THE DEVELOPMENT OF THERMIONIC VALVES FOR NAVAL USES.

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SUMMARY.

The first four sections of the paper describe the introduction of valves into naval wireless telegraph installations, and the early work, expe.imental and theoretical, on the elucidation of their observed behaviour.

Section 5 deals with the principles of the numerical design of power valves, more particularly triodes, and with the rapid development of the manufacture of valves so designed.

The three following sections, 6, 7, 8, deal with the investigation and improvement of small valves for use in reception, including both high-vacuum and gas-filled types.

Successive stages of approximation in the calculation of the characteristics of small valves with low operating voltages are illustrated in section 9, the final result of calculation indicating the degree oi closeness with which the observed behaviour of a high-vacuum valve can be accounted for in terms of known physical phenoména.

The concluding section deals with the standardization of valves and their specification for quantity production.

(1) INTRODUCTION.

The thermionic valve passed during the period of the war through all the various stages of the transition from an instrument the value of which was already recognized, but whose operation was erratic and theory obscure, to a product as reliable and as thoroughly standardized in manufacture as the incandescent lamp, and in addition capable, as regards all the main principles of its action, of explanation in terms of well-established principles of physical science, some of which had waited long for so definite an application.

This paper traces the course of this transition, as exemplified by the valves of various kinds with the development of which the wireless telegraphy departments of H.M.S. "Vernon," and later of H.M. Signal School, Portsmouth, were concerned.

The contributions of various laboratories and works to the work described amount to a considerable proportion of the whole, but the author hopes that, in the endeavour to distinguish such contributions, at least no injustice has been done.

Similarly, references are given to such published work, mostly of relatively early date, as influenced the course of development of the series of valves described, but no attempt has been made to refer to the considerable volume of work recently published.

The subjects of consideration relate to valves themselves, rather than to their mode of action in the electrical circuits in which they are used, and include the investigation of the special properties of valves of various kinds, and the methods of design, manufacture, and standardization, as far as these were developed. This treatment of the subject has necessarily made the current/voltage characteristics observed under steady current conditions the criterion both as to the phenomena within the valve, and as to its probable action in a given circuit.

Among the valves described as "high vacuum," that is, valves whose behaviour is in large measure independent of variations in such traces of residual gas as they may contain, those valves which are designed for power circuits providing operating voltages of hundreds or thousands of volts fall for many reasons into a class clearly distinct from the valves used in reception, where the operating voltages are measured by tens of volts, seldom nowadays by hundreds, and where the quantities of energy controlled by the valve are relatively minute.

If apology is needed for the space occupied by the description of "soft" valves, that is, valves whose action is dependent in one way or another on the presence of gas, it may be pointed out that no one can expect to understand the faults and limitations of so-called "high vacuum" valves who has not some understanding of the action of valves which contain gas in more than negligible quantity.

(2) THE APPLICATION OF EARLY VALVES TO NAVAL WIRELESS.

At the outbreak of the war one of the chief problems before the wireless telegraphy department of H.M.S "Vernon" was to find a good method of continuous-wave reception. This was more particularly pressing because Poulsen arc generators of various powers were already in a well-developed state. Small arcs had also been on trial as local oscillation generators for heterodyne reception, but small arcs tend to be more troublesome than large ones, and the smallest conveniently manageable at the time were of a power greatly in excess of what was really needed for use in reception. With these arcs, however, it had been clearly established that the use of the heterodyne itself gave enhanced sensitivity. It may be remarked here that the order of sensitivity so attained was deemed sufficient for all purposes in view, and there was no question at that time of developing amplifiers for use on any large scale.

Hence it was as a generator of low-power oscillations that the valve came to make its first appearance as a component of a naval installation. The advantages of eliminating the less steady of the two arcs, and at the same time substituting a generator of a more nearly suitable order of power, were obvious from the first.

For heterodyne reception the existence and stability of the local oscillation are the important matters rather than its actual strength, and it seems in retrospect that this requirement was a very simple one to satisfy. Almost any triode valve will fulfil it if suitably connected. Indeed, this elasticity influenced the development of the valves up to a very late stage; and rigidity of specification, for instance, was an unnecessary luxury as long as this simple requirement was the only one.

In the early days, however, the standpoint from which we viewed the valve and its ways was somewhat different. The first duty, and at the same time the first opportunity for beginning the study of the valve, was to examine and regulate the behaviour of certain concrete instruments. The two instruments receiving the most attention embodied respectively the ultraudion circuit (shown in Fig. 2) and De Forest "audion," and the Lieben circuit of Fig. 1 with one of Round's

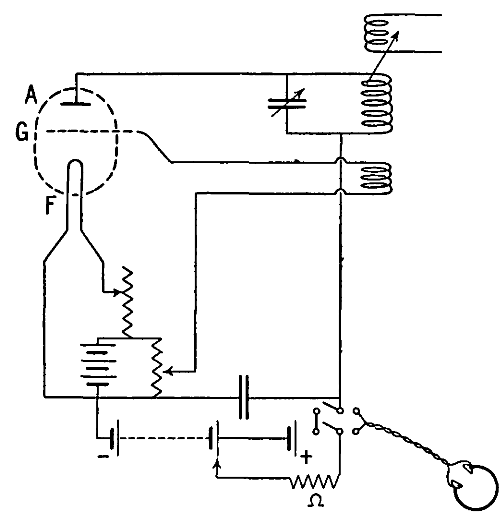


Fig. 1.—Lieben circuit heterodyne; Round valve.

earlier valves. Sets of this latter type, though eventually superseded, were in use to a considerable extent at one time. They had, however, the disadvantages of high anode voltage, excessive filament current, and the high mortality of platinum filaments working near their fusing point.

The first general principle to be thoroughly understood by us was that of the stability of the oscillation in this Lieben circuit, namely, that the resistance of the oscillatory circuit should be less than the product of the ratio of the mutual inductance to the oscillatory capacity into the rate of change of anode current with grid voltage. The establishment of this principle directly from the fundamentals of electro-dynamics by Professor Fortescue in December 1914, and its verification with the apparatus available, were a comforting beginning. Allied subjects of study were less promising. The internal action of the Round valves, with their relatively high gas pressure, high anode voltage, and necessarily extremely close grid is very complex, and to this day the author makes no claim to any clear comprehension of it. This valve is mainly dependent on a true multiplication of the ionic current by collision, giving poor results unless the gas pressure is high. Now most people who have taken up the study of valves have tended to exaggerate the importance of positive ions derived from the gas. The properties of this particular valve went to confirm us in this error for some considerable time. That was one source of difficulty. The electro-dynamics of the ultraudion circuit, again, are by no means so simple as those of the Lieben, even when all the essential electrical components are recognized. The inventor's diagram does not show them all, and one at least, of the greatest theoretical importance, had to be separately discovered. Further, the soft audion was a bad valve for use in

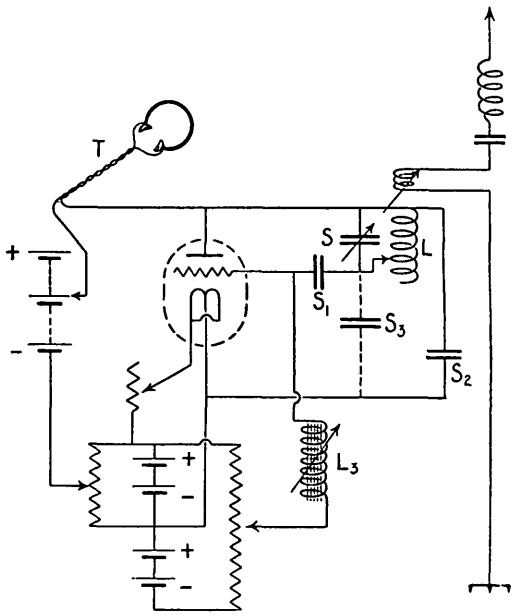


Fig. 2.—Modified ultraudion receiver; audion or R2 valve.

careful experiment. In this valve, as was demonstrated by G. B. Bryan at Greenwich in the winter of 1914–15, the equilibrium determining the amount of free gas present in the valve at a given moment was very easily disturbed by any marked change in adjustments. Reliable direct-current characteristics and other similar observations on the valve itself were difficult to obtain. However, the complication of the circuit would in any case have obscured the real connection between the characteristics of the valve and its functions in operation. The sets of this type were developed by direct trial using the audion as then available. The circuit seems peculiarly suited for use with valves of varying properties, and a good deal of solid progress was possible in spite of ignorance of the principles concerned.

The "missing link" in the circuit diagram was the capacity S_3 in Fig. 2 from the grid side of the oscillatory circuit to the filament, that is, usually to earth. The importance of this became sufficiently obvious experimentally. If, as at first, it was left as a mere distributed capacity of leads, ends of coils, etc., the set was fickle in action, oscillations coming and going with the movements of the hand of the operator. Such occurrences were common enough in later work, and we were perhaps lucky in starting with an example the cause of which was so easy to run to earth. The insertion of an actual capacity, even though as little as 20 micro-microfarads, gave a marked improvement in stability and was embodied in various naval sets of this type. Re-arrangement of the circuit diagram eventually provided the explanation of the action.

at radio frequency in L and S, and the other at audio frequency in T, L_3, S_1. The advantages, such as they are, of reaction at audio frequencies were therefore available.

In the fully developed circuit of Fig. 2, therefore, a single valve acted as generator of radio-frequency oscillations and rectifying detector with reaction amplification at audio frequency for one beat note, and, it may be added, for one value of the coupling between the aerial and secondary circuits. This circuit was singularly little perturbed by changes of wave-length or of valve characteristics, these last being particularly

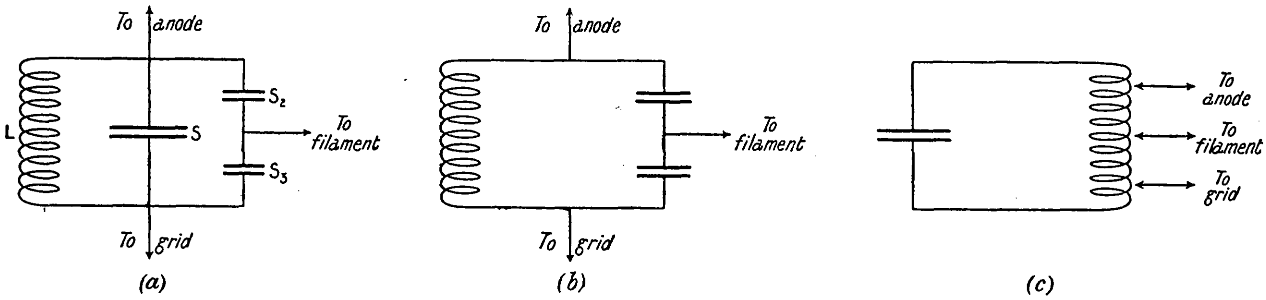


FIG. 3.

The circuit of Fig. 3 (*a*), so obtained, is clearly analogous to that of Fig. 3 (*b*), and this again to the generalized oscillatory circuit of Fig. 3 (*c*), the action of which is explained in one of Fortescue's recent papers.* In Fig. 2 will be seen a choke coil L_3 of some henries' inductance between the filament and grid. This was added to the original ultraudion circuit with the object of controlling the grid potential without disturbing its radio-frequency action, but it also provided the first

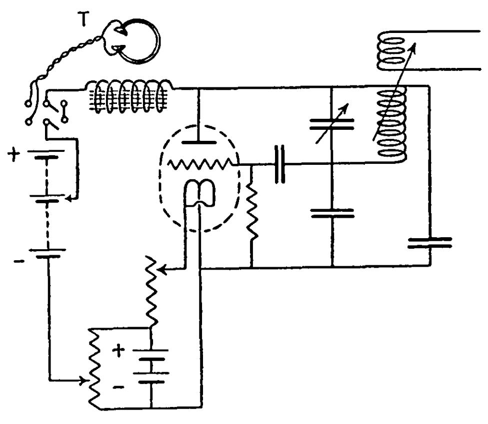


FIG. 4.—Modified ultraudion heterodyne; audion, R2, or R4 valve.

example known to us of the circuit of Fig. 3 (*c*), of which this inductance L_3, together with that of the telephones T, and the capacity of the grid coupling condenser S_1 form the essential components, the remaining circuit components in Fig. 2 being inactive at audio frequencies. The receiver could be adjusted in such a way that two sets of oscillations were simultaneously produced, the one

* C. L. FORTESCUE: *Radio Review*, 1919, vol. 1, p. 83.

variable in the early audions. Still, a receiver of this sort, covering a wave-range of 300 to 10,000 metres and prepared for valve variations, had an elaborate wiring diagram and many operating handles. It was not a good form for introducing a novel type of instrument. Its versatility had uses, however; for when a shortage of audions at one time occurred the resourceful obtained serviceable results with the "Q" valve,

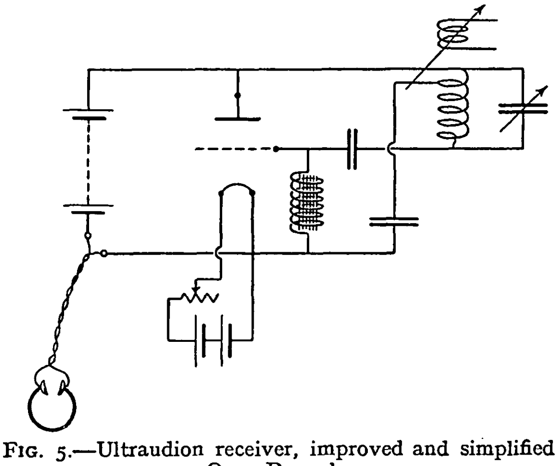


FIG. 5.—Ultraudion receiver, improved and simplified; Q or R4 valve.

whose characteristics differ extremely from those of the soft audion.

Simplifications of this circuit were therefore made at different times. The first was a simplification of function, and simple heterodyne sets were made (Fig. 4) for use with a crystal detector, leaving the spark reception circuits practically untouched. These sets, it will be seen, employed the capacity-coupled circuit of Fig. 3 (*a*) and call for no comment here, except that with them was done most of the continuous-wave reception in both small and large vessels. Later sets were simplified as regards operation, retaining the full multiple functions of the valve. They took the form of Fig. 5, which is the same as Fig. 3 (*c*) with the audio-frequency circuit superadded, and showed in many ways the advantages that come with a clear comprehension both of how a set works, and of what purpose it is intended to serve. Such improvements in style are of slow growth; in this case study of the valve, with which this paper is chiefly concerned, was one of the essentials.

(3) Preliminary Experimental Studies.

So much, then, may be said about the circuit arrangements which were employed when valves first came into service use. For the functions of the valve in some of the circuits later developed reference can be made to three papers already published by Professor Fortescue.* We now pass on to work in what is, in most of its aspects, an entirely different field. This is the study of the mechanism of electrons, ions, electrostatic fields and so forth, the action of which, sometimes intricate, sometimes simple, underlies the observed electrical characteristics of valves of various types.

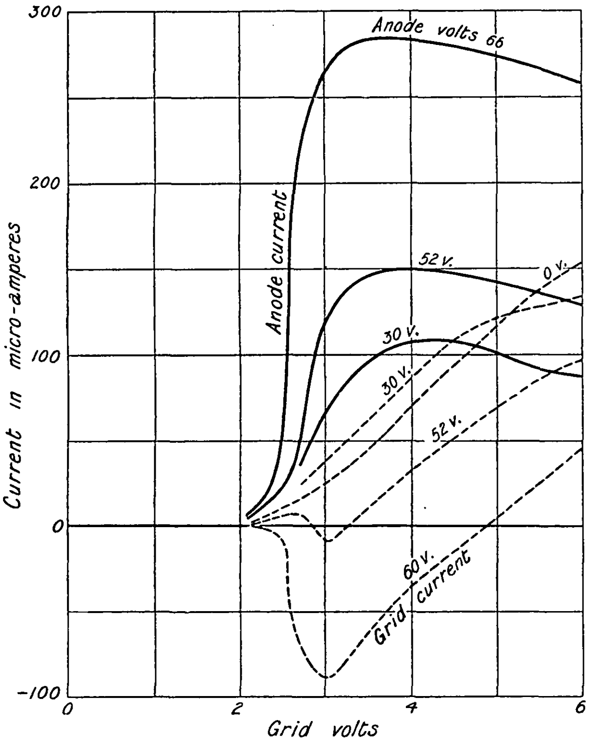


FIG. 6 (*a*).—Round's "C" valve, filled with nitrogen at 0·31 mm. pressure.

As already mentioned, the start was made in the direction of what proved to be somewhat of a cul-de-sac. However, we struggled along for some distance with the investigation of the Round valve, and found out a good many things besides our immediate object, which was the effect of the positive ions from the gas, the peculiar importance of which is perhaps confined to valves of this type.

The valves as received sometimes contained much too little gas, and to get any action at all the filament had to be over-burnt to a very dangerous extent. An investigation of the amount of gas actually required was planned and, in the case of nitrogen gas, was carried through, the valve being connected up for the purposes of the experiment to a special Sprengel pump, McLeod gauge, and gas-filling apparatus. The construction of this piece of plant was the occasion of some superhuman efforts in the way of glass-blowing under difficulties on the part of Lieutenant (now Lieut.-Colonel) Morris Airey. The so-called coal-gas came from a cylinder, usually much too eagerly, and no two pieces of tubing had the same working properties. The tangible results are summarized in some specimen characteristic curves shown in Figs. 6 (*a*) and 6 (*b*), and were confirmed by precisely similar work carried out at the National Physical Laboratory.

At the same time, however, it was brought home to us, and an attempted extension of the work to the more difficult case of the audion went to confirm the view, that the rapid solution of problems relating to the inside of the valve was a full-time occupation for some-one working under very different conditions, and with very different equipment from any which could be contemplated on board the "Vernon." Still, laboratory work was an essential and we were very fortunate in our opportunities for furthering it.

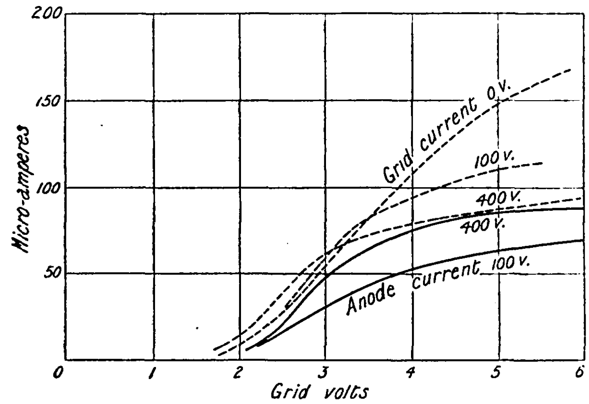


FIG. 6 (*b*).—Round's "C" valve, with trace only (0·0025 mm.) of residual gas.

Ever since the autumn of 1914, work on valves had been going on under Sir J. J. Thomson at the Cavendish Laboratory, Cambridge, where the experiments of Wright and Ogden, and later of White, led up to the "White" valve. With this work "Vernon" had been generally in touch, and it was just when we had arrived at a proper sense of our own difficulties that Sir J. J. Thomson suggested arranging for Mr. G. Stead to devote his whole time to valve work at Cambridge. This solution of the laboratory difficulty marked a new stage in the work of valve development. Hitherto we had

* C. L. Fortescue: (1) *Proceedings of the Physical Society*, 1919, vol. 31, p. 319; (2) *British Association Report* 1919; *Radio Review*, 1919, vol. 1, p. 83; (3) *Journal I.E.E.* 1920, vol. 58, p. 65; *Radio Review*, 1920, vol. 1, p. 178.

had little opportunity of, as it were, getting inside any valve. We had been content with comparing the construction and external electrical properties of sundry types of valve. To use a medical metaphor, the anatomy and comparative physiology of the article had progressed, but what we were now able to embark upon was the experimental physiology, not to say vivisection, and, as might be expected, we found plenty to learn.

Stead's early experiments, like those of others working on similar lines, were with valves having electrodes which were movable from the outside. The results began to dispel the prevailing fog, but were not fully appreciated until later. Progress with the technique of valve making, however, soon made possible a series of investigations of the audion under conditions of high vacuum, and also when filled with various gases under various pressures. These experiments showed how wide were the variations existing and permissible in the audion. They were contemporaneous with the beginning of the manufacture of valves of this type in England. This was undertaken in the summer of 1916 by the British Thomson-Houston Company, at Rugby, Mr. R. C. Clinker submitting some samples which, while generally as good as the original, were a considerable improvement on the original in respect of working life.

(4) The Calculation of the "Grid Constant."

At this stage we were still a long way from a comprehension of what was going on inside any valve. This was perhaps not surprising considering that we were proceeding in a physical problem by the methods, to revert to the former metaphor, of physiology rather than those of physics. Phenomena were observed, and measurements made when possible, and some attempt was made at correlating results, but there was as yet no numerical analysis of the figures obtained in the light of established physical theory. In dealing with an instrument containing so many component parts the geometrical form of which largely determine its mode of action, a theoretical basis of this kind is immensely preferable to a large collection of empirical formulæ. As it turned out, the materials for making a start were soon available. These were various specimen valves of types showing a closer approach to a thorough and permanent exhaust, judged by modern standards. There was the oscillion, of which more is to be said later in connection with power valves; but the valves from which the most illuminating data came were some small high-vacuum valves examined in the summer of 1916. These were a few audions exhausted by some improved process, but ordinary as regards the use of the flat plate and zigzag grid, and together with these audions a valve of the kind which later became so familiar, the cylindrical "French" or "R" valve, as our Army later called it. In spite of the marked differences in their construction, these valves gave current/voltage characteristics which were very closely identical. This was enough to confirm that the form of these characteristics was governed by principles more fundamental than, let us say, the use of any particular form of electrode. For the elucidation of one at least of these principles all was ready.

One of the first things to attract the notice of most observers of the characteristics of well-exhausted valves is the fact that, if curves are drawn showing the variation of anode current with grid voltage for successive fixed values of the anode voltage, the grid voltage being the variable plotted horizontally as in Fig. 7, the effect of changing from one anode voltage to another is simply to displace the anode-current curve without sensibly altering its form. This implies that the anode and grid voltages are in a sense interchangeable; a given increase of anode voltage, for instance, can be counteracted by a corresponding change of grid voltage, which latter change is the same at all points of the curve. Mathematically speaking, whatever be the formula expressing the relation between the anode current and the two voltages, the anode voltage e and the grid voltage e' must always occur together and in an expression of the form $e/m+e'$. The quantity m in this expression is thus a "constant of the valve" independent of its current and voltage adjustments. To be able to explain this theoretically, and to calculate it numerically in certain practical cases, was as comforting a first fruit, in valve theory and design, as had

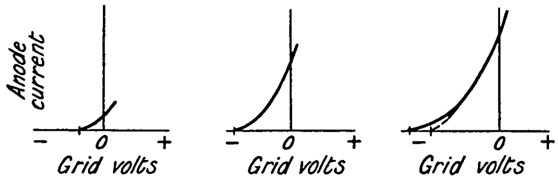


Fig. 7.

been the similar achievement for the Lieben circuit already mentioned.

When this effect was first observed by us, in the oscillion, the negative movement of the curve on raising the anode voltage was ascribed to a penetration into the neighbourhood of the filament of lines of force—electric force—derived from the anode and opening a direct path from filament to anode for the electrons emitted by the filament.

Experiments illustrating this by the analogy of current lines in a conducting sheet were suggested to Mr. Stead, but actually called forth something far more valuable. This was the communication by Sir J. J. Thomson of a formula giving the proportionate effects produced at the surface of the filament by the grid and anode voltages. The case given was that of a cylindrical anode and a grid of parallel wires spaced round a smaller circle. In the notation most familiar to those who have used it this formula gives the constant m as

$$m = \frac{\pi N d' \log (d/d')}{\log [1/(\pi N d_g)]}$$

where d and d' are anode and grid diameters respectively, and d_g the diameter of the grid wires which are spaced out at N per cm., whether round the circumference of the grid cylinder as in Fig. 8 (a), or as successive turns of a helix as in Fig. 8 (b).

A corresponding formula for plane anode and grid with a plane instead of a filamentary cathode can be obtained from Maxwell's "Electricity and Magnetism," 1892, vol. i, p. 312, but as cathodes of tungsten in the form of an incandescent plane do not occur in valves, it was to the cylindrical formula and the specimen French valve lent by Captain C. S. Wright, R.E., that we owed the establishment of this first point of primary importance in the theory of the triode valve. In the French, as in many other later valves of cylindrical form, the observed and calculated values of m agreed within about 10 per cent, so one property at least was shown to be calculable. For

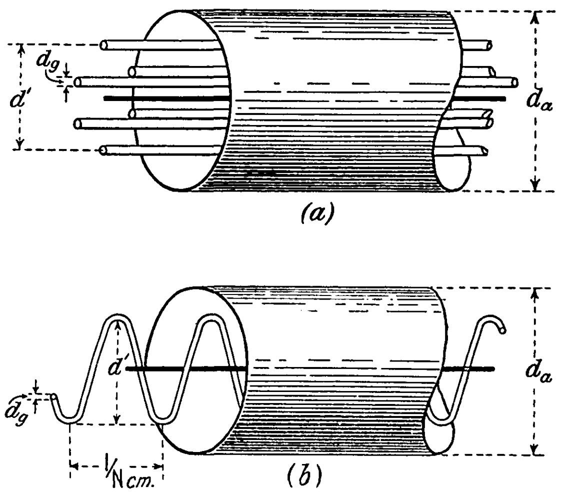


FIG. 8.

the small valves it was, as a matter of fact, for a very long time the only calculable one, but in another direction we were more fortunate.

(5) THE DESIGN AND DEVELOPMENT OF POWER VALVES.

The design and manufacture of larger valves for use in the power circuits of transmitter sets, and handling powers of the order of $\frac{1}{2}$ kw. per valve, was fortunately a much more straightforward affair than the development of new types of receiving valves. Indeed the next chapter of the history of valve development dealing with these larger valves was in point of time extremely short, a period of four or five months in the winter of 1916–17 covering all the main points, theoretical and practical. On the practical side our preliminary experience had been satisfactory as regards circuits, tantalizing as regards valves. Oscillions had been difficult to obtain and barely up to the desired standard of reliability. An attempt to obtain a supply of valves of this sort from a source in this country for use in a 100-watt aircraft set developed by Lieutenant Morris Airey did not make rapid progress. On the other hand there was a single large pliotron, obtained from the General Electric Company of America, capable of handling some 700-watt power input, and showing that the development of valve transmitting circuits was likely to be a straightforward matter and that the real need was simply for valves.

On the theoretical side we were by then well provided with material relevant to the problem. We had had enough experience of the effects which progressive improvement in the exhaustion of a given valve produced on its characteristics to appreciate the conditions to which Langmuir's work on the "pure electron discharge" might be expected to apply. The main principles of the electrostatic action of the grid were established, as we have already seen.

In the Schenectady publications again, there was information in a strictly practical form concerning filaments for use as sources of electron currents, and more yet of the same sort was available.*

With so much thoroughly worked out and verified there was, it was found, only one small addition required to bring all together into a theory sufficiently complete for the design of triode valves, provided only that they should operate at voltages 10 or more times those in use for receiving valves. This was to introduce into Langmuir's formulæ for the value of an electron current, when the determining factor is the field applied to draw it away from the filament, terms enabling the composite field due to anode and grid acting together to be substituted for the field due to the single collecting electrode in the diode cases covered by the Schenectady formulæ. The composite field could, it was found, be considered to be equivalent to that set up by a single continuous electrode the surface of which was a plane or cylinder passing through the centres of the grid wires, provided that this electrode was at a potential

$$\frac{e/m + e'}{1 + 1/m}$$

Taking this in conjunction with the formula for the rising portion of the characteristic of a high-vacuum diode, it was now to be expected that under conditions normally obtaining in transmitting valves the cathode current I, i.e. the total number of electrons leaving the filament, in a cylindrical valve would be given from the given dimensions of the electrodes, and the various combinations of the two potentials by the equation,

$$I = 2\cdot 92 \times 10^{-5} \frac{l_f (e/m + e')^{3/2}}{\beta^2 d' (1 + 1/m)^{3/2}} \text{ amperes}$$

where l_f is the length of the filament system measured along the axis of the concentric electrode cylinders. Also, this amounts to establishing that under conditions that the grid current is negligible, i.e. as long as the grid is negative or not very positive to the filament, the whole of the cathode current goes to the anode, giving an anode current,

$$I = 2\cdot 92 \times 10^{-5} \frac{l_f}{\beta^2 d'} \frac{(e/m + e')^{3/2}}{(1 + 1/m)^{3/2}} \text{ amperes}$$

This was the general formula taken as the basis of the design of the characteristics of transmitting valves.

The anode-current grid-voltage slope k_1 or $d\,I/d\,e'$,

* DUSHMAN: *General Electric Review*, 1916, vol. 18, p. 156; and LANGMUIR: *Physical Review*, 1916, vol. 7, p. 302, and 1913, vol. 2, p. 450.

is obtained in regions where the grid current is negligible by differentiating with respect to e', obtaining :—

$$k_1 = \frac{3}{2} \times 2 \cdot 92 \times 10^{-5} \frac{l_f}{\beta^2 d'} \frac{(e/m + e')^{1/2}}{(1 + 1/m)^{3/2}}$$
$$= \frac{3}{2} \times \frac{I}{e/m + e'}$$

The anode current slope, k_2 or $d\,I/d\,e$, is similarly

$$k_2 = \frac{3}{2m} \times \frac{I}{e/m + e'} = \frac{k_1}{m}$$

The ratio k_1/k_2 of the two slopes being equal to m.

Our information was less complete as regards the saturation value of the electron current emitted by the filament. This determines the height of the horizontal portion of the characteristics reached when a sufficient positive voltage is applied to either electrode, and is itself determined by the area and temperature of the filament surface, but we were fortunate in receiving from Professor O. W. Richardson in January 1917, just when it was wanted, a copy of a set of curves made for him from the elaborate collection of numerical data relating to tungsten filaments published by Langmuir some months previously.*

By adding suitable curves giving, from Langmuir's figures published elsewhere,† the specific electron emission of his tungsten, we became able to calculate the dimensions of filaments to give stated electron currents at stated working currents or voltages and at known temperatures, always provided that the corrections to allow for the cooling of the ends of the filament should be negligible. This was luckily not far from being true, as later demonstrated by Stead,‡ for the 15- or 20-volt filaments which we then had in mind. But in any case, since even the preliminary design of an idealized filament without end cooling adds three more variables, namely the length and diameter of the filament wire and its temperature, to those already enumerated, one would necessarily begin by designing a valve with an ideal filament as a first approximation. Re-arrangements of Langmuir's formulæ are then often useful for bringing together into close juxtaposition the quantities considered to be of particular importance in any given design. For instance, if the length of the filament wire and the voltage of the heating supply are considered more important than the corresponding wire diameter and heating current, the formula

$$l_f^{3/2} = \frac{E_f}{E_f'} \sqrt{\left(\frac{I_e}{I_e'}\right)}$$

obtained by eliminating the diameter and current from the primary expressions is useful. Here the quantities accented, E_f', I_e', are the heating voltage and electron emission for a tungsten cylinder of unit length and diameter, and are functions of the temperature, their value being obtainable from Langmuir's tables or Stead's curves. Again, if the heating current is of special importance the corresponding formula

$$l_f^{3/2} = \frac{I_f'}{I_f} \left(\frac{I_e}{I_e'}\right)^{3/2}$$

would be used in determining the length of the filament wire, or its working temperature. After the length of wire which will be available has been so determined, the possibilities of looping or coiling it so as to build up a filament system of axial length l_f' suitable for giving the proposed characteristics according to the anode-current formula already given can be considered.

Collecting them together, the main formulæ for the design of a power triode valve are

$$I = 2 \cdot 92 \times 10^{-5} \frac{l_f'}{\beta^2 d'} \left\{ \frac{E/m + E'}{1 + 1/m} \right\}^{3/2}$$

$$\frac{l_f}{l_f'} = \text{factor determined by construction of filament system}$$

$$l_f^{3/2} = \frac{E_f}{E_f'} \sqrt{\left(\frac{I_e}{I_e'}\right)}$$

$$m = \frac{\pi N d' \log (d_a/d')}{\log [1/(\pi N d_g)]} \text{ [see Figs. 8 (a), 8 (b)]}$$

Here the quantities usually determined by external considerations are the two supply voltages E and E_f, saturation current I_e, and ratio of saturation current I_e to anode current I_0 at zero grid potential. The temperature of the filament then determines its life, and the dimensions of the anode surface give the limit of power that can safely be dissipated in the valve. Of the remaining quantities, the length and form of the filament system and the diameter of the grid are usually fixed by mechanical considerations. In the final design the only quantities in respect of which there is much range of choice are usually found to be the diameter and spacing of the wires of which the grid is built up.

A numerical example will illustrate the values likely to be arrived at for the various quantities which represent in the formulæ given the various dimensions of the three electrodes.

Suppose that we have to design a valve for an anode supply at 1,500 volts, and a filament supply at 20 volts, the anode being so dimensioned as to dissipate by radiation the energy of impact of the electrons constituting the anode current at the rate of 250 watts, without its temperature being raised sufficiently to impair the vacuum. Suppose also that the anode current at zero grid potential is to have the value 0·17 ampere, the anode being at 1,500 volts, and the power in the anode circuit being therefore 250 watts. This valve will evidently be just safe should the oscillations in the circuit which it has to feed be interrupted. Again, when the oscillations are taking place the anode current will vary with the grid potential, but its mean value will usually not exceed one-half of the saturation current given by the filament. If we choose a saturation current of 0·34 ampere, the mean power taken from the high-voltage supply happens to be 250 watts

* Langmuir: *Physical Review*, 1916, vol. 7, p. 302.
† Langmuir: *Physical Review*, 1913, vol. 2, p. 450.
‡ G. Stead: *Journal I.E.E.*, 1920, vol. 58, p. 107.

again, and as some of this will be dissipated in the oscillatory circuit the power lost in the valve will be less than 250 watts. This valve will therefore be quite safe as long as oscillations are taking place, and just safe when they stop. This example is typical of the earliest naval power valves. As the proportion of I_e to I_0 is made to exceed that given, the valve will become less and less safe when oscillating. However, a valve designed to work in a modern high-efficiency transmitting circuit of efficiency η would have the ratio I_0/I_e of the order of $(1-\eta)/2$, and a 250-watt valve such as that here considered would be given a saturation current considerably greater than 0·34 ampere.

We have first to select a suitable filament temperature. This will be done from consideration of the working life required. Suppose that this is to be long, over 1,000 hours, and that previous experience, as is actually the case, indicates 2,310° K. on Stead's scale as suitable for ensuring this. We now proceed to find the length of an ideal filament which is fully hot right up to the ends. Allowing a margin on the 20-volt supply, we take the filament voltage to be 18·2 volts. From Stead's curves the values of E_f' and I_e' at 2,310° K. are found to be 0·165 and 0·91 respectively.

Now $$l_f^{3/2} = \frac{E_f}{E_f'}\sqrt{\left(\frac{I_e}{I_e'}\right)}$$

whence we obtain 16·5 cm. as the length of the filament which when arranged in a single hair-pin loop will give a filament system of axial length 8·25 cm.

The length of the anode to be bombarded by such a filament should preferably be somewhat less, for instance, 6·5 cm. This with a diameter of 3·2 cm. will mean at 250 watts a radiation as low as 3·2 watts per square cm. even without allowance for radiation from the open ends, which is little more than one-half the limiting value found for nickel.

In this example we will take a grid diameter of 1·0 cm., which, though practicable, represents the limit of narrowness for use with so long a filament loop; something nearer 2 cm. would now be more usual.

In the anode-current formula all quantities except m are now known. Transposing the formula we have

$$(m+1)^{3/2} = \frac{2\cdot92 \times 10^{-5} l_f'}{d' I_e} E^{3/2}$$

the value of m calculated from which is 12·0. Applying a deduction from this required value of m to allow for longitudinal supports to the grid, we find that a value of m of about 12 will be given by a helical grid having 4·6 turns per cm. of 0·02 cm. diameter wire, with three longitudinal supports 0·06 cm. in diameter.

The ideal filament used up to this point has now to be replaced by one in which proper allowance is made for the cooling of its ends. This is done using Stead's methods and data, and the resulting length of wire in the filament is found to be 17·6 cm. and its working voltage 18·2 volts. At the same time its diameter is 0·0023 cm. and the working current 5·4 amperes.

It may be of interest to add that the anode-current grid-voltage slope for this valve at 0·17 ampere anode current is given by

$$k_1 = \frac{3}{2} \times \frac{I_o}{E} m$$

and has the value 2·0 milliamperes per volt.

This example gives a valve having good margins of safety in all respects except the clearance between grid and filament. This, however, could readily be increased with the sole effects of slight reductions in the values of m and k_1.

If, however, a filament temperature 150 degrees higher had been taken, the filament supply would have been reduced to 3·6 amperes at 10·8 volts, but its life would have been much shorter, about 300 hours only. The whole construction would have been more compact, the anode being only one-half the size, and the valve generally closely similar to the T2B valve designed for the Royal Naval Air Service. This, owing to the high temperature reached by the small anode, and the small size of the bulb, is more difficult in manufacture and less safe in operation. It shows great economy in filament power and in space, but represents approximately the limit in these directions for a valve of this power.

It will be noted that the power at which the valve is rated is that which can safely be expended in it, not that which it will control, this latter being dependent on the efficiency of the circuit arrangements as well as on the valve.

This network of interlocking formulæ, together with the appropriate numerical data for tungsten, made it possible to calculate essential dimensions for all the electrodes of various experimental valves designed to meet anticipated needs. These designs, and suggested procedure for the exhaust of the valves, were discussed with several lamp-manufacturing firms in the first weeks of 1917. Very shortly afterwards it became apparent that the problem had been taken up by Mr. F. P. Driver of the Osram-Robertson lamp works and his staff with notable energy and persistence. The results of these efforts constitute a model of industrial research.

The start was made with a material equipment which included nothing out of the ordinary. The pump was the Gaede mercury pump, a rotary pump working by displacement, and slow at high vacua. In the latter stages of the exhaust this was therefore supplemented by a large charcoal tube immersed in liquid air. This would condense the residual gases very completely, but only provided the quantity did not exceed the limited absorbing capacity of the charcoal. The combination is not to be compared as regards either speed or effectiveness of working with the rotary and other molecular pumps in use at the time in America. However, in this case it proved enough for success; improvement came later.

The essential dimensions of the electrodes being stated from the calculations, the method of attachment and mounting was left entirely to the works. The processes of cleaning the metal parts before exhaust and of heating the glass were those which all lamp manufacturers recognize to be necessary for metal-filament lamps; the construction of the metal work recalls the half-watt lamp in some details, but was mainly original.

It did not take long for a form to be produced which was sufficiently nearly perfect to persist with none but minor alterations through a number of subsequent designs. The T1 valve (Fig. 9) was one of the first to be manufactured in quantity. Its evolution, though short in point of time, was a very active process. The number of the unfit which perished before survival was achieved was surprising. A contemporary of the first half-dozen survivors, of whose fitness there was incidentally little question, has been lent by the makers. It dates from a time only five or six weeks subsequent to the communication of the designs. The kind of performance of which these early specimens were capable is indicated by the case of the pair which were in regular and very frequent use in the Fleet flagship for over a year.

In these valves, that is to say in those following the very first, it was found necessary to make an empirical correction to the electron data to allow for differences between English and American tungsten. This correction served until the data were redetermined by Stead as described in a recent communication to the Institution.* Otherwise comparison between the observed and calculated characteristics in the neighbourhood of the working adjustments showed agreement to within less than 10 per cent.

The T4A valve (Fig. 10), a later design, is rated at 400 watts and is therefore capable of converting over one kilowatt of input power in a circuit of good efficiency.

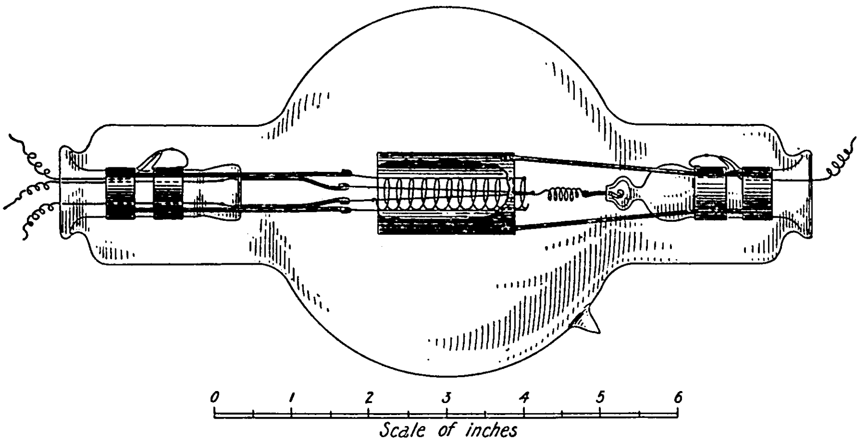


FIG. 9.—Transmitting valve, type T1.

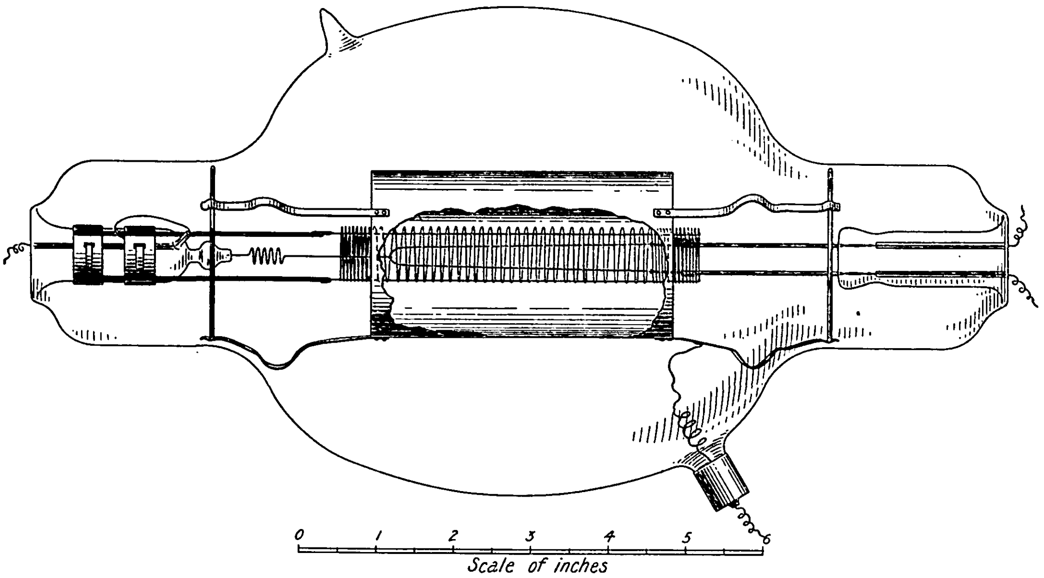


FIG. 10.—Transmitting valve, type T4A.

* *Journal I.E.E.*, 1920, vol. 58, p. 107.

Several essential points to be observed in manufacture were established at an early stage.

The high vacuum was found to be permanent, provided that the power expended in heating the anode, and indirectly the other metal work in the valve, during the final stages of the exhaust was considerably greater than that expended under the most severe conditions permitted in working. This was the basis of the system of rating the valves by the maximum power which could be expended at the anode for a definite period, 10 minutes. It was necessary, therefore, to have the anode large enough to leave a margin between the rated power and the power required to melt the nickel anodes fitted.

Uniform heating of the anode was found to be necessary if the vacuum was to be permanent, and for this

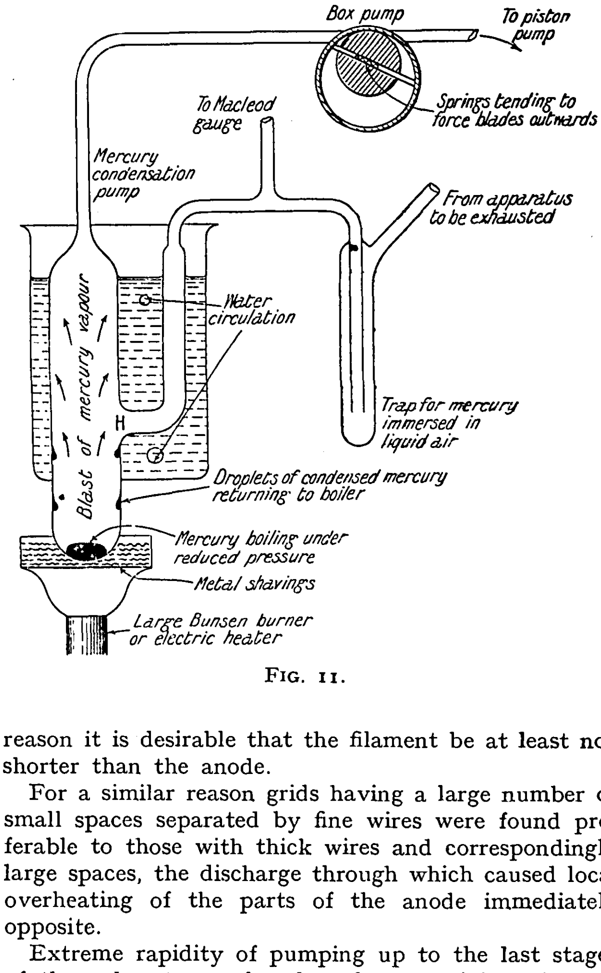


FIG. 11.

reason it is desirable that the filament be at least not shorter than the anode.

For a similar reason grids having a large number of small spaces separated by fine wires were found preferable to those with thick wires and correspondingly large spaces, the discharge through which caused local overheating of the parts of the anode immediately opposite.

Extreme rapidity of pumping up to the last stages of the exhaust was found to be essential, and there was a great improvement on substituting for the combination of Gaede rotary mercury pump followed up by charcoal in liquid air as at first used, the mercury-vapour condensation pump, the first of which to be used was lent by Professor Sir J. J. Thomson in the spring of 1917.

This pump is shown diagrammatically in Fig. 11. It works by a kind of ejector action, the velocity of the dense blast of mercury vapour up the central space past the side aperture H being great enough to prevent completely all possibility of any gas molecules leaving H in the ordinary course of diffusion ever returning.

The tube immersed in liquid air prevents diffusion of mercury vapour back to the valve and also condenses much of the evolved gas. It is not, however, essential, particularly when small valves are being exhausted.

On the lower vacuum side of the vapour pump comes a box pump, the chamber of which is divided into two halves by a pair of spring blades which rotate eccentrically pushing the air before them, the rubbing surfaces being kept gas-tight by a liberal supply of oil. Beyond this again is a piston pump.

It was observed that when an alternating voltage was applied between anode and filament the valve conducted both ways as long as any blue glow (indicating the presence of positive ions derived from gas) was present. If the glow was allowed to become very bright the mean current through the valve might even reverse, implying that the conductivity was higher when the filament was positive than when it was negative. As might be expected under these circumstances, the valve still conducted momentarily after the filament current was switched off.

Overheating of the filament seals owing to conduction of heat back from the filament led to electrochemical decomposition of the glass, indicated by a black deposit on the platinum in the seal, and consequent leaks. The combination of heat and high-frequency electric strain caused breakdown of the glass between the filament and grid seals as soon as the oscillatory voltage in the grid circuit became high. This was, however, easily prevented by separating the seals.

The first power-rectifying valve U_1 was produced by simply omitting the grid of T_1 and gave no trouble. Another, U_2, which was equally successful, was designed by Lieutenant Sleeman to suit a particular set of circuit requirements.*

This description of its early stages covers practically the whole of the relatively uneventful history of power valve development. The manufacture proceeded by dozens, and then by hundreds, reaching a total of some 5,000 in the period considered. Six principal types of power valves were finally in use.

(6) The Development of a High-vacuum Receiving Valve.

At the end of 1916, the difficulty of reproducing soft valves of the audion type was becoming serious, and Round's "Q" valve, in spite of the high voltage it required to produce fair characteristics (Fig. 12), was used in an ultraudion receiver designed at this time.

The British Thomson-Houston Company, having made progress with a method of producing high-vacuum valves of the French pattern for the Royal Naval Air Service in particular, suggested an attempt at developing a high-vacuum substitute for the audion on similar lines. It was known that the French valve itself would not produce the heterodyne oscillations over the full range of wave-lengths required of the

* Fortescue : *Proceedings of the Physical Society*, 1919, vol. 31, p. 319.

receivers for which valves had to be found, but various sets of modified trial valves were made up and by accident one of these specimens provided a solution of the problem in an unexpected way. In all the trials the grids had been made too open, the full importance of keeping down the slope of the anode-current/anode-voltage characteristic not being realized, owing to the complication of the modified ultraudion circuit in use. However, in one specimen valve a warping of the filament brought grid and filament so very close together that the effective closeness of the grid was more than doubled, the variation of anode current with anode voltage was much reduced, but the corresponding variation with grid voltage was unaltered. This freak valve did all that was required, but was not itself reproducible. However, a further trial valve was designed using what had been learnt from the power valves as to the general effects of the different dimensions of the electrodes, and it was found possible to reproduce the desired characteristics sufficiently closely, using a symmetrical and readily reproducible form of construction.

The new valve had the same filament as Mr. Edmundsen of the B.T.H. Company had fitted in the experimental one, but had the other electrodes cylindrical. The grid diameter was made as small as possible, as this, together with the length of the filament, which was

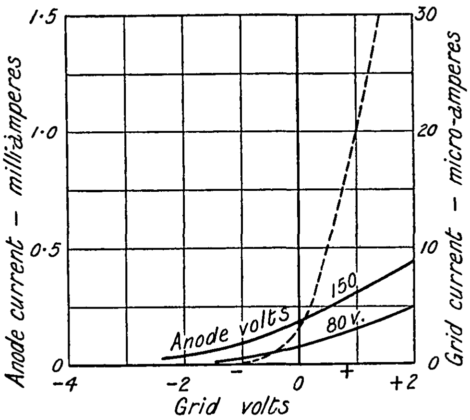


FIG. 12.—"Q" valve.

greater than in the French valve, were now known to be factors in determining the slopes of the characteristics. The diameter and spacing of the grid helix were chosen so that the calculated value of the grid constant *m* should be the same as had been observed in the freak valve. As the double-ended audion construction was now replaced by the French method of mounting all the electrodes on a single stem, so that they could be finally adjusted before sealing into the bulb, Mr. Edmundsen brought the filament leads round the outside of the bulb to a screw cap secured to the sealing-off point.

This valve, known as R4, met practically all requirements for a year or more, ousting the soft valves giving the audion characteristics in most cases where they were issued as an alternative. It was sufficiently similar to the soft valve to give comparable results for most purposes; but for various reasons it turned out to be more reliable than any soft valve in existence at the time of its appearance. This would tend very much in its favour, for a small gain in reliability is felt far more by the receiving operator who passively waits for and takes in the signal than by the transmitter who makes it on his own initiative. The most serious form of unreliability, sudden failure of the filament, proved to be very rare in this valve, the dimensions given to the filament providing in the first place that it could not be overloaded to the fusing point in a 4-volt, or even in a 6-volt circuit, and, further, giving to all filaments not locally damaged in exhaust or strained too tightly an expectation of life which was excellent, indeed, almost excessive. More than one R4 valve on

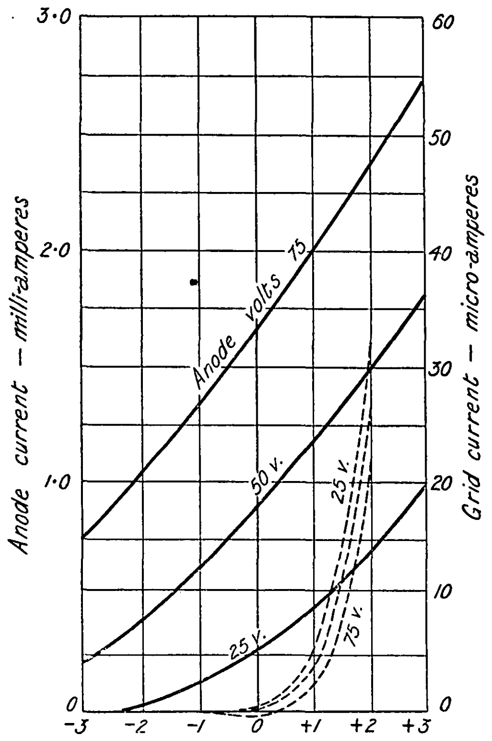


FIG. 13.—"R4" valve.

life-test survived 8,000 hours (i.e. 12 months) of continuous burning. The life on service may have been shorter, but apparently several thousand hours was the rule. Such a life was a great advantage to isolated ships, and the corresponding small rate of consumption of valves in the receivers in use made it easier to build up stocks in the dockyards for the use of more accessible vessels, and for new ships.

The characteristics were good. As shown in Fig. 13, the slopes at an anode voltage of 50 are comparable with those of the French or the hard audion valves at 70 or 80 volts (Fig. 14), while the corresponding anode current was less in the proportion of three to one. The low anode voltage, besides reducing the number of cells in the anode battery, made possible the use of a much less severe exhaust, for at the lower anode voltage the effects on the characteristics of traces of residual gas are much less marked. This imperfect exhaust, again, was later found to steady the emission of electrons from the thoriated tungsten filament fitted.

Some of these virtues, however, were latent for a time. Although a life of 1,500 hours had been shown to be possible by life-tests conducted at the National Physical Laboratory on high-vacuum audions, and was attained by the first delivery of the R4 valves, it was soon found that the process developed by the B.T.H. Company for exhausting French valves for other services would require modification if such a life was to be ensured. The makers were not prepared to make modifications at the time, but preferred to concentrate on the French valve. Other sources of supply were therefore sought.

After some work at Cambridge on the emitting properties of the filament, and on the proportion of grid to anode current, a specification was drawn up and other lamp makers called in. The specification was a simple one, the electrical tests covering first a saturated emission current some five times the normal anode current, to be attained with a filament voltage not exceeding the 4 volts of the supply accumulators, and current within the range of the 1·2-ampere instrument fitted, and together with this a vacuum test permitting a reverse grid current of 2 micro-amperes with 100 volts at the anode. This corresponds to a positive ionization current of an order as high as 1/1000th of the primary electron current. The dimensions of the cold electrodes were given but the method of mounting was left optional.

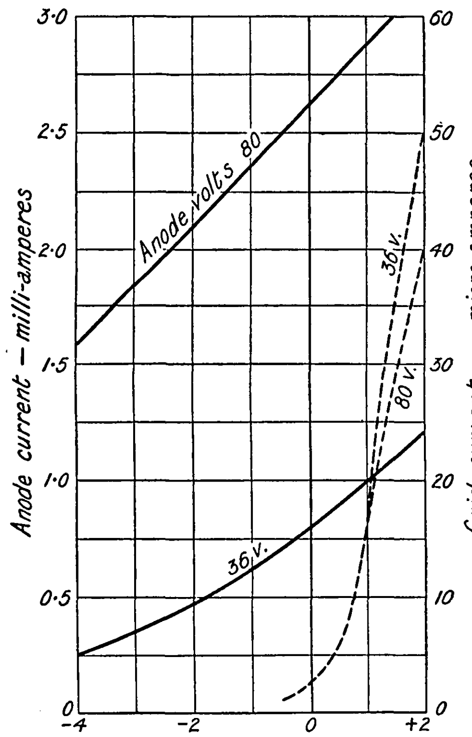


FIG. 14.—French valve.

In the subsequent development of the manufacture the Osram-Robertson Company, using the experience acquired with the power valves and soft receiving valves, made the most rapid progress. From observations on the rapid disappearance of gas from some of their soft valves on life test, it had been hoped that high-tension bombardment of the anode and consequent damage to the filament could be dispensed with. It is now known, indeed, from recently published accounts that many German receiving valves were exhausted on such lines. However, in this case the method was found to be too sensitive to variations in the quality of the materials used, and the process finally developed in conjunction with the Osram works employed the minimum bombardment which would give a permanent vacuum and so damage the filaments as little as possible.

In arriving at this minimum, much information was obtained as to the way in which the high vacuum in valves is maintained.

If the bombardment is severe and the exhaust thorough, the high vacuum is permanent and no softening occurs until the electrodes are overheated, as might occur in transmitting valves.

With reduced bombardment there is a tendency to a slow continuous evolution of gas during working, favoured by a high filament temperature. Counteracting this, however, there is a continuous absorption or " clean-up " of gas taking place at a rate dependent on the largest potential difference applied between any of the electrodes. The origin and ultimate destination of the gases is obscure, though the " clean-up " effect is a well-known one, occurring in lamps, and also at much higher voltages in X-ray bulbs.

Thus, for each particular value of the working anode voltage these two actions strike a different balance ; the higher the voltage the lower is the equilibrium pressure and the better the vacuum. Equilibrium is not instantaneously obtained or disturbed. In the case of R4 valves running continuously with the filament at normal brilliancy (3·5 to 4·0 volts) the vacuum deteriorates at first, the valves softening rapidly for the first two or three hours. After this, provided they have not reached a state corresponding roughly to the softness of an R2 valve, i.e. a reverse grid current of 1 micro-ampere with only 30 volts applied to the anode, a progressive hardening begins and continues, if the exhaust was carried sufficiently far, until the vacuum is much better than that specified as the limit for R4, and often also much better than immediately after the removal of the valve from the pump. Trials at the Royal Naval College, Greenwich, established that a considerable amount of gas is given off when the glass of the outlet tube is heated for sealing-off. If the sealing is too rapidly done much of this gas is left in the sealed valve.

The definite nature of these effects being established by many trials, it was decided that the process of " ageing " by running the valves at the works for a few hours between exhaustion and test was preferable to over-bombardment, as the filament was saved and it was also ensured that each valve had before test and issue a preliminary run under working conditions, so that greater reliance could be placed in its constancy.

In the course of these trials many opportunities occurred of observing the connection between the amount of gas present in a given valve and the emissive power of the filament for electrons. It was clearly established that the greater the amount of gas the greater the watts expended in heating the filament and therefore the higher the filament temperature required to produce a given total electron current, the effect continuing down to gas pressures far below those required to produce any appreciable cooling of the filament such as can be detected in gas-filled valves. This effect is also a slow one, and if it is pronounced the emission current may take several minutes to attain a steady value after the working conditions have been changed. This is one probable reason for the lack of reliability of the early "audion" valves. The effect is favoured to some extent by a low filament temperature, but more markedly by the application of voltages above 25 or 30 volts to either or both of the cold electrodes. It is thus probably a case of the electro-chemical contamination of the surface of the tungsten by the gas ions as investigated and described by Langmuir (*Physical Review*, 1913, vol. 2, p. 450). If present, it makes any true estimate of the form of the "saturation" portion of the characteristics difficult to obtain, the values of the currents at or near the saturation value tending to be too low unless taken by some instantaneous method.

A kind of inverse of this effect, that is to say the occurrence of cases where the filament watts for a given total electron emission were abnormally low, was investigated at the Royal Naval College, Greenwich, and shown to be associated with the presence of impurities derived from the body of the filament, and especially with the presence of thoria added to the tungsten ore to improve the mechanical properties of the wire. As it is observed to occur whenever the bombardment of the filament by positive ions, especially those derived from volatile metals present as impurities in the electrodes, is more than ordinarily violent, it is supposed to arise from the exposure of thoria or of thorium-tungsten alloy by the disintegration of the filament surface, and therefore practically from the substitution of another emitting material for the pure tungsten. The effect is fairly permanent and may under certain conditions persist during several hundred hours of running.

During the development of the R4 valve, it was established that any over-straining of the filaments with the object of preserving accurate centering resulted in a very troublesome defect. Under such conditions a filament, although to all tests perfect and undamaged, would fail suddenly after less than 10 hours' normal running under conditions where a life of many hundreds of hours was to be expected. Various methods of spiralling or waving the filament wire may be used to prevent this effect, but without them a very little warping of the supports during exhaust is likely to bring it on in a considerable proportion of the valves.

Some preliminary experiments were carried out which confirmed that it was desirable to make the grid of the R4 valve consist of a number of turns of fine wire rather than fewer turns of thick. There are theoretical grounds for supposing that the proportion of the electrons leaving the filament which the grid does not succeed in deflecting as they pass—in a cylindrical valve it does not begin to attract them until its potential is nearly the same as that of the anode—depends amongst other factors on the extent to which the grid wires block the "field of view" from the filament. This may be measured by the area of the grid "projected" on to the anode.

Experiments were carried out on the effect of different grids on the ratio of the anode and grid currents. Three valves were used, each fitted with a different type of grid. These grids all had the same effective closeness (i.e. the same de/de' or m defined as previously described), but were made of wires of different diameters, their projected areas differing in the extreme cases in the proportion of two to one. The valves were exhausted as completely as possible by means of a Gaede pump, followed up by liquid air and charcoal, and curves were then drawn for each valve showing how the ratio of grid current to anode current varied with grid and anode voltages. The curves are of the general form shown in Fig. 15. The anode and grid voltages

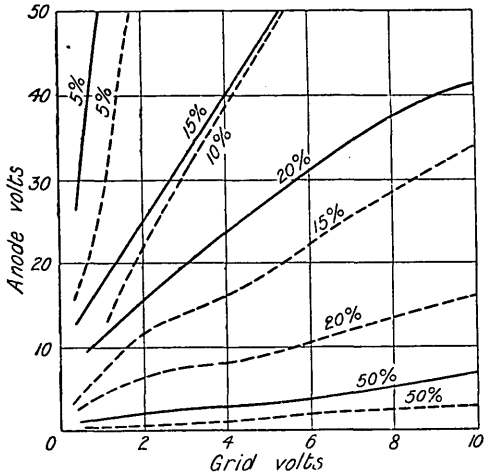


FIG. 15.—Curves showing the voltage adjustments for given ratios of grid current to anode current.

Full lines are for coarse grid, 0·04 cm. wire and 5·5 turns per cm. Broken lines are for fine grid, 0·01 cm. wire and 12 turns per cm.

are plotted along the two axes, and each curve is a line along which the grid current is some constant percentage of the anode current.

It was found that, for a given anode and grid voltage, the valve with the largest projected grid area showed the largest percentage grid current, as might be expected. Further, for the region in which the form of the curves could be predicted theoretically (i.e. the region where the grid voltage is positive, and fairly large, but considerably smaller than the anode voltage) it was found that the agreement between theory* and experiment was good.

The proportion of grid current to anode current throughout the range of working adjustments can therefore be reduced without affecting the screening effect of the grid, measured by the value of m, simply by making the grid of a larger number of finer wires. This reduces the mechanical strength of the grid, which can, however, be restored by making a mesh of the fine wires, this naturally being much stiffer than a helix.

As far as the effect of the form of the grid is concerned, the numerical investigation of grid currents has not been carried further than this.

* Due to Sir J. J. Thomson and extended by Lieut. Brundrett.

For receiving valves there is another factor of great importance controlling the form of the lower part of the grid-current/grid-voltage curve, the part used when rectification takes place at the grid. This part is, in all high vacuum valves below the point where the traces of gas cause reversal of the grid current, of a form such that if successive equal changes of the grid voltage are made in the positive direction, the value of the grid current is multiplied each time by the same amount, the curve being therefore an exponential one. The reason for this is that, although the electrons do not all leave the filament with the same velocity, there is, nevertheless, a very definite law connecting the proportion having one velocity and the proportion having another, that is the numbers which will overcome different degrees of repulsion by the grid consequent on different voltages being applied to it. This law was established by O. W. Richardson. It is found that the observed factor of multiplication for the lower part of both curves, grid and anode—in round numbers twice for every fifth of a volt—agrees very closely with that to be expected from the law of the distribution of initial velocities.

As long as a heated surface is used as the source of the electrons, this variation in initial velocity and therefore the general form of the characteristics up to about the 20 micro-ampere point is uncontrollable by any simple means.

The form of the grid curve is thus determined by the exponential law, and its vertical scale by the projected area of the grid. It is also observed that a change in the nature of the surface from which the electrons are emitted may result in the curve being shifted bodily by as much as 1 volt. Thus, these thoriated filaments which give an abnormally large electron emission for a given temperature give rise to a grid curve displaced by anything up to 1 volt in the negative direction, i.e. to grid currents up to 70 times as great for a given grid voltage.

(7) "Soft" and Gas-filled Valves, Properties and Development.

If the quantity of gas in a valve is not extremely minute its presence gives rise to certain special modifications, both in the characteristics of the value and in its behaviour in use. Owing to their many common properties such valves are often classed together and spoken of as "soft" valves, the name being taken from X-ray tubes in a similar state. The softer a valve is, the more gas it will in general contain, and, correspondingly, the harder it is the more nearly perfect will be the vacuum within it.

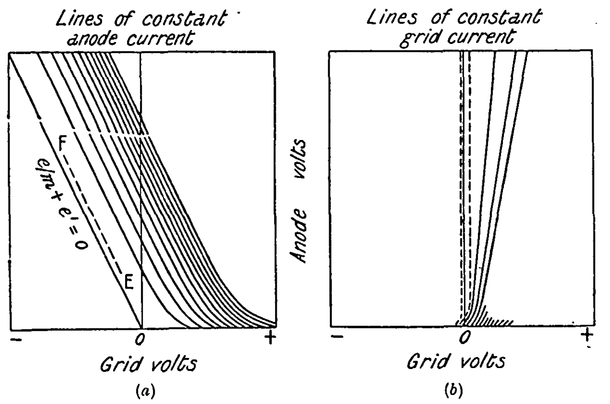
A more coherent explanation of the special properties of soft valves can perhaps be given if they are treated as variants on the high-vacuum valve which, though a later development, is now more generally understood, having come into far greater prominence, both in practical use and in the literature of the subject. In dealing with soft valves, therefore, departures will be made from the roughly historical treatment followed in the rest of this paper.

The chief point of distinction is that in the soft valve as soon as the potential difference between filament and anode, or between filament and grid, exceeds a certain value characteristic of the gas present, positive ions arising from the disruption of gas molecules appear near the high potential electrode. These ions are directed by the electric field towards the neighbourhood of the filament, where their presence tends to cause a neutralization of the dense space-charge in that region due to the negative electrons from the filament. Under working conditions the neutralization is usually only partial, and the result is simply that the applied field tending to draw the electrons away from the filament has less space-charge to contend with and, consequently, is competent to produce a larger electron current than if no positives were there. As the positive ions owe their origin to the collision of electrons with gas molecules, such adjustments of the voltages as produce no space-current in a high-vacuum will produce none when the gas is present. As regards the position of its foot, therefore, the characteristic curve will be unaltered, but as one follows the curve it will sooner or later be found to depart from the form which it would have in the high-vacuum case. Take, for instance, the curve connecting anode current and grid voltage, for an anode voltage of about 30. This will become steeper and steeper, and, unless either the effect of the gas is small or the saturation value of the current low, a point of discontinuity of the curve will be reached corresponding to an instantaneous rise of the current to a value several times at least larger than that immediately preceding, and often reaching the full saturation value at one leap. If after passing the point of discontinuity the potential is reduced again, the former characteristic is not usually retraced, but the high value of the current persists and the point of discontinuity comes at a lower potential than the corresponding discontinuous rise. This is sometimes spoken of as a "hysteresis" effect, and its appearance renders the valve either inactive or very difficult to adjust.

The possibility of this effect, which might easily escape the notice of an operator, was a source of much trouble in the earlier soft valves. We shall return to it in connection with the steps by means of which it was eliminated. The essential properties distinguishing a less pronouncedly soft valve are, however, more regular and more capable of prediction than this, and in general considerably extend the possibilities of a particular arrangement of electrodes. In a triode valve the appearance of the positives results merely in a more or less marked increase in the anode current, owing to the partial neutralization of the space-charge. The effect on the grid current is, however, less simple. If the grid is the most negative by one or two volts of the three electrodes, no electrons can reach it, but, on the other hand, a considerable proportion of the positives are arrested by the grid, either in transit towards the filament, or after missing it owing to the small target which it presents. This influx of positives produces a grid current in the reverse direction to that observed when the grid is picking up electrons. If now the potential of the grid is changed in the positive direction until it repels the electrons less completely, so that in the high-vacuum case it would pick up an appreciable number of them, this number may be increased by the presence of the positives, somewhat in the same proportion as the total number of electrons escaping from the filament is increased. If the grid is made sufficiently positive to the filament, this effect may mask the picking up of positives and the direction of the current may become the same as in the high vacuum.

These effects are well illustrated by means of a particular method of plotting the characteristics, the use of which had some value in throwing light on the physical actions described as underlying the modifications of the currents observed to occur when gas was present.

Instead of plotting to a horizontal axis of grid voltage with a vertical axis of current, make both axes represent voltage, the horizontal for the grid, and the vertical for the anode. The various values of the current have then to be indicated by means of lines of constant current, like the isothermals on an indicator diagram or the contour lines on a map. The characteristics indeed take the form of a contour map of a surface of which the more usual curves of current against grid voltage are sections in vertical planes. When, therefore, the difference in current between successive lines



FIGS. 16 (*a*) and (*b*).—General characteristics of high-vacuum valve.

is large, or the distance between them small, a steep slope of the sectional characteristic is indicated. It is generally as well to show the grid current and the anode current on separate diagrams. Intersecting curves, which cause some confusion in sectional characteristics of soft valves, are thus entirely avoided. Further, as the successive intervals of current can be selected at will, it is possible by using small intervals where the currents are small, and increasing the intervals more or less in proportion to the currents, to give an equally faithful rendering of all parts of the surface. This is particularly useful, for it is generally necessary to trace the variations of a current from a fraction of a micro-ampere to 10 milliamperes or more.

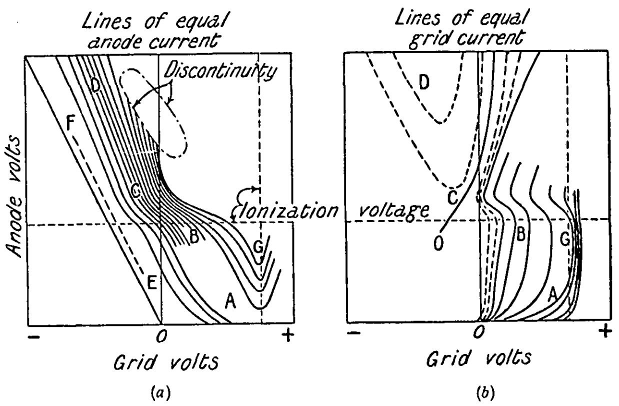
In the case of the high-vacuum valve both surfaces depicted in this manner are simple, that of anode current particularly so, Figs. 16 (*a*) and 16 (*b*). For all the region where the grid current is much the smaller of the two, that is, for all but the right-hand bottom corner of the diagram, the lines of constant anode current are nearly straight and nearly parallel. Now the inclination of the lines to the horizontal—measured as a slope of n to 1—is the measure of the effective value of the grid or amplification factor m at the point considered. Their straightness and parallelism is therefore a very clear and striking expression of the fact already mentioned, that in this region m is sensibly independent of the value of either grid or anode voltage, and that the current is a function of $e/m + e'$.

As would be expected also, the anode current becomes vanishingly small to the left of the line $e/m + e' = 0$, the crossing of which implies the reversal of the field at the surface of the filament.

The lines of grid current, also, as long as the current is small, are straight and parallel to the axis of anode voltage, the grid current being then independent of the anode voltage. For larger values of the current they approximate to radial lines spreading out from the origin.

If secondary emission of electrons from either of the cold electrodes occurs, as for "dynatron" adjustments, the surfaces illustrate the progress of the effect very clearly but become rather complicated.

The general differences between the characteristics drawn in this way, for high-vacuum and for gas-filled



FIGS. 17 (*a*) and 17 (*b*).—General characteristics of soft valve. Minute currents are shown by broken lines.

valves is illustrated by comparison of Figs. 16 and 17. The soft valve is clearly not so simple as the hard, but it is noteworthy that up to the point B there is little difference between a valve with the highest vacuum and one which is filled with gas to the maximum practicable extent. At A on the diagrams, where most of the current is going to the grid, the anode current varies little with the grid voltage, rather more between A and B, but very little again beyond B. B is a point at which the gas begins to ionize. The ionization, which is consequent on the anode voltage exceeding the ionization value, causes a large increase of both anode and grid current, and so both sets of current contours swing off sharply to the left, the horizontal direction of the lines indicating that the valve is in this region much more sensitive to the value of the anode voltage than to that of the grid voltage.

The curve marked O on the grid-current diagram is the line of zero grid current, whilst the curves to the left of this near the point C represent reverse grid currents or "backlash." The curve E F is drawn for a very small anode current (e.g. 10 micro-amperes). It is a nearly straight line, and the slope of the lower part of it is of importance, as it gives a close approximation to the value of *m* for high-vacuum conditions. It is only the lower contours like E F that can be used thus for measuring the effective closeness of the grid fitted, the others such A B, C D, are profoundly modified by the presence of gas.

Extending the diagram in the direction of increasing positive grid voltage, until the grid voltage exceeds the ionization value, the grid current is found to rise very steeply, and there appears in the anode surface a bulge or shoulder G, followed by a hollow indicating a reversal of the anode current, just as previously described for the grid current at high anode voltages. That the functions of the two electrodes should be thus interchanged even in the soft valve, simply by making a suitable transposition of their voltage adjustments, is remarkable, and provides, when all parts of the complete surfaces are passed in review, a great variety of combinations of characteristic slopes, very few of which have as yet been utilized in practice.

This conception of the generalized characteristics of the soft valve as distinct from the hard owed its full development to the study of an experimental valve sent by Professor F. Horton in October 1916. This valve was filled with helium which was and remained very pure, so that the valve was very steady, and the appearance of the ionization effects as either voltage attained the critical value of 21 volts was very sharply defined. Shortly afterwards similar observations were made on some experimental valves received from Professor O. W. Richardson. These, together with a re-plotting on the contour system of Stead's characteristics of valves with movable electrodes, both plane and cylindrical, all confirmed the general form of the soft valve characteristics shown in Figs. 17 (*a*) and (*b*).

Richardson's valves were exhausted for many hours in a vacuum furnace, and were beautiful instruments for experimental investigation. The ionizable atmosphere consisted of mercury vapour from a reservoir containing mercury. By enclosing the valve in an oven and suitably warming it, standard characteristics at any desired degree of softness could be obtained. It is interesting that when discontinuities began to occur as the valve was softened, they were limited at first to a small enclosed region just above the shoulder of the anode surface at C, disappearing again when the anode voltage was sufficiently raised. Richardson's series of valves of this kind completely bridged the gap between the audion and the Round valve, indicating that the general effects of the admission of gas were the same in both of them, but were essential in the close grid valves if reasonably steep characteristics were to be obtained.

Of all the combinations of characteristic slopes which a soft valve can give, those used in practice seem to have been confined to the area near the point C on the general diagram, which lies on the shoulder of the anode surface where the slope is steep, but the run of the contours has swung back almost to its original direction, bringing the factor *m* back to something approaching its value for the same valve with a high vacuum.

On the grid-current surface the corresponding area comes at the head of the hollow representing the reversal of the grid current due to the positive ions. Here the curvature in the direction of grid voltage is often particularly sharp, giving good rectification in circuits where a condenser is included in the grid connection to receive the rectified charge.

On the current-contour form of diagram simultaneous variations of grid and anode voltage, such as occur in practice in almost all circuits, can readily be followed.

The course of a cycle of voltage variation can be shown as a closed curve described on the surface. The successive intersections of this curve with the current contours indicate the current variations during the various parts of the cycle. For a valve which is generating oscillations of measured amplitude in a circuit the dimensions of all components of which are known, the form of the ellipse depicting the simultaneous voltage variations can be calculated by means of vector diagrams.

A mathematical theory of a soft triode valve idealized as regards the structure of the grid and filament, but showing how for any gas there would be an upper limit of the pressure, and voltage adjustments, at which indefinitely steep characteristics would be obtained, and showing further the relative behaviour of different gases in this respect, was communicated by Sir J. J. Thomson early in 1916. An extension of this showed that the more open the grid the lower would be the limiting pressure, and gave some approach to the observed form of the characteristic surface for anode current in the region of negative grid voltage, indicating, for instance, that the increase in velocity of the positive ions with increase in anode voltage would have the effect of increasing *m* above its high-vacuum value, as actually observed.

The general investigation of the characteristics and behaviour of soft valves had progressed almost to the extent covered by the preceding sections, when serious difficulties in the manufacture of audions began to be encountered by the B.T.H. Company early in 1917.

The audion suffers very much from discontinuities in its characteristics, and the point of discontinuity is particularly susceptible to change in the pressure or composition of the contained gas, the limiting quantity of which is in any case small with so open a grid. As the best working adjustment came only too close to the point where a general glow diffused throughout the bulb appeared, accompanied by a break in the characteristics, which made the valve either inactive or at least very erratic, such faults could be very troublesome, particularly to those who were not used to them or content with less sensitive adjustments.

The glow point, indeed, was at first actually used to indicate the degree of softness in manufacture, but proved an erratic and unsatisfactory guide, the performance of the test itself giving rise to changes of the nature and quantity of the gas sufficient to alter the properties of the valve.

A deliberate attempt at so modifying the design of the audion as to make its characteristics specifiable and reproducible was begun in the spring of 1917. The question of the glow point was dealt with first. In experimental soft cylindrical valves made by the B.T.H. Company it was found to be practically nonexistent. This makes it appear that the general glow is due to ionization along the tracks of electrons which travel from the filament to the anode by long paths outside the electrodes. The grid has no control over what occurs in these regions. The probability of such paths is greatly diminished by adopting a cylindrical construction for the electrodes, and it has been found possible by this means to use much higher gas pressure than before. To test this point further a special valve was constructed in which the anode consisted of a cylinder, one end being permanently closed and the other end capable of being closed when desired by means of a cup carried on a stem floating in mercury. Observations were made on this valve with the anode open and closed, and it was found that by closing the anode the general glow could be entirely eliminated and "kinks" in the characteristics avoided.

In other respects besides this matter of the glow-point manufacturing considerations were much in favour of the cylindrical construction as used in the French valve. In particular, this construction, like that of the ordinary incandescent lamp, allowed all adjustment of the electrodes to be made before they were put in the bulb, and involved no hand glass-blower's work.

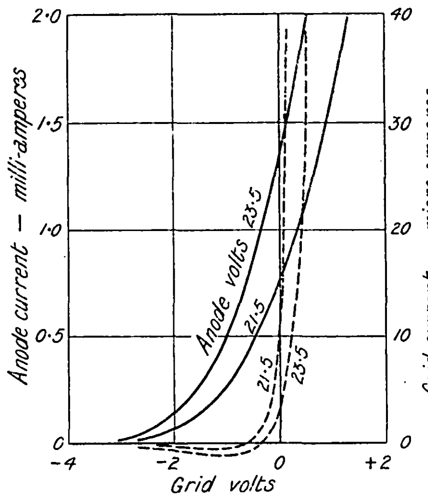


FIG. 18.—"R2" valve, filled with nitrogen at 0·1 mm. pressure.

The possibility of reproducing the audion characteristics with this construction had therefore now to be investigated. Four cylindrical valves were taken as a preliminary and characteristics were taken in a nitrogen atmosphere at pressures ranging from 0·018 mm. to 0·056 mm. These indicated that much higher pressures were practicable with these valves than with those of the audion type with flat anodes and zigzag grids. It was hoped that greater constancy would result from the presence of so much more gas, and trials of a substitute for the audion were decided upon.

Three cylindrical-type valves, with different grids, and two audion-type valves, also with different grids, were then sealed on to the pump and exhausted, and a long series of trials were carried out in nitrogen at various pressures. These trials involved tests of the working of the valves in circuits of the ultraudion type, the upper and lower limits of anode voltage for which the valves would produce oscillations being determined for a series of pressures between 0·0074 mm. and 0·6 mm. In most cases these oscillations were produced under difficult conditions with an inductance of 1,000 microhenries and a capacity of 0·005 mfd., together with an additional resistance of 2 ohms in the oscillating circuit, though other wave-lengths and other resistances were also tried.

Characteristics, e.g. Fig. 18, were drawn for the different valves and different pressures, for anode voltages chiefly in the neighbourhood of the upper and lower limits for which oscillations were possible.

The trials in the ultraudion detector circuit showed that a cylindrical valve with a thick wire grid was the most sensitive, and this construction has been adopted in valve No. R2, the grid of which is of 0·4 mm. wire in a spiral of 5·5 turns per cm. and mean diameter 4·5 mm. Full characteristics were therefore drawn for reference purposes for this type of valve, using a nitrogen atmosphere at various pressures between 0·0045 mm. and 0·5 mm.

As a result of these experiments a pressure of about 0·06 mm. was adopted for the nitrogen-filled R2 valves. It was a matter of great importance for the manufacturer of valves to be able to get an estimate of this pressure easily, before sealing off the valves from the pump. It was also highly desirable to have some method of estimating the pressure in a valve after it had been sealed off. The method which has been adopted for estimating the pressure in a valve while still on the pump was to have a special "vacuum tube" attached to the apparatus and measure the width of the "cathode dark space."

The electrodes of the tube were of aluminium, the cathode being a large disc. When a discharge from an induction coil is passed through the tube, there is a glow separated from the cathode by a dark space of sharply defined width. This width increases as the pressure diminishes, and also depends somewhat on the current density through the tube. The latter effect is sufficiently eliminated by using a tube of standard dimensions, and an induction coil of a definite size. Curves were drawn showing the connection between the pressure and the width of the dark space for nitrogen, hydrogen, helium, argon, and carbon monoxide. This was the method used in adjusting the gas pressure in the first 6,000 R2 valves containing mixed nitrogen and electrode gas.

In order to estimate the pressure in a closed valve, use has been made of the variation in the amount of "backlash" with the pressure. When the grid is one or two volts negative to the negative end of the filament, a reverse grid current is obtained as soon as the anode potential exceeds the ionization potential of the gas, and this increases as the anode potential is further increased, owing to the increase in the number of positive ions present. The anode voltage required to produce any particular backlash current increases as the pressure diminishes, and this is used to give an estimate of the pressure. For this purpose, curves were drawn showing the relation between the pressure and the anode voltage required to give a backlash current of 1 micro-ampere, the grid being 1·5, 2·0 or 2·5 volts negative to the negative end of the filament. Curves of this kind are now available for nitrogen, hydrogen, helium, argon, and carbon monoxide. Fig. 19 shows the curves for pure helium and for helium contaminated by a considerable amount of electrode gas.

The dimensions of the electrodes, vacuum-tube tests, and a curve of pressure and reverse grid current were all embodied in an outline specification of the R2 valve, together with suggestions as to the method of exhaust, and were communicated to several lamp-making firms. As before in the case of the high-power transmitting valves, the Osram-Robertson works were the first to begin production in quantity, and from this point, June 1917, there was never any acute shortage of receiving valves for the naval sets in use.

The first nitrogen-filled R2 valves were found in practice to have one serious defect—the nitrogen gradually disappeared during the running of the valves,

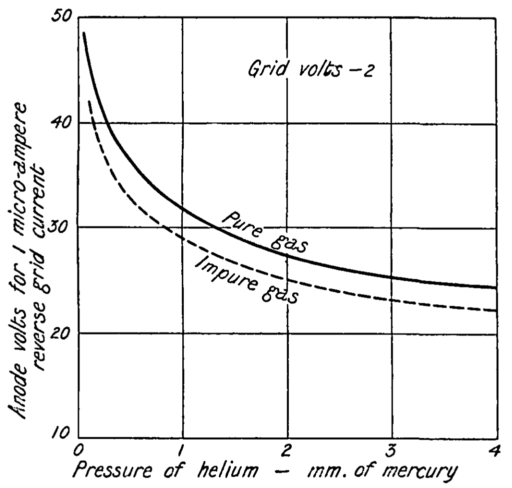


FIG. 19.

presumably being absorbed in the electrodes. For this reason it was thought that a chemically inert gas might be more satisfactory. Argon was first tried and experiments on oscillating points were carried out, thoroughly satisfactory results being obtained. Characteristics were also obtained for various pressures. It was found, however, that tungsten filaments disintegrated rapidly in an argon atmosphere, probably owing to the large mass of the positive ions, the life being so short that the use of this gas had to be abandoned.

Helium was next tried, for reasons which had gradually been coming to light.

Experiments had been carried out with an audion valve containing hydrogen at various pressures between 0·051 mm. and 0·0025 mm. and characteristic curves obtained. Similar experiments were made for a nitrogen atmosphere over a range of pressures from 0·038 mm. to 0·0005 mm. Special attention was paid to the small reverse grid current, often referred to as "backlash," obtained when the grid is made slightly negative to the negative end of the filament. The variation of the backlash current with the pressure and the nature of the gas was studied, and it was found that in nitrogen, and still more in hydrogen, the effect is much greater (at a given pressure) than in mercury vapour, which had been previously studied.

In a theoretical investigation of the "ideal" case communicated by Sir J. J. Thomson, it was shown that the characteristics of a valve in which gas was being ionized would become extremely steep whenever the product

$$\text{mass of positive ion from gas} \times (\text{current of positive ions})^2$$

became greater than the corresponding product

$$\text{mass of negative electron from filament} \times (\text{current of negative electrons})^2$$

This conclusion is confirmed by the results obtained with actual valves.

In hydrogen, where the positive ion is light, a large positive current is required. The presence of this is shown by the large "backlash" in hydrogen. To supply the ions for this current a correspondingly large quantity of gas is necessary, i.e. very much more of a light gas like hydrogen or helium is required to produce a given steepness of anode characteristic than of a heavy gas like mercury vapour.

This method of obtaining corresponding pressures was successfully applied to the purpose of obtaining from the known pressure of nitrogen a first estimate of the pressure of helium which would give a satisfactory R2 valve.

Now Horton's experimental valve with helium filling had shown the advantage of this gas in giving constancy of behaviour, and he had also used it in many other experimental valves both before and after the one we examined. Advantages on the theoretical side had, as described, become obvious in the meantime. His advice was therefore sought on the question of converting the R2 valve to a helium filling, in particular as regards the supply of gas, which turned out to be by no means so rare in the eyes of Messrs. Tyrer, from whom we obtained it, as we had imagined. He also refilled several R2 valves with helium at pressures indicated by the theory as corresponding to the pressure of nitrogen previously used; and these valves were found to be as constant as had been hoped throughout tests of several hundred hours' duration.

The experiments originally carried out for nitrogen, as described above, were repeated for helium. It was found to give most satisfactory results, and it was adopted in R2 valves in place of nitrogen. It is not absorbed by the electrodes, like nitrogen, nor does it cause disintegration of the filament, as in the case of argon. For a given pressure a helium valve is much harder than a nitrogen valve; in other words, a much higher pressure of helium must be used to obtain given characteristics than is required in the case of nitrogen. Roughly, the pressure of helium required is about 10 times the corresponding pressure of nitrogen. In R2 valves the pressure adopted for the helium is about 0·6 mm. As in the case of nitrogen, standard characteristics, e.g. Fig. 20, at various measured pressures of helium between 0·05 and 4·0 mm. were examined.

Manufacture of helium-filled R2 valves was begun in September 1917, but owing to the same changes in the gas-content of the metal parts as had given trouble in the development of the R4 valve, they did not all behave as helium valves. In some the working anode voltage was lowered by contamination of the helium by more easily ionizable gases—one of the few difficulties special to helium. These valves had merely the same exhaust as a vacuum lamp, mechanical pumps only being used. All diffusion pumps and bombardment installations were at this time required for the supply of " R " valves to the Army, which was then, and for some months after, a pressing need. To expel the electrode gases the filaments were somewhat overburnt, and it was difficult to avoid shortening the lives by so doing. On the other hand it was necessary to expel enough gas for the valves to be constant. There were,

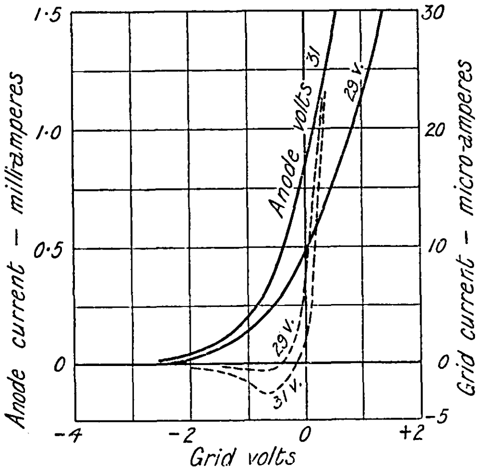


FIG. 20.—" R2 " valve, filled with helium at 0·6 mm. pressure.

however, many good valves giving lives of about 1,000 hours.

The final step of exhausting the valves as if they were to have a permanent high vacuum, and then admitting the helium, was not taken until about a year later. By this process, provided that precautions against the introduction of mercury vapour were observed, valves are obtained which are all as constant throughout their life as are high vacuum valves. Like them also, they differ amongst themselves somewhat, but to the same extent, and apparently for the same reasons.

Thus the reliable soft valve, the evolution of which began before that of the high-vacuum valve, and finished later, attained reasonable perfection and equally reasonable obsolescence at very nearly the same moment.

The soft valve, however, divides the honours of service actually done during the war in naval installations on equal terms with its high-vacuum rival, the R4, which ultimately accompanied it into obsolescence.

(8) LATER RECEIVING VALVES.

It was the extension of the use of valves to other receiving instruments besides the simple heterodyne that made the R4 valve obsolete. Multiple-valve amplifier sets were on trial for special purposes in 1917, and the properties of valves suitable for use in them were made the subject of general inquiry next after the power valves. The chief result of this work was to illustrate the difficulty of designing small valves. For instance, if the formulæ already given for power valves are applied to receiving valves, and further compact formulæ evolved embodying the essential properties of a valve for use, for example, in a resistance amplifier, the results are of far less practical value than had been found in the more fortunate previous case of the power valve, for the very good reason that the simple formulæ correspond to characteristics differing too widely from those actually observed in small valves. The discrepancy is due, in the first place, to doubt as to the effective length of the filament. Given the diameter of a filament the temperature of its central portion corresponding to a particular value of the heating current can readily be determined, and thence also the saturated electron emission per unit length of the filament in question. If now the length which would give the observed total emission is taken as the effective length, it is found that in filaments working at 4 volts or so the correction thus made amounts to a very large fraction of the total length of the actual filament.

Again, in most receiving valves the filament voltage is of the same order as the potential difference $e/m + e'$ between the negative end of the filament and the region of the grid. Hence it becomes necessary to know, not only the number of electrons which each small section of the filament is capable of emitting, but also its potential relative to the negative end in order to correct the value before assigned to the field tending to remove the electrons. For any exact knowledge of the effects responsible for the observed form of the characteristics of small valves, a previous determination of the distribution of temperature along the filament was required. Mr. Stead undertook, and very soon completed, an experimental investigation of this, adding a theoretical extension enabling the temperature distribution to be calculated for filaments of any dimensions. This work has already been fully described in a paper published in the *Journal* of this Institution.*

As a result, apart from the light thrown on the origins of the characteristics, it became possible to design alternative filaments without experimental trial, just as previously with alternative grids by the use of Sir J. J. Thomson's formula. For example, given the filament supply-voltage as determined by the accumulators fitted in an existing set, and the desired value of the saturation current, it became possible to calculate the dimensions of a whole series of alternatives ranging from cold, thick, and long filaments on the one side to short, thin and hot ones on the other. The members of such a series differ in heating current and in life.

* STEAD: *Journal I.E.E.*, 1920, vol. 58, p. 107.

Fig. 21 gives a set of curves so calculated for filaments all of which will give a saturated emission current of 80 milliamperes, and require a 6 volts supply for the heating current. The extent to which reduction of heating current has to be paid for by sacrifice of working life is here clearly shown. This series refers, it should be said, to the design of small transmitting valves. The Army B valve comes near the low-current end, and the results of the life tests were the basis of the design of the filaments of the R.A.F. F valve which comes near the middle, and of the naval T5 which, in order to obtain a longer life still, was given a current a little above the highest shown.

Similar series of receiving valves were worked out and tested, and a substitute for the R4 valve known as R4A having little more than one-half the filament current, and therefore better suited to double-valve sets were selected. In this case the diameter was actually selected so as to give a reasonable margin of

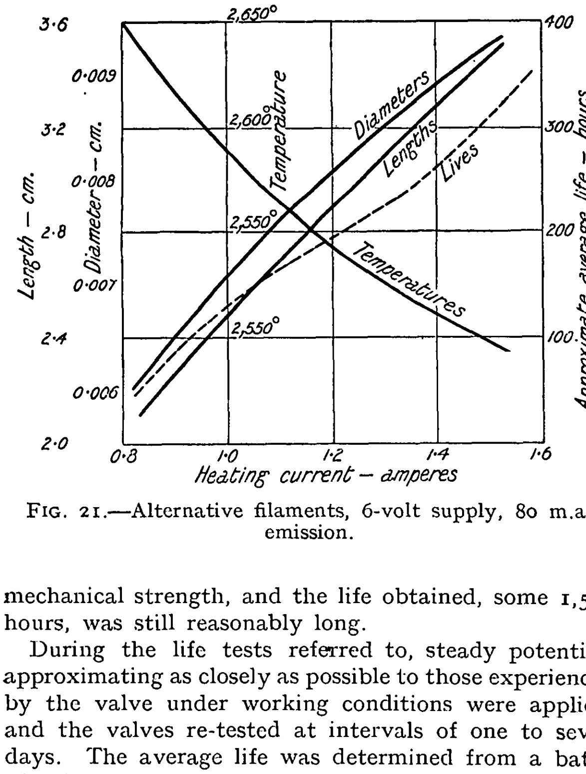


FIG. 21.—Alternative filaments, 6-volt supply, 80 m.a. emission.

mechanical strength, and the life obtained, some 1,500 hours, was still reasonably long.

During the life tests referred to, steady potentials approximating as closely as possible to those experienced by the valve under working conditions were applied, and the valves re-tested at intervals of one to seven days. The average life was determined from a batch of at least five valves, and the longest life was commonly observed to be about twice as long as the shortest. Many tests of this kind were carried out at the Signal School during 1917–18, involving a very large amount of careful work, the results of which were of the greatest value in setting a proper standard of reliability in working, and also making correct estimates of supplies required for naval purposes.

As in other similar cases the trials of cascade circuits of high amplifying power soon made conspicuous the existence of "valve noises" ascribable to rapid variation in the action of the valve. The deleterious effects of the presence of thoria in the "tungsten" filament were studied by Dr. Hodgson, Capt. Mullard, and Prof. G. B. Bryan in connection with the R valve at the end of 1917. Almost all filaments are noisy if the temperature is sufficiently raised. In the R4 the working temperature is so low that in many cases the crackling noise characteristic of thoria is absent although thoria was actually present. In the R4A, the reduced diameter was accompanied by a rise of temperature sufficient to make most R4A valves too noisy for use in amplifiers.

For some amplifiers a similar valve, called "R4B," was used having a filament of unalloyed tungsten. The R4B filament thus arrived at has practically the same dimensions as that of the original French valve, but is somewhat quieter in working, because the slightly smaller grid diameter makes the working anode current of the R4B distinctly the smaller. The saturation current, and therefore the filament temperature can thus be lower, and the noises are consequently reduced. The change from thoriated to pure tungsten made no appreciable difference to the working life. Evidently the temperature is not high enough for the special advantages of thoriated tungsten to appear. In all later receiving valves, therefore, pure tungsten was used, and it was found that silence was generally obtained up to a working temperature of 2,300° K. on Stead's scale, and with selected specimens of metal up to 2,600° K. The conditions for noise-testing were particularly severe, all extraneous disturbances, acoustic and electrical, being eliminated by most elaborate screening, and amplification of the order of at least three stages at audio frequency being employed.

During the early part of 1918 the trials of the various valves mentioned in the preceding paragraphs absorbed the available facilities for experimental work on small valves. It was, however, sufficiently clear that an amplifying valve should have a filament working below the noise point, and that its response to changes in the combined voltage, $e/m + e'$, should be as large as possible while keeping down the power expended in heating the filament, the anode voltage, and also, particularly where the anode circuit was to include a high resistance, the anode current. A further attempt was therefore made at selecting, on theoretical grounds, a combination of electrode dimensions so as to obtain some approach to an optimum in respect of these essentials.

In order to trace the several effects of the different factors, the theory was idealized to a considerable extent, the stage of approximation corresponding to curve 4 in Fig. 22, as described later. It became clear that the distance between grid and filament was the chief controlling factor, and that no very marked improvement on existing valves was therefore likely, though some reduction in the various currents and voltages was possible without spoiling the characteristics.

The results when valves came to be made up were somewhat disappointing, and showed that such experimental confirmation of the theory as had been available was spurious as regards the average valve, being based on freak observations such as are usually obtained in a small proportion of cases, as explained later in connection with the standardization of small valves. That the optimum was not reached at the first attempt was only too clear, for the characteristics obtained were not so good as those of Round's "V24" until the filament had been re-designed so as to give a saturation current four times the working current instead of, as expected, about twice.

Fortunately, the margins allowed in respect of noisiness and life both permitted the change without marked disadvantage.

With this modification these valves, called "R5," showed only one advantage in working over their collateral relatives, the "V24." They gave generally equal results in operation with a filament voltage just within, instead of just outside, the capabilities of a 4-volt accumulator.

The theory had thus been simplified to too great an extent and the final design of the R5 was really empirical, filament is incandescent. It could, however, be further reduced by about 0·5 cm. if the anode and grid connections were not taken out side by side through the stem.

The R5 among high-vacuum receiving valves, and the R2A among the gas-filled types, mark the final stage of development as far as valves actually used in naval installations during the war are concerned.

There was another and very different type, however, the evolution of which was all but completed. This was a valve distinguished by having a grid consisting of a flat plate close to the filament and on the opposite side from the anode, also a plate. It was the outcome of a long series of trials undertaken by Professor O. W. Richardson and Mr. F. S. Robertson at King's College at the invitation of the Admiralty rather more than a

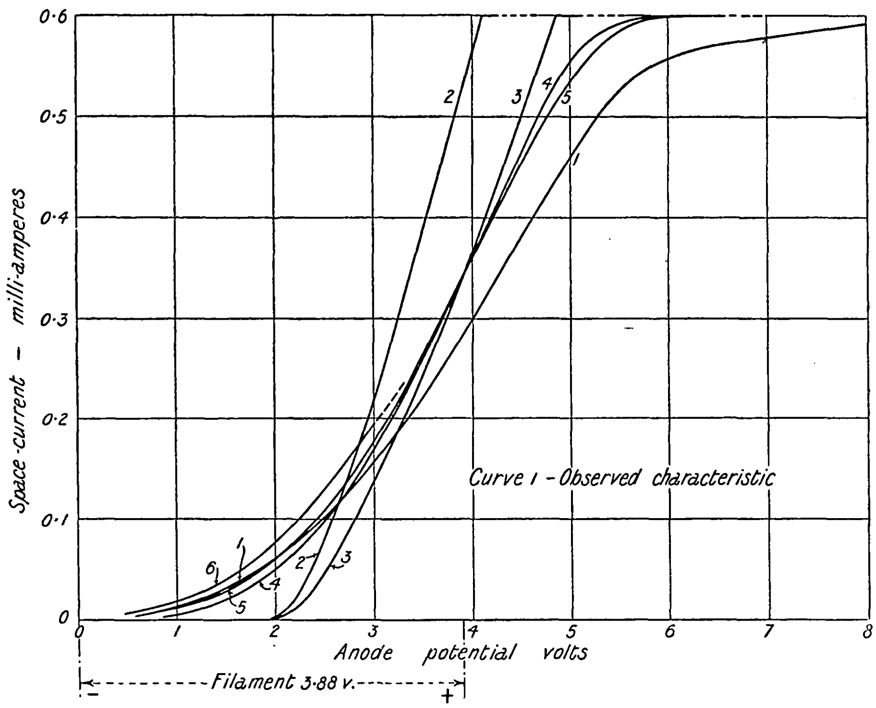


FIG. 22.

but the nature of the discrepancy between calculation and observation showed that either of these valves represented some approach to finality in valves of this type. All the small valves developed in the period covered by this paper, whether French, English, American, or German stopped at points not far from that here reached.

In standardizing these valves it was decided to adopt the bulb and cap developed by Captain Mullard for the Royal Air Force shortly before, at a time when it appeared that the demand for a rapid acceleration of output could not be met by the V24 owing to the manual skill required in its construction. The anode of the R5 was made short and wide in order to reduce the electrostatic capacity between anode and grid, a matter of great importance in high-power amplifiers. The actual capacity is 2·0 cm., and is less still when the year before. It gave characteristics identical in the usual working region with those of the "R" valve, thereby demonstrating that the cylindrical construction with grid interposed between filament and anode is more conventional than necessary.

(9) VALVES WITH LOW OPERATING VOLTAGES, CALCULATION OF CHARACTERISTICS.

That it is possible to build up a theory which accounts with some approach to completeness for the several parts played by the various factors influencing the passage of current through a small valve may be illustrated by comparing an observed characteristic with characteristics calculated using successive stages of approximation.

Curve 1 in Fig. 22 shows the curve connecting space-current and anode voltage plotted from observations on a small diode valve which was well exhausted and had a cylindrical anode of diameter 0·45 cm., i.e. the same as that of the grid of an "R" valve. The filament also was near to that of the "R" in diameter, 0·0057 cm., but its length was greater, 3·05 cm. instead of 2 cm. Each end of this filament would show an appreciable temperature gradient due to conduction to the supports for a length of 0·8 cm., leaving 1·45 cm. in the middle at a uniform temperature, which could be calculated from the diameter and the heating current.

In attempting to reproduce this observed curve by calculation we may start with the extreme assumption that the whole 3·05 cm. of the filament is active, and is all at the same potential, which we will take as that of the centre of the real filament, i.e. 1·94 volts, from the conventional zero at the negative end. Using Langmuir's formula we have

$$I = 2{\cdot}95 \times 10^{-5}\,(l_f/d_a)\,(e - 1{\cdot}94)^{3/2}$$

and obtain curve 2. Simplification to this extent clearly takes away all value from the calculation here, although in most power valves it would have been quite legitimate.

As a next step, recognizing the extent of the end cooling given above, we may substitute for the full 3·05 cm. length of the wire the length of an equivalent filament, obtained by dividing the observed saturated space-current by the emission per unit length of a filament of the given diameter maintained throughout at the full central temperature. The revised length is 1·9 cm., and curve 3 shows the effect of the reduction. The approximation is closer, but not yet near enough for practical use, particularly as regards the top and bottom sections of the curve.

The largest stride comes with the next stage, where we allow for a uniform potential gradient along this equivalent filament, retaining the uniform electron emission.

Curve 4 is the result. Here Stoekle's* modification of Langmuir's formula would apply to the central portion, where the electrons constituting the space-current are drawn from all points of the filament, but it fails when any point is saturated, or is still inactive because its potential is positive to that of the anode. The method of obtaining the full curve, as shown, requires more detailed explanation.

In the method now to be described the temperature of the equivalent filament is supposed to rise to its full value at a negligibly small distance from the filament end. Such a filament is alike at all points along its length. If, therefore, we plot distance from the negative end against the supply of electrons available according to the temperature at each distance, we get a very simple diagram [Figs. 23 (*a*) and 23 (*b*)]. In this diagram the ordinate gives the total number of electrons which can be emitted by a small element divided by the dimensions of the element measured along the axis of the filament. As the voltage gradient along this ideal filament is the same at all points, the horizontal distances on the diagram can be taken as representing either centimetres from the negative end, or volts from the negative end. In the first case [Fig. 23 (*a*)], the ordinate is simply the total emission per unit length of the filament, i.e. in the usual notation, $i'd_f$; in the second, Fig. 23 (*b*), it is the emission per unit voltage displacement along the filament. Now the voltage per unit length is E'/d_f, where E′, like i' above, is a specific function of the temperature. Hence in Fig. 23 (*b*), the ordinate is

$$\frac{i'\,d_f}{E'/\sqrt{d_f}}, \quad \text{i.e.} \quad \frac{i'\,d_f^{3/2}}{E'}$$

In both cases the value of a current is indicated by an area on the diagram.

This, then, is the distribution of the available supply of electrons in this simplified case. It is to be remarked, however, that the same form of diagram is equally applicable and very convenient in the case where allowance is made for a progressive fall of temperature as either end is approached. Stead's work on the design of short filaments can therefore be applied directly to the extension of the methods here developed.

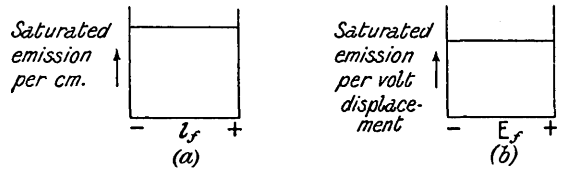


FIG. 23.

In a valve which is not entirely inactive through saturation, the whole of the available electrons do not, of course, take part in the space current. How many of them do so is a question of the field available for removing them from their starting-point on the filament.

As the voltage variation along the filament is not negligible, this field will be greater at the negative end than at the positive end, and as the voltage variation is assumed, for the present, to be ideally uniform, the field will decrease as in Figs. 24 (*a*) and 24 (*b*). If the applied potential is small, the field may be reversed at the positive end, Fig. 24 (*b*).

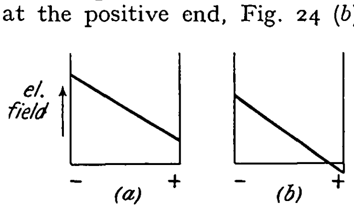


FIG. 24.

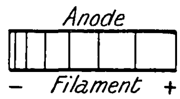


FIG. 25.

Knowing the field at each point of the filament, we can construct diagrams on the same lines as Figs. 23 (*a*) and 23 (*b*), but showing the distribution of the possible emission as limited by the field available at each point. Take an element of the filament distant λ cm. from the end and therefore at a potential E_λ, where

$$E_\lambda = E'\,\lambda/\sqrt{d_f} = \lambda\,E_f/l_f$$

If the potential of the collecting electrode is e, the field at our element will be due to the potential difference $e - E_\lambda$, or very nearly so, provided the lines of force run straight across and do not bend appreciably towards either end (Fig. 25).

* E. R. STOEKLE: *Physical Review*, 1916, vol. 8, p. 535.

If the length of the element is $\delta\lambda$, the maximum electron current which this potential difference will remove will be

$$A\,(e - E_\lambda)^{3/2}\delta\lambda$$

i.e. the ordinate in Fig. 26 (*a*), where the horizontal distances denote actual distances from the filament end, will be

$$A\,(e - E_\lambda)^{3/2}\,.\,\delta\lambda/\delta\lambda, \quad \text{i.e.} \quad A\,(e - E_\lambda)^{3/2}$$

The constant A depends on the form of the electrodes, for a cylindrical valve it will be

$$\frac{2 \cdot 92 \times 10^{-5}}{\beta^2 d_a} \text{ in amperes and cm.}$$

The corresponding ordinate for Fig. 24 (*b*) with a horizontal scale of volts, is obtained by dividing by

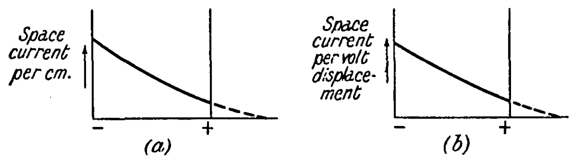


FIG. 26.

δE_λ, the voltage drop in the element $\delta\lambda$, i.e. by $E'\,\delta\lambda/\sqrt{d_f}$, and is therefore

$$A\,(e - E_\lambda)^{3/2}\frac{\sqrt{d_f}}{E'}$$

It must be noted that it is only because the voltage variation is uniform, i.e. because $dE_\lambda/d\lambda$ is constant all along the filament, that the two curves of Fig. 26 (*a*) and Fig. 26 (*b*) have the same form. Otherwise Fig. 26 (*a*) would be a more or less distorted copy of Fig. 26 (*b*).

From this point we will use the horizontal scale of voltage only, as in Fig. 26 (*b*).

If the field reverses before the positive end is reached, as in Fig. 24 (*b*), part of the filament will be idle (Fig. 27).

We are now in a position to show by superposing

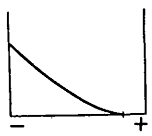


FIG. 27.

Figs. 23 (*b*) and 26 (*b*) the contribution of each element of the filament to the total space current.

Several cases arise.

In each case the proportion which the anode current actually flowing under the conditions shown bears to the total available supply of electrons is given by the relative sizes of the shaded area and the full rectangle.

Of these cases, those shown in Figs. 28 (*a*) and 28 (*c*) must clearly occur in all valves, Fig. 28 (*a*) at the very bottom of the characteristic curve, Fig. 28 (*c*) just before saturation is reached. Whether the intermediate condition is that of Fig. 28 (*b*) or Fig. 28 (*d*), will depend on the proportion of the strength of the field to the total supply of electrons. In a good receiving valve when the field can be strong, owing to the small grid diameter, and space-currents are small, we should expect Fig. 28 (*b*); in a power valve where the currents are large and the anode voltage has to be very considerably greater than the filament voltage before saturation is attained, Fig. 28 (*d*) will be the rule.

As the voltage applied to the collecting electrode is increased, the curve of limited emission [Fig. 26 (*b*)] will be displaced in the positive direction, and the shaded area correspondingly increased.

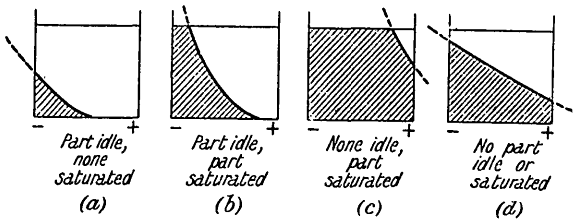


FIG. 28.

The increase in the shaded area for a given voltage displacement will be the measure of the slope of the characteristic.

Figs. 29 (*a*) and 29 (*b*) show by direct inspection the value of the slope under any conditions, because the height of the point of intersection of the two curves, or the difference of the two heights if there are two points of intersection, can be shown to be a measure of the slope. For, since the curve of limited emission is displaced without change of form, the increase of area [shaded in

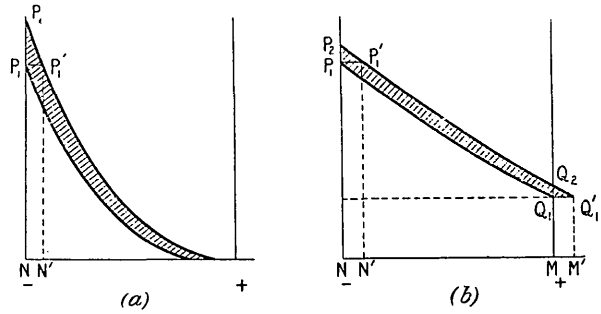


FIG. 29.

Fig. 29 (*a*)] may be supposed to be that included between the new ordinate of intersection, P_2N, and the displaced old one, $P_1'N'$. As the actual displacement employed is made less and less, this area becomes more and more indistinguishable from the product of either ordinate, new or old, and the displacement.* Hence we have :—

Slope, k, $= dI/de$

$$= \frac{\text{Increase of area}}{\text{Voltage displacement}}$$

$$= \frac{\text{Area } P_2NN'P_1' \text{ between ordinates of intersection}}{\text{Voltage displacement } NN}$$

$= \text{Ordinate of intersection, } P_2N$

* It has been pointed out to the author by Mr. A. C. Bartlett that when P Q becomes sensibly horizontal the difference of the ordinates can no longer be taken to represent the slope; the effects of the filament voltage are then, however, all negligible.

If an intersection occurs on the right-hand vertical, the change of area will be less than expected by the area, $Q_2 M M' Q_1'$, Fig. 29 (*b*). In this case then the slope is given by the difference between the ordinates $P_2 N - Q_2 M$.

We can now write down expressions for dI/de in the various sections of the characteristic curve, beginning from the bottom :—

(*a*) Lower curved section :

$$dI/de = \frac{A\sqrt{d_f}}{E'} \cdot e^{3/2} \quad \text{Fig. 28 } (a).$$

The 3/2 power of e appears because the length of the filament in action is proportional to e; E' is a specific function of the filament temperature as before.

(*b*) Central straight section :

$$dI/de = \frac{i'}{E'} \cdot d_f^{3/2} \quad \text{Fig. 28 } (b).$$

(An approximately straight central section for a very hot filament has another explanation, see next paragraph.)

This expression for dI/de does not involve the dimensions of the collecting electrode, and holds for all valves, actual as well as ideal, provided that the filament temperature and the applied field are both low enough for the single intersection in the central constant temperature region to be obtainable [Fig. 28 (*b*)].

(*c*) Central section, not quite straight :

$$dI/de = \frac{A}{E'}(\sqrt{d_f})\left\{e^{3/2} - (e - E_f)^{3/2}\right\}$$
$$= \frac{A}{E'}(\sqrt{d_f})\, e^{3/2}\left\{1 - (1 - E_f/e)^{3/2}\right\} \quad \text{Fig. 28 } (d).$$

As already stated, this expression applies to the case of a hot filament in a weak field.

If E_f is at all small compared with e, we have approximately,

$$dI/de = \frac{A}{E'}(\sqrt{d_f})\, E_f \cdot \frac{3}{2} \cdot e^{1/2}$$

But $E_f = E' \cdot l_f/\sqrt{d_f}$, so $dI/de = (3/2)\, A\, l_f e^{1/2}$, just as in the simple case of high-voltage valves where E_f is negligible. Curves have been calculated for intermediate cases where E_f and e are comparable in size.

(*d*) Upper corner :

$$dI/de = \frac{i'}{E'} d_f^{3/2} - A(\sqrt{d_f})(e - E_f)^{3/2} \quad \text{[Fig. 28}(c)]$$

and diminishes to zero when the intersection has passed beyond the upper right-hand corner of the diagram.

Returning to the case under consideration, curve 4 (Fig. 22) was obtained by means of Figs. 28 (*a*), (*c*), and (*d*). The two corners, upper and lower, show some approach to the observed form, and this approximation, imperfect as it still is, may perhaps be taken as the nearest likely to be of use in actual design, for at the next stage one can hardly avoid departing from algebraic formulæ and resorting to graphical methods.

As might be expected, one does come closer to the truth if one substitutes for the uniform emission and potential gradient assumed for curve 4 the distribution of temperature, and corresponding distributions of emission and potential gradient along the length of the filament obtained by Stead's method.

For our case this gives the emission diagram shown by the full line in Fig. 30 plotted with a horizontal scale of voltage. From this successive values of the space-current are obtained by placing the curve of self-limited emission (dotted lines) successively in the proper positions corresponding to the selected values of the voltage e and counting the squares under the dotted line and the parts of the full line which it cuts off. Curve 5 thus obtained is better than curve 4, though it is only at the bottom end that the improvement is worth the trouble. At the top end the departure is considerable, largely owing to the gradual approach to saturation shown by the observed curve. This effect is not covered by any existing thermionic theory, and has not been allowed for in our calculation. The error at the top of the curve is, however, somewhat

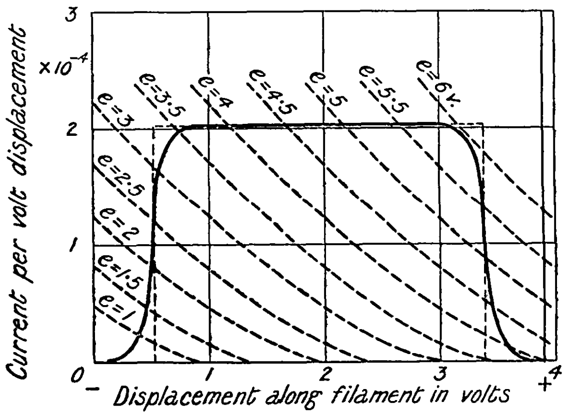


FIG. 30.

exaggerated in appearance owing to a false verisimilitude at the lower end, where some important effects have been left out of account.

In the first place, it is known that the extreme foot of the curve has an extension beyond the origin in the direction of the negative voltages. The scale of the diagrams is not suitable for showing this, but it has an exponential form and the current increases with change of voltage at the rate which would be expected if the distribution of velocities of projection of the electrons as they leave the filament is supposed to be the ruling factor. To make allowance for the velocity distribution in attempting to approximate further is therefore sound, though the rough method used in obtaining curve 6 is perhaps open to criticism. This was to suppose that the electrons leaving any particular portion of the filament with a high velocity behave in every respect as if they came from a point nearer the negative end by the fraction of a volt, by falling through which they would acquire this velocity. It is assumed that the proportion of the electrons from any point which have a given velocity is given by Maxwell's distribution law.

The second point is that curve 6 is displaced to the left of the observed curve by almost the same amount as the upper part of curve 5 into which it merges.

This means that we have now obtained a curve of nearly the right shape, except at the extreme top, but referred to a zero of potential which is displaced a few tenths of a volt with respect to the negative end of the filament. It seems reasonable to refer a zero displacement of this order of magnitude to the contact potential difference between the body of the hot tungsten filament and that of the cold nickel anode, especially since the zero displacement varies from valve to valve and the contact potential is well known to be very sensitive to changes in the surface condition of the metal electrodes.

In extending this theory to triode valves by substituting for the single anode voltage e the expression $e/m+e'$, combining the effects of the grid voltage e' with those of the anode voltage e, it must be remembered that in most small valves the value of m is by no means constant all along the filament, particularly when the ends of the filament are not sufficiently covered by the grid.

(10) Specification of a Standardized Valve.

It was always the practice to test each valve individually before issue. Uniformity as between one valve and another is a thing obviously desirable of attainment, seeing that the duties of an operator on service lie in other directions than the investigation of troublesome individual peculiarities in the valves issued to him. At first, when the action of valves was little understood, the test took the form of an actual trial in a receiver. This single comprehensive test was, no doubt, ideally satisfactory as long as the flexibility of the receiver and the simplicity of requirements make it a test which all of the valves pass; but it is often the reverse of illuminating when rejections begin to appear. Experience showed more than once that unless the physical cause of failure was explored and eradicated on its first appearance, the proportion of defective valves was liable to grow at an alarming rate. Testing by the pragmatic method also becomes impracticable as valves come to be used in different instruments.

The alternative of taking steady current conditions and making tests which amount to observing a few suitable points in the working region of the characteristics under standard conditions of filament adjustment, was gradually substituted, tests in a receiver being confined to special or doubtful cases, and ultimately eliminated.

A set of essential test conditions for a valve for general use in receiving instruments, amplifiers, heterodynes, or detectors was ultimately arrived at by summing up the experience of the members of a small committee which jointly represented the Admiralty, War Office, and Royal Air Force in furthering the rapid expansion of valve production in this country which took place during 1918. The committee was very fortunate in its composition, and the respective shares of the members in the details of the outline specifications which summed up the technical aspects of their work would be difficult to estimate. What follows is an account of methods which the author found useful in exhibiting the results of tests and trials during the transition from the easy specifications of the early days of simple heterodynes to the stricter requirements of amplifiers and other later types of instrument.

For the purpose of scrutinizing test results, observations on valves were considered under two heads. First, there were the current and voltage adjustments required to produce a specified saturation current of electrons from the filament, and secondly there were observations indicating the form of the characteristics in the working region when the filament had been so adjusted.

Taking the case of the filaments, the current and voltage adjustments for 100 valves may be shown together by representing each valve by a dot on a diagram such as Fig. 31 where the horizontal axis represents " volts " and the vertical " amperes." The figure gives an actual case for 100 filaments of fairly pure tungsten. The diagonal line is added to show, for an average valve in the centre of the group, the normal course of current variation as the voltage adjustment is changed. Any valve appearing below

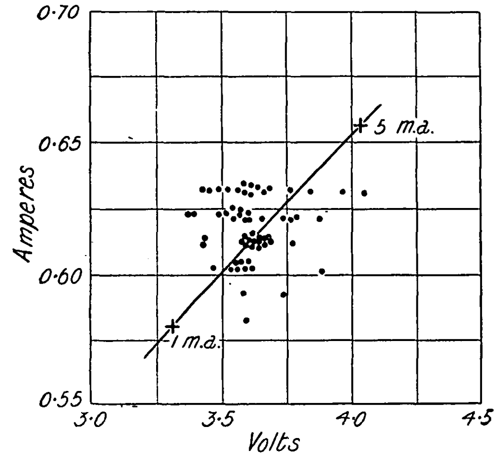


Fig. 31.—Filament adjustments for 2 m.a. saturated emission.

this line requires abnormally high voltage for a given current, and is therefore probably either longer or else thinner than the average, the latter defect being usually traced to damage during bombardment. Similarly points above the line represent filaments either thicker, or, more probably, shorter than the average. As each valve is adjusted to a given emission, points occurring in positions close to the line represent differences in electron-emitting properties. The extent of the differences in the batch shown is indicated by the crosses on the line giving the adjustments of the average filament for 1 and for 5 milliamperes as well as for the usual 2 milliamperes.

The best emitters are seen to give 2 milliamperes where the average would give $1\frac{1}{2}$, and the worst 2 instead of 4.

The diagram thus illustrates how the variations of the thermionic property which, not so very long ago, was regarded as very fickle, have been brought within bounds. With specially selected specimens of metal target, diagrams covering one-third of the range shown have been obtained. A tendency for the group to extend upwards in the direction of poor emission is found to be associated with imperfect exhaust (cf. Langmuir's work on the effects of residual gases, thus statistically confirmed),* and on the other hand extensions in the opposite direction indicate impurity of the tungsten, and are especially well shown where thoria is present, and also give warning of probable noisiness in amplifiers.

The earlier observations of standard points on the characteristics made very conspicuous the fact that the characteristic " constants " of small high-vacuum valves differ among themselves very widely. This is so even when the valves are all well exhausted and to outward inspection well made. The factors most observed, the records covering many thousands of valves, were

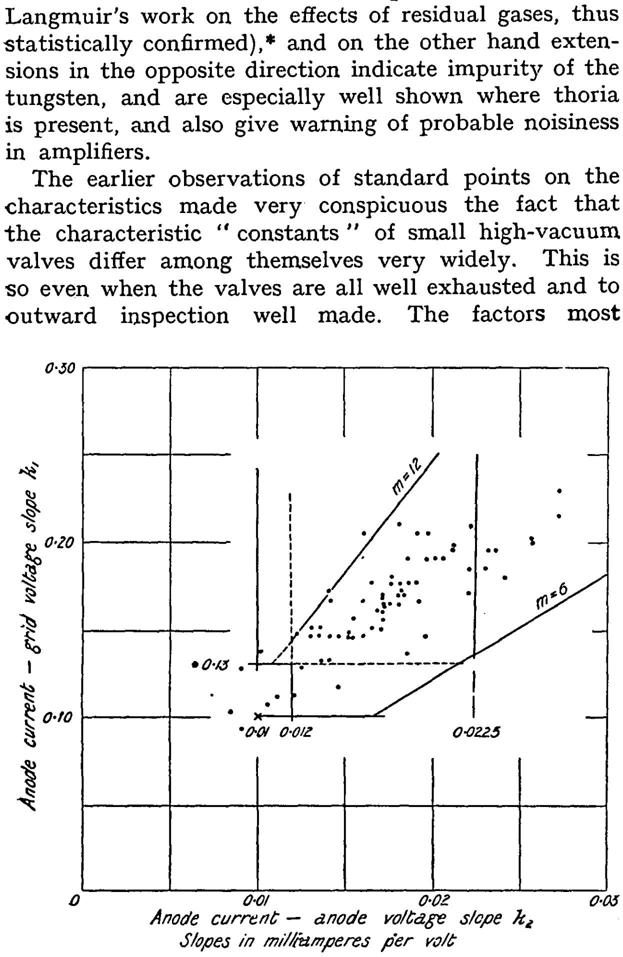


FIG. 32.

Anode-current/grid-voltage slope, k_1.
Anode-current/anode-voltage slope, k_2.
Grid closeness factor $m = k_1/k_2$.

In any batch of 100 valves or so the lowest value of any of the above quantities is commonly as low as one-half of the highest value observed in the same batch.

The characteristics are thus actually almost as variable as the life of the valves.

Fig. 30, in which each dot gives simultaneous values of k_1 and k_2 for a particular valve, shows the range of variation occurring in an ordinary batch of valves. The diagrams for all types of high-vacuum valves of which sufficient numbers have been available—R4, R4A, R4B, R5, R, and V24—show the same degree of variation, and gas-filled valves still show the same effect even when, as in R2A, which is a true high-vacuum valve before the gas is admitted, there is no question of variation in the quantity or nature of the gas.

One of the first uses to which these diagrams were put was in making minor modifications in the construction of valves by different makers so as to bring the average in each case midway between the specified limits.

In determining the limits of the permissible range of variation in respect of a particular characteristic quantity for a particular receiver in which the valves are to be used, subsidiary diagrams of the same type were used.

In Fig. 33, for example, each pair of dots shows horizontally the anode-current/anode-voltage slope k_2 for a pair of valves used together in a two-valve audio-frequency amplifier. The two valves of each pair were selected as having as nearly as possible the same k_2, but in respect of all the other characteristic quantities all the valves taken were allowed to vary in an arbitrary manner. The vertical scale of Fig. 33 gives an inverse estimate of the sensitivity of the combination, the quantity represented being the coupling required for obtaining a signal of standard strength, so the smaller the coupling the greater is the sensitivity.

The way in which the dots arrange themselves, in an elongated diagonal group, indicates that the anode-current/anode-voltage slope has a very marked influence on the sensitivity independently of all other factors, but that the two combinations, themselves somewhat unlikely, of a pair of good, and a pair of bad valves, differ in respect of the necessary coupling in a ratio of no more than two to one, which represents with the apparatus used about one signal " strength." Considering that the range of variation of k_2 covered by the group is nearly two to one, this observed effect is somewhat surprisingly small. This is, however, just as well, for reference to the full test diagram (Fig. 32) shows that it would have been possible to find worse valves in either direction of variation. The fixing of specified limits for k_2 at 0·0225 and 0·012 milliampere per volt, finally decided upon from trials in this and other pieces of apparatus, involved a considerable proportion of rejections, but practice in manufacture ultimately gave some improvement. In all cases

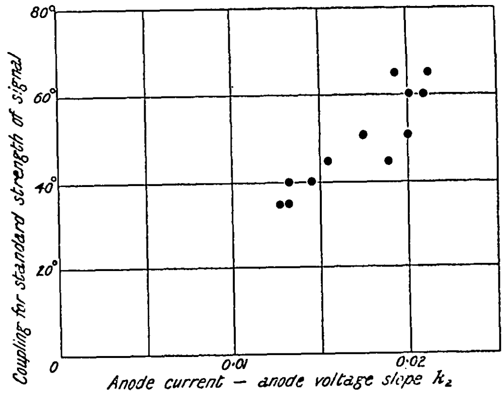


FIG. 33.—Effect in amplifier of changes in a characteristic.

* LANGMUIR: *Physical Review*, 1913, vol. 2, p. 450.

where the valves were intended for multiple-valve receivers it was decided that the probabilities were so much against an operator being forced to use a combination of valves all differing to a marked extent in the same direction from the average, that tolerances giving extensions in respect of the limits for a limited proportion of the valves were permitted in some cases.

In some of these trials it was found that the quantity under observation had no direct influence on the effectiveness of the receiver, the form of the group on the diagram being either circular, or a circle distorted by purely vertical or horizontal elongation. This was the case, it is of interest to note, with the anode-current/grid-voltage slope in the audio-frequency amplifier.

The narrowest limit required for each characteristic quantity by the most exacting receiver can be shown by a line on Fig. 32, and the size of the group relatively to the frame of lines so formed indicates the strictness of the specification or, conversely, the quality of the manufacture. A general displacement of the group shows by its direction which factors tend to be at fault, and the effects, often unexpected, of steps taken to remedy such faults can readily be followed. It is apparently established that variations of m are caused more by differences in the extent of exposure of the filament ends than by irregularities in the convolutions of the grid itself, and that simultaneous low values of both anode-current slopes, k_1 and k_2, are due to a specially large change of contact potential in the direction of retarding the electron flow.

The electrical tests decided to be necessary for receiving valves were as follows :—

Filament.—An upper limit, imposed by the supply arrangements, for the current and voltage for a specified saturated electron current, and a lower limit of voltage if great uniformity is required, or valves are used with a common filament control.

Characteristics.—Anode current observed at two stated grid voltages and two or three anode voltages, the differences of readings indicating the values of the characteristic slopes and of their ratio m. Lower limits are specified for both slopes, and for m, but an upper limit for the anode voltage slope only.

The value of the reverse grid current, if any, at a stated negative grid potential is taken as indicating the degree of exhaustion of the valve, and the direct grid current at the working grid potential as indicating the damping effect of the valve on the input circuit.

Life.—Sufficient information for rigid life-test clauses was not available at the time considered.

For power valves the filament specification followed the same lines. A power-dissipation test of a few minutes' duration for the anode was included, and this was to be carried out under such conditions that the space current actually flowing was less than the saturation current which the filament had been previously adjusted to give, and was therefore controlled by the voltages of the other electrodes and by the space charge, that is, by the state of exhaustion.

A dissipation test so carried out gives a clear indication of the stability of the valve as regards the vacuum.

The testing of each individual valve on these lines was quickly learnt by previously untrained testers, and was carried out with very satisfactory accuracy, with the result that complaints of electrical misbehaviour of valves became very rare.

In conclusion, the author desires to express his thanks to the Captain of H.M. Signal School for assistance in the preparation of the paper. It is impossible to indicate how much the author's own share in the work described has benefited throughout so long a period by the co-operation of Professor Fortescue, of Mr. Stead, and of the various members of the wireless telegraph departments of H.M.S. "Vernon" and of H.M. Signal School, particularly by that of Mr. T. E. Goldup, late Lieutenant R.M., and Mr. C. O. Moss, late Warrant Telegraphist R.N.R., in their unfailing help in the work of standardization described in the later sections.

He wishes also to make some acknowledgment, however inadequate, of the ready kindness on all occasions of those with whom he has been privileged to confer, whether in the discussion of physical principles, or of the action of circuits, or of practical considerations in manufacture.

APPENDIX.

(*Received* 4 *October*, 1920.)

When the paper was read before the Institution use was made of a three-dimensional model to illustrate certain internal actions of the valve. The object was to represent to the eye the motions of electrons in an electric field by the analogy of those of a ball rolling on an undulating surface, the differences of level on which reproduce potential differences between the corresponding points in a longitudinal section of a cylindrical valve. The actions resulting in the control of the space-current through the valve are essentially dynamical, and it is necessary to adopt some such representation as this in which allowance is readily made for the momentum of the electron which prevents it following a curved line of force.

The ordinary line-of-force representation of the field shows directly only those lines along which an electron in free space will certainly not move, for the electron will only follow the line of force in the exceptional case when this is perfectly straight. A diagram of equipotential lines is more useful, but even so it is necessary to visualize the surface of which it is a contour map.

By imagining such a surface one can readily trace out the effects of a change in the potential or in the shape of an electrode. The composite potential function $e/m + e'$ in the triode acquires a more concrete significance as the level of the sinuous equipotential which winds in and out of the row of grid wires and indicates what is for the other electrodes the average or effective potential in the plane of the grid. The partition of the electrons between anode and grid is also sufficiently explained without recourse to the mathematical analysis of central forces, and the effects of the velocities of projection of the electrons and of the space charge can be allowed for, but the effort of viewing the surface as it were from the other side, or alternately of reversing the supposed direction of gravity, in order to represent the field from the standpoint of a positive ion is unfortunately usually too much for the imagination.

DISCUSSION AT A WIRELESS SECTIONAL MEETING OF THE INSTITUTION, 23 JUNE, 1920.

Professor C. L. Fortescue: Problems which, in the early days, seemed formidable now appear, as we look back upon them, quite simple, but at the time we were struggling with them they were very real, and such success as we achieved was due in no small measure to the persistent zeal with which the author attacked them. In the course of investigating these problems it was interesting to note the extent to which we reached at times the limits of knowledge. A lot of the work done on the valve was really almost pure research, and the valve actually produced was a good example of pure research running in parallel with its immediate application. Almost any paragraph of the paper would provide a text for a long discussion, and I propose therefore to deal with only three points. The first is the question of the contour diagrams on page 684. This method of delineating the characteristics of the valve was devised by the author of the paper and has proved to be very useful, and I know of no other method of bringing out so compactly and clearly the whole of the necessary properties of the valve, either from the point of view of the physics of the valve itself or from that of the circuits associated with it. They have many other advantages, particularly as regards the transmitting valve. In the great majority of transmitting-valve circuits the trace of the variation of the grid and anode voltages becomes merely a straight line drawn across these contours, and they tell immediately what the nature of the currents will be, what conditions will lead to the presence of harmonics in the make-up current, and so on. They also have the advantage that they can be actually obtained in practice. If one takes Fig. 16 (*a*), for example, a very few points on all those straight lines are all that are necessary. Next I will consider the target diagrams. I think those who are inclined to regard the valve as having very definite constants should consider Fig. 32 carefully. There is no doubt whatever that the range of variation actually found in practice explains many of the difficulties which have been met in high-power amplifiers. There are amplifiers where a small percentage change at one of the steps will cause either oscillations or a falling-off of the amplification. The standard of uniformity necessary is higher than shown in these diagