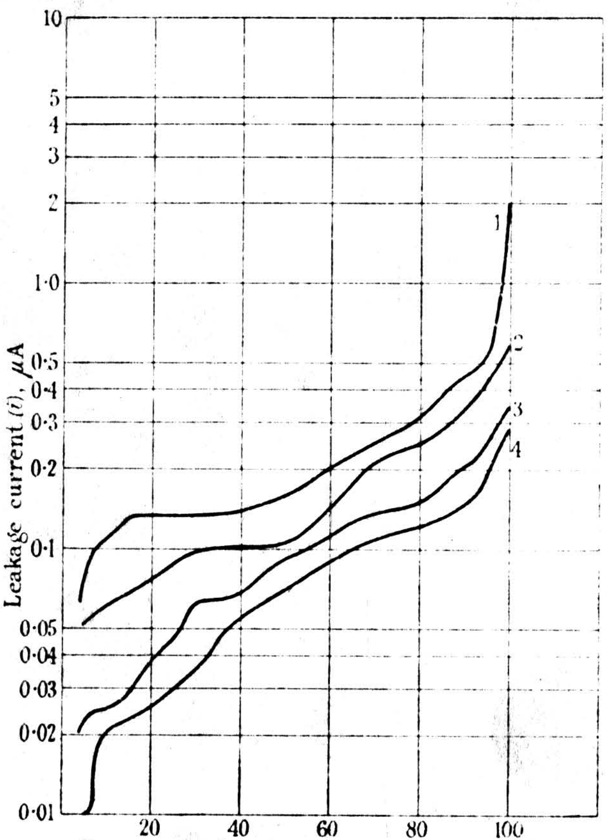

Fig. 39.—Insulation distribution curves.

Curve 1. Alumina.
Curve 2. Washed alumina.
Curve 3. Alumina presintered at 1 750° C.
Curve 4. Alumina + 1 per cent BeO.

(i) As much alkali as possible is removed by prolonged acid washing. Generally the alkali can be reduced to 0·02 per cent. It is essential to store the washed alumina so that atmospheric contamination is reduced to a minimum.

(ii) After spraying, the coated heater is heated in hydrogen at a high temperature. This removes the binder, sinters the coating, and removes a certain amount of sodium and other impurities. Sometimes it is necessary to sinter the washed alumina in hydrogen at 1 600° C. before it is used for spraying purposes.

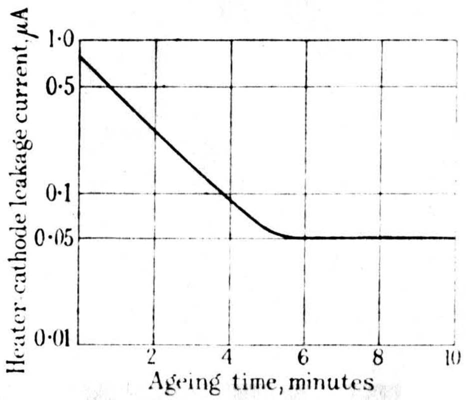

Fig. 40.—Effect of ageing with + 45 volts applied to cathode, for alumina coating.

One other method of improving the insulation has been found to be effective. If a small amount (1–2 per cent) of beryllia is added to the alumina, the insulation is improved to a level reached by taking the precautions described above. It appears that the beryllia combines with the alumina to form a compound of the type $(BeO)_y(Al_2O_3)_x$. Its exact formula has not been established, but it is not the ordinary beryllium aluminate. It may be that in this compound the different crystals produced may have different energy levels, which result in the altered conductivity.

The effect of these treatments on the insulation is shown in Fig. 39. It is a remarkable fact that at the operating temperature of the heater (1 400° K.), heater-cathode resistances of 80 megohms or more can be obtained.

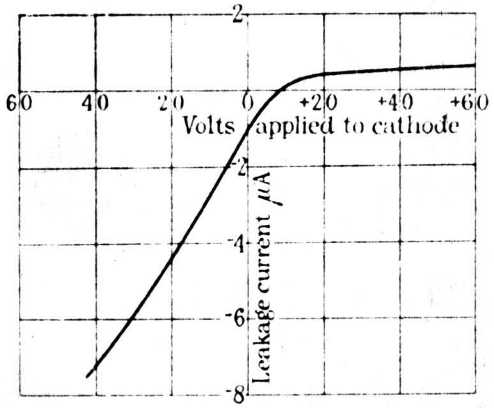

Fig. 41.—Current/voltage characteristic of magnesia coating.

One other feature leading to poor insulation is contamination by handling during assembly. It is not always possible to avoid this, and the remedy is to apply a potential between heater and cathode during ageing. A "poisoning" of the conductivity occurs, and the insulation improves. The improvement is permanent, but the reason is not clear. The effect is shown in Fig. 40.

Magnesia has been used as an insulating coating, but the authors have found it to be unsatisfactory. It can be readily obtained pure, but it cannot be sintered in the presence of tungsten without some combination occurring. Further, at 1 700° C. magnesia has an appreciable vapour pressure, so that coating may be lost during sintering, and during pumping. In the valve, the heater lighting treatment results in further reaction between the magnesia and the tungsten core, and a compound of the tungstate class is formed. The electrical characteristics of a magnesia-coated tungsten wire are extremely interesting, and are shown in Fig. 41. It will be observed that initially the greater current flows when the cathode is negative with respect to the heater, but prolonged running with the voltage applied so that the cathode is positive (the normal condition) results in electrolysis of the coating, and tungsten is deposited on the coating surface adjacent to the cathode. A short-circuit results, and the heater fails. The objections to magnesia coatings apply to magnesia tubes, which have been used by valve makers to sleeve tungsten heaters.

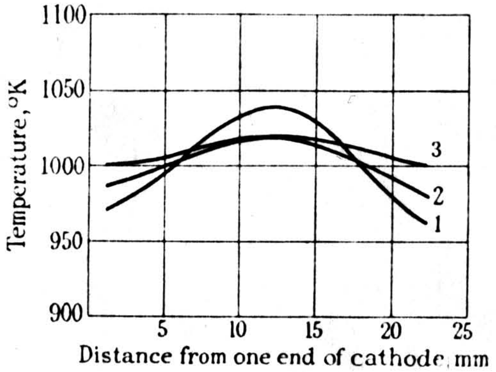

Fig. 42

Curve 1. Single hairpin heater.
Curve 2. Reverse helix heater.
Curve 3. Single coil heater with centre return lead.

(c) Heater-Cathode Design

In indirectly-heated valves the design of the combined heater-cathode system is important, judged from the standpoint of emission efficiency. For a cathode of a given area, dissipating a given number of watts, it is desirable that the energy should be distributed as evenly as possible over the cathode surface. With the ordinary hairpin type of filament, the temperature-difference between the end and centre of the cathode may be as high as 80 deg. C. This can be brought down as low as 5–10 deg. C. by suitable heater design.

The operating temperature of the heater is decided largely by the disposition of the heater in the cathode, for the latter is heated mainly by radiation (any conduction can only take place at a number of points or live contacts). It follows, therefore, that the lowest temperature of a heater which is dissipating a given number of watts, will be obtained when the radiating area of the heater is the greatest. Thus the most efficient heater would be a close-fitting cylinder. The nearest approach to this is a single helix wound with turns as close together as is possible.

In Fig. 42 are some interesting curves for temperature distribution along the cathode, when various shapes of heaters are used. It must be borne in mind that heater design is influenced by such factors as magnetic-hum effects and coating problems, so that it may not always be possible to use the lowest-temperature heater. One other disadvantage of low-temperature heaters is their greater heating-up time due to their larger thermal capacities and smaller differences between their cold and hot resistances. In Table 5, characteristics of a cathode with three different heaters are given.

"GETTERS"

A getter is used for maintaining the vacuum in a valve after it has been sealed off. The alkaline earths, the alkali metals, and magnesium, are common getters; and the getters mostly used to-day are an alloy of barium and magnesium, and barium. The alkaline-earth oxides, singly or mixed, are also good getters.

Table 5

Heater	Heating-up time of cathode	Temp.-diff. between centre and ends of cathode	Operating temperature of heater
	sec.	°C.	°K.
Hairpin	11·2	80	1 460
Double helix . .	15·0	40	1 400
Single helix . .	17·9	10	1 360

(a) Method of Use

(i) Metal getters.

If the metal is relatively stable in air, it is welded to a metal disc and dispersed by high-frequency heating of the disc. If the metal of which the getter is composed is an unstable one such as barium, it is packed inside a closed container before welding. The high vapour pressure generated on heating is sufficient to burst open the closed ends of the container, and the metal is dispersed. In order to avoid any deposits forming over the electrode bonding system and so causing electrical leaks, the getter dispersal is usually directed towards the bulb wall by a suitable design of container.

(ii) Non-metallic getters.

Where very high inter-electrode insulations are required, as in certain special types, the non-dispersed form of alkaline-earth oxide getter is used. This is usually sprayed on to a metal disc in the form of cathode coating, and decomposed by high-frequency heating to the oxides. The oxides, when cold, act as getters. Although the authors believe this to be the first time that the oxides have been used in this way, for many years some valve manufactures applied a paint of alkaline-earth carbonates to the pinch.

It will be appreciated that since the emitting cathode itself is a mixture of alkaline-earth oxides, it too, in the active state, will adsorb gas, and this point must be carefully watched when valves are being made.

(b) Mechanism of Clean-Up

The gettering action of dispersed metals is twofold.* During dispersal a clean-up occurs, referred to as " volume gettering." Then when the gas comes into contact with the dispersed getter deposit a second gettering action occurs, known as " contact gettering." The gas is taken up either because it is adsorbed into the metal, or because it combines chemically with the metal. The actual nature of the clean-up depends on the type of getter, the nature of the gas, and the conditions prevailing at the time. For example, magnesium will adsorb hydrogen in contact with it, and this can be liberated again by heating the magnesium deposit. It will not adsorb CO_2, except under discharge conditions. Sodium will not getter hydrogen except under discharge conditions, and then it chemically combines with it to form the hydride. Barium will adsorb all the permanent gases, and it forms chemical compounds with oxygen and hydrogen. Hence barium is the most desirable getter, because of its affinity for most gases, and because the chemical nature of the clean-up means that the gas will be held even when the getter surface is hot.

The alkaline-earth oxide getters clean up by an adsorption process and are most efficient when dealing with CO_2. The gas is easily liberated on warming or by electron bombardment.

(c) Precautions in Use

Since getters may liberate adsorbed gas when warm, they should be deposited on the coolest part of the system. Direct electron bombardment may also liberate gas, and care should be taken to put the deposit in such a position that it is unlikely to acquire a positive potential. If possible, the getter deposit should be at cathode potential. In any case, since the metal disc always contains some getter residue, it is desirable to connect it to the cathode.

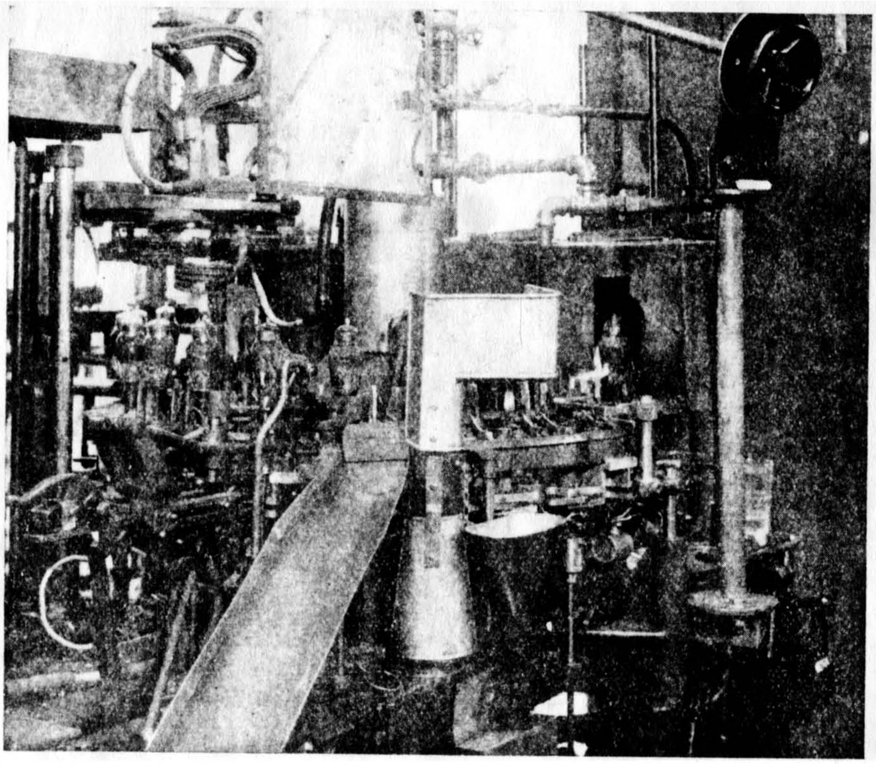

Fig. 44A.—Pumping unit.

PUMPING TECHNIQUE

The pumping of a modern receiving valve is designed to remove the greatest amount of gas in the shortest possible time. All the materials used are rendered as gasfree as possible before assembly (see section on " Properties of Materials "), and the completed valve is heated on the pump to remove any remaining gas. In Fig. 43 (Plate 2) a complete valve assembly of a power output (type N43) valve, including the heater, cathode, multiple electrode system, and getter, is shown. The pumping system used consists of a series of 2-stage machine pumps. Figs. 44A and 44B respectively show photographs of a pumping unit and a battery of pumps. The speed of pumping is given in Fig. 45.

The pumping procedure is as follows: (*a*) The system is baked at 450° C. in order to remove water vapour.

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* See Reference (33).

(*b*) The electrode system is heated by high-frequency induction in order to remove adsorbed gas. (*c*) The cathode is heated in order to decompose the carbonates, the electrode system again being heated to prevent it picking up cathode gas. (*d*) The getter is dispersed, and the valve sealed off. The time taken to treat an individual valve varies according to type, but a speed of 400 valves an hour is an average figure when using a unit of the type shown.

The precautions to be observed are as follows: (i) The electrode system should be heated in such a manner as to ensure that excessive peaks of gas pressure are avoided. (ii) The cathode temperature should be maintained throughout the pumping process, since once the carbonates are decomposed the cathode is in an active state, and, as has already been pointed out, it will adsorb gas at low temperatures. (iii) The getter should be dispersed when the pressure is low, so that it is not employed in cleaning-up gas from the pump system. For this reason, the valve should be sealed off as soon as the pump has had time to remove any gas liberated by the gettering operation.

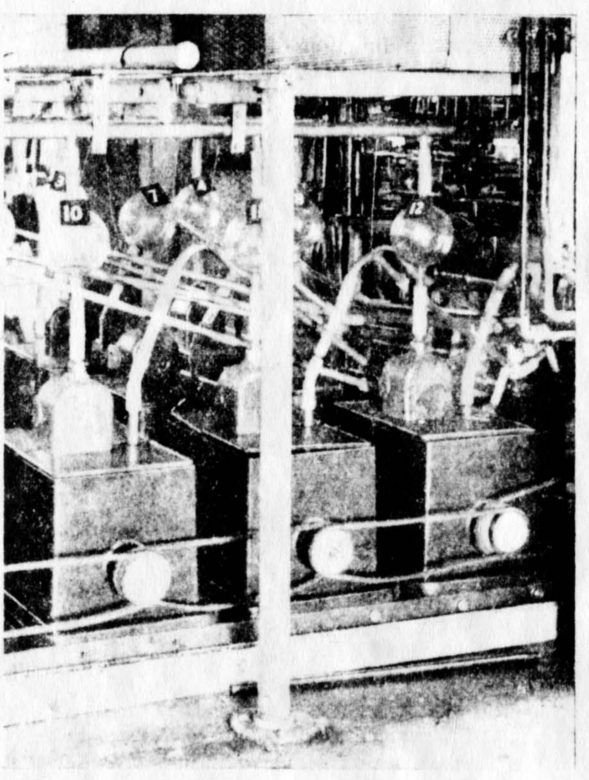

Fig. 44B.—Battery of pumps.

ACTIVATION PROCESS

The process of keeping the cathode hot after decomposition results in partial activation of the cathode. Activation is completed by drawing current from the cathode whilst it is run at a temperature of 900° C. The electrolytic process going on in the coating results in the formation of more barium, and the space current grows with time. Further, the voltage across the valve and the current flowing ionize any gas present, and enables the getter to clean it up. The time and nature of the activation depend on the specific type, but as a general rule the cathode is run at 850°–900° C. with all other electrodes strapped at a common positive potential, and a space current of 100 mA per cm.[2] is drawn for 2–5 minutes. The valve is then run for 30 minutes under normal operating conditions, except that the cathode temperature is still maintained at 850°–900° C.

The initial bombardment period cleans the first grid surface, and any barium deposited from the cathode during the second period comes down on to a clean surface. This is important, particularly in high-μ types. The contact potential between grid and cathode determines the voltage at which grid current starts, and the activation schedule outlined above enables some measure of control to be exercised over the contact potential.

VALVE LIFE

(a) Emission Life

The life of the finished valve depends on the temperature of the cathode, and its resistance to poisoning by evolved gas.

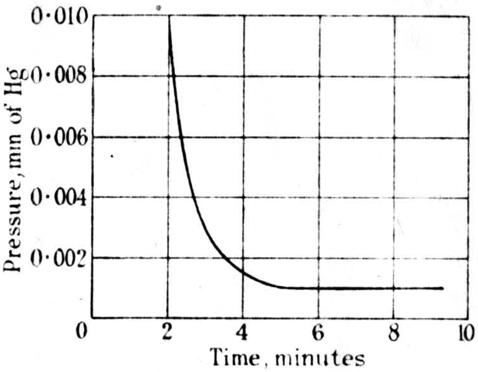

Fig. 45.—Pumping speed of a machine pump.

As is shown in Fig. 31, the emission from the solid solution of oxides is a function of the proportions of each oxide present. The oxides evaporate, and the barium oxide is considerably more volatile than the strontium oxide. Thus if the coating is run at such a temperature that appreciable volatilization of BaO occurs, the composition of the solid solution changes and the emission slowly falls. The rate of fall decreases with time, because the rate of evaporation of BaO decreases with increasing strontium content. The lowest possible temperature consistent with the emission demand will give the longest life, providing any poisoning effects are absent.

The oxide cathode usually fails because it adsorbs gas and is "poisoned." One of the factors which contribute to poisoning is the gas evolved from the electrode system because of the energy dissipated. As has been shown, the cathode readily adsorbs gas, and the lower the temperature of the cathode the more readily is the gas adsorbed. The getter is present in order to cope with evolved gas, but its capacity is limited, and the valve needs only a very little of a gas such as oxygen or carbon monoxide, both of which are readily adsorbed by the cathode coating, to poison the emission. Poisoning occurs at pressures of oxygen as low as 10^{-6} mm. of mercury, and recovery is generally impossible.

The cathode ceases to adsorb gas at about 1 000° C., but this temperature is too high from the point of view of coating evaporation. In actual practice, the cathode temperature must be adjusted to suit the type of valve. Where very little emission is required, as in a high-μ triode, and where few watts are dissipated in the anode, the operating temperature can be as low as 750° C.; but for a rectifier which requires a large emission throughout life, and in which considerable watts are developed, the temperature during life must be not less than 850° C.

One other factor influences life. The design of the heater-cathode system determines the temperature distribution along the cathode. If the temperature-difference between end and centre is great, then the ends will become poisoned, and the valve will fail because part of the cathode has been rendered useless.

(b) Mechanical Life

Apart from failure of the emission, the valve may fail because it develops a mechanical defect. One such form of failure is for the heater of an indirectly heated valve to fracture, particularly when it is of the hairpin type. This is usually due to the fact that the tungsten expands and contracts much more rapidly, when the heater temperature is varied, than the insulator coating, which adheres tightly to it. The condition is particularly severe when the valve, as in practice, is switched on and off several times a day. To avoid this difficulty it is desirable for the coating, instead of forming a smooth shell, to consist rather of a series of beads. The difference in appearance is shown in Fig. 46. The effect is obtained by careful control of the initial density of the insulating material, so that the coating on the heater can shrink during sintering.

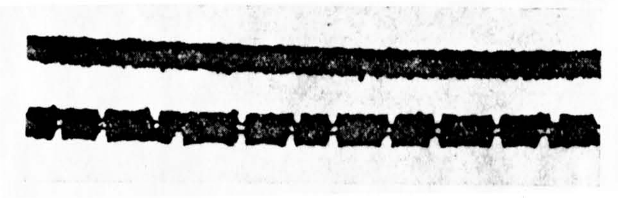

Fig. 46

(c) Electrical Life

Other causes of failure are the development of electrical leaks, grid emission, and gas in the valve during life. No specific cure for any of these troubles can be listed, but any particular type must be treated according to the symptoms observed.

Electrical leakage may be due to volatilization of active cathode material and getter, and designs must be modified to overcome these defects. Grid emission must be looked after by suitable design of the grid cooling arrangements which have already been described. The evolution of gas during life must be studied from the point of view of the gas content of electrode materials, the pumping, and the gettering techniques. All these factors are dealt with in detail in various sections of the paper.

Where very long lives (20 000 hours and more) are required, as in valves for use in P.O. telephone repeater circuits, low-temperature operation of the cathode is essential. In order to avoid poisoning during life, the pumping schedules are lengthened to an extent quite impracticable for ordinary manufacture of valves for broadcast reception. The lengthened pumping treatments are necessary in order to ensure that practically no gas is evolved in the valve during subsequent operation.

LIMITATIONS DUE TO BACKGROUND NOISE

Since the main function of a receiving valve is to amplify signals it follows that any noise generated by the valve itself will set a limit to the maximum useful gain which can be employed.

In the early days of bright-emitter valves a phenomenon known as "crackling" was often met with. This was an intermittent effect which was ascribed to irregular emission from the hot tungsten filament. With the introduction of thoriated tungsten dull-emitter valves the filament became less ductile and was more easily excited by mechanical shock into a state of transverse vibration. In consequence the limit of amplification at that time was determined mainly by the microphonic properties of the valve.

(a) Alternating-Current Hum

When the need for the operation of receiving-valve cathodes from an alternating-current supply arose, a fresh limitation presented itself in the form of a.c. hum. Early attempts to use valves with a.c. heating of a filamentary cathode met with considerable difficulty. The first modifications were heavy-current low-voltage filaments, which avoided flicker due to temperature-changes and reduced the electrostatic control of the electron stream. Unfortunately, the heavy current produced a strong magnetic field, which set a limit to this method. Nevertheless, commercial receivers were manufactured for a time on these lines.

The functions of heater and cathode were now separated, so that the current did not flow through the cathode material. Difficulties arose due to the need for providing insulating material between heater and cathode. Vacuum insulation was of course satisfactory but required liberal dimensions, which resulted in high-consumption heaters and inefficient valves from the mutual-conductance point of view. The development of special insulating materials has been dealt with elsewhere in this paper, and it will be sufficient now to indicate the present limitations of indirectly-heated-cathode valves.

Where the heater can be operated with cathode return to the centre point of the heater supply, the main source of hum is magnetic in origin. The effect can therefore be reduced by reducing the heater current and to some extent by special arrangements of the heater. Assuming the heater watts to remain constant, the low-current method results in increased heater voltage with a greater increase in the hum produced when the slider of the potentiometer shunting the heater is moved from the centre point. This is due to: (1) Heater ends producing a grid effect on the electrons from the end of the system. (2) Thermionic emission from the heater being collected by the grid (especially with high resistance in grid circuit). (3) Ends of heater robbing electrons from the main system, either at the ends or strays. (4) Capacitive coupling between heater leads and grid lead.

These effects are set forth quantitatively in Fig. 47. The curve for the MH4 valve shows the hum produced by the straight "hairpin" heater operated at 4 volts, 1·0 amp. Contrasted with these is an MH41 valve fitted with a heater of spiral or reverse "helix" form. The difference in hum at the ends of the potentiometer is a feature of the electrode arrangement, but the reduction in magnetic hum at the centre point is marked. The third pair, for the H30 valve, concerns a further heater of spiral form but operating at 13 volts, 0·3 amp. Here the magnetic hum at the centre is still further reduced by the lower current, and the steep rise at the end has been minimized by taking the grid connections to the top of the bulb and by the use of screens round the heater leads.

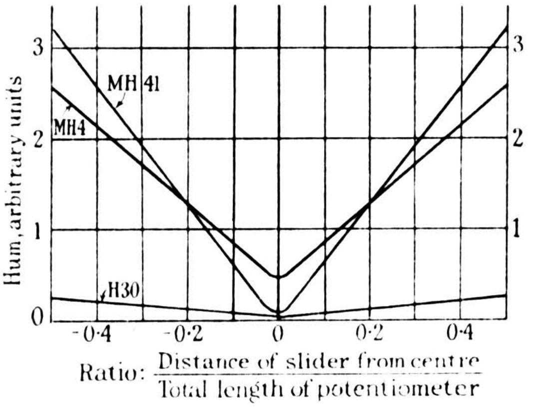

Fig. 47.—Effect on hum of various heater-cathode designs.

A special case of commercial importance arose with the introduction of the d.c./a.c. set, where for the sake of economy the heaters are operated in series on an a.c. supply. It is necessary for the cathodes of all the valves to be connected to one end of the a.c. supply, so that large a.c. voltages exist between the heater and cathode in many of the valves. In this case the a.c. voltage between heater and cathode may be several times as great as the voltage across one heater. All these effects can be minimized by enclosing the ends of the heater in metallic shields connected to the cathode and by removing the grid lead as far away as possible from the heater leads.

In general, it can be said that it is now possible to make valves which, when operated on an a.c. heater supply, will give rise to a hum no greater than the basic "hiss" level arising from the shot and resistance noises. Such valves, however, demand special construction and are more expensive to manufacture than ordinary types.

While these latter effects are now well known as limitations to the amplification obtainable with valves, it is proposed to refer to them briefly.

(b) Shot Noise

The noise due to this effect arises from the random nature of the arrival of electrons as discrete particles at the surface of the anode. They generate a wide band of frequencies, and have been shown by Moullin and Ellis* to be equivalent to a mean-square voltage of approximately $11 \times 10^{-20} Idf/g_m^2$ at the grid of the valve in the case of an amplifier covering the range of audio frequencies given by df, where I = anode current (amperes) and g_m = mutual conductance (amperes per volt).

(c) Resistance Noises

In most applications of the valve it is necessary to connect a high resistance or impedance in the grid circuit. This resistance gives rise to further noises, which again cover a wide frequency band. Johnson and Nyquist† have shown that the effect of these is equivalent to a mean-square voltage of $1 \cdot 6 \times 10^{-20} Rdf$ across the resistance when the latter is measured in ohms.‡

A practical case where noises of this kind prove a serious limitation is in the application of the photoelectric cell, where a high grid resistance is imperative owing to the low currents produced by the cell. In this field the electron multiplier, described by Dr. V. K. Zworykin,§ is of particular interest. By dispensing with the need for a coupling circuit the resistance noises are eliminated, and the limiting noise becomes of the smaller order arising from shot noise due to the multiplier.

(d) Parasitic Noises

Apart from these fundamental limitations, designers are faced with more immediate problems by reason of noises of a greater magnitude which can be classed as "parasitic." In the manufacture of modern oxide-coated cathode valves it is necessary to heat the electrodes, including the cathode and heater, to high temperatures during evacuation. It is also essential to employ some form of "getter," usually in the form of a volatilized film to assist in removing occluded gases. These operations may result in the evaporation of the electrode metals, which tend to form conductive films on the materials used to support and insulate the electrodes. The cathode also will release barium metal during pumping and activation. These films may give rise to high-resistance leaks of variable effect due to the bad contacts between them and the electrode supports. Various types of "umbrella" insulators have been employed with success to obviate these effects, while careful attention to pumping technique may also yield beneficial results.

Again, it is found that noise may arise as the result of ionization in the valve. At quite low pressures, of the order of 10^{-5} mm. of mercury, these noises may easily exceed those produced by the shot and thermal effects, if a high grid resistance is used. They are, of

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* See Reference (34).

† *Ibid.*, (35), (36).

‡ For a complete bibliography on valve noise, see Reference (38).

§ See Reference (39).

course, of a similar nature, but are set up by the positive ions resulting from the ionization of the gas.

In the manufacture of modern receiving valves having a large number of grid electrodes with very small inter-electrode spacing, the problem of excluding foreign material is a very real one. A considerable quantity of dust and fluff is normally present in the air and this may settle on the electrodes during assembly and be sealed in with the system. During heat treatment much of this material will be carbonized and provide loose-contact short-circuits in the final valve. It will be appreciated that only one fragment of suitable shape is necessary in a valve to render it useless for normal purposes. Elaborate precautions have been found to be necessary to exclude this material.

Another parasitic effect with which all users of valves will be familiar is that of microphonic noise. This of course arises from movements of the electrodes relative to one another, resulting in slight changes in the characteristics.

In filament (battery) valves the main source of the effect is the transverse vibration of the filament wire or strip. Much has been done to limit this vibration by the use of insulated members to contact with the filament at intermediate points and so produce a damping action. Each contact of this kind, however, robs the filament of some of its heat and so limits the number which can be used. Moreover, owing to the small clearances used in modern battery valves, the insulating path is necessarily short and the difficulties of avoiding noise due to films are considerably increased.

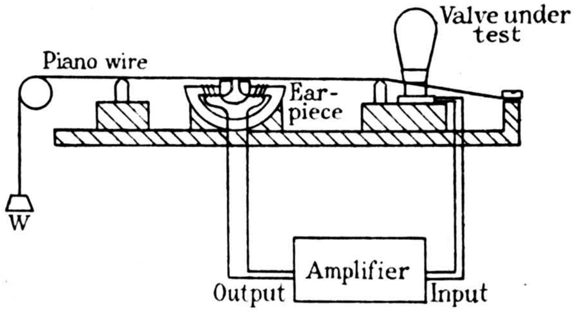

Fig. 48.—Test for microphone noise.

In indirectly-heated valves the cathode is a comparatively rigid structure, and if the electrodes are well bonded at the two extremities a much lower level of microphonic response is possible than in the case of battery valves. If the gain now be increased it will be found that microphonic effects arise due to a cantilever vibration of the whole system, and improvements can be secured by reducing the flexibility and moment of inertia of the system. In general, stiffer supports, lighter and shorter systems, and reduced height of mounting, are all beneficial.

In the study of microphonic noises it has been found useful to employ the apparatus shown in Fig. 48. The valve is mounted on a platform provided with two bridges over which a steel wire passes. The output of the valve is amplified and used to actuate a magnetic earpiece which drives the steel wire. With correct phasing the system will build up to a continuous vibration whenever the wire is tuned by means of the movable bridge to the resonant frequency of any part of the electrode system. The electrodes can now be examined with a binocular microscope, when the cause of vibration will usually be apparent.

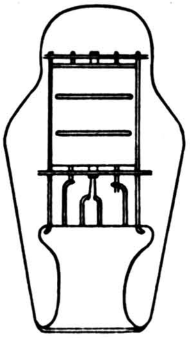

Fig. 49

ROBUSTNESS

The early users of radio valves were content to treat them as delicate articles, and manufacturers generally relied on cotton-wool methods in order to ensure safety in transit. This method was made more than ever necessary by the advent of thoriated-tungsten filaments, especially when they were carbonized or of very low current consumption.

With the general introduction of oxide-coated filaments and cathodes the emissive member ceased to be the chief factor limiting mechanical strength. Improvements were secured by bonding the electrodes by means of insulating members and by the use of thicker supports from the glass " foot " or " pinch." These changes had the unfortunate effect of increasing the difficulties of the glasswork, resulting in greater wastage in manufacture. By a choice of stiffer materials such as nichrome, magno-nickel, etc., some further improvement was secured, but it was not until the system was supported at the upper as well as the lower end that a real step forward was achieved.

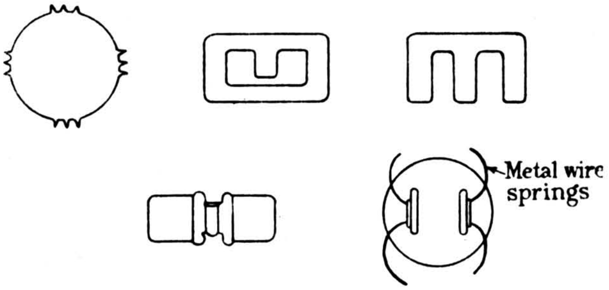

Fig. 50.—Types of locating members.

In the case of glass valves this was made possible by the use of glass bulbs with specially-shaped tops, generally known as " dome top bulbs " (see Fig. 49). Naturally there must be some variation in the internal diameter of the dome portion of these bulbs, and in consequence a great variety of methods have been used to compensate for these variations. As shown in

Fig. 50, these include various designs of flexible supports of mica and metal, and the use of serrated edges designed to break off according to the diameter of the bulb. In the metal-anode valves introduced in this country in 1933 (see Fig. 51) the inside of the anode became the supporting surface and, owing to the greater accuracy obtainable in a metal pressing, these devices were unnecessary.

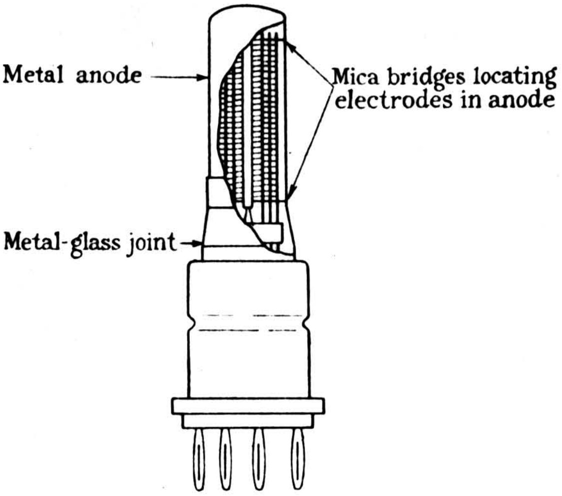

Fig. 51.—Air-cooled-anode output pentode.

The strength of each individual electrode can be greatly improved by the use of heavier-gauge metals. In the case of grid electrodes, however, this tendency conflicts with the technical requirements in many cases.

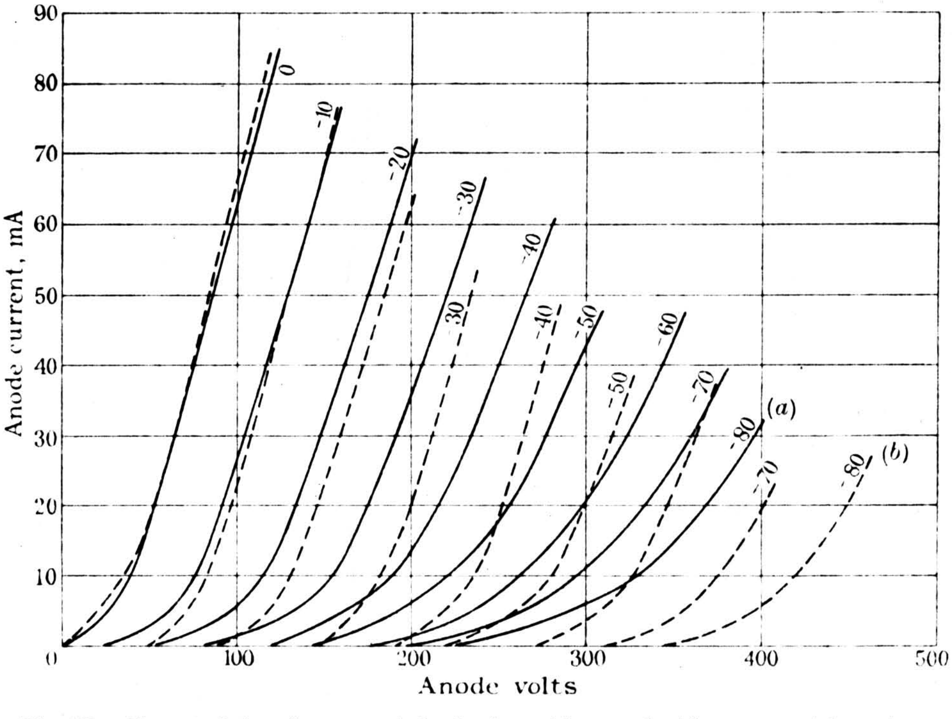

Fig. 52.—Characteristics of output triodes having grids wound with coarse and fine wires.

The amplification factor (μ) of a triode valve of cylindrical form is given approximately by the equation

$$\mu = a p n^2 K$$

where ρ = diameter of grid wire, a = clearance between grid and anode, n = number of grid turns per unit length, and K = a constant depending on electrode form.

It is possible, therefore, to secure the same μ value by using either a heavy wire with open pitch [(*a*), Fig. 52] or a fine wire with close pitch [(*b*), Fig. 52]. In both cases the characteristics will be similar in the region of zero grid volts. As the anode voltage and grid bias are increased, however, it will be found that in the case of the heavy-wire grid a characteristic " tail " will more quickly become evident. This tail is due to a failure of the grid to control the electron stream completely, and will produce second-harmonic distortion in output triodes. This effect has been dealt with earlier in the paper.

From the point of view of the characteristic, therefore, fine grid wires are desirable, and a compromise is necessary between the mechanical and electrical requirements.

FREQUENCY LIMITATION

The maximum frequency at which a radio valve will operate is entirely controlled by the physical dimensions, configuration, and potentials, of the electrodes.

In the case of triodes used as self-oscillators the input and output capacitances are of considerable importance. Of greater importance, however, is the inductance of the electrode leads and of the electrodes themselves. Assuming that the oscillatory circuit comprises inductance only, then the wavelength can be progressively reduced until the external circuit provides insufficient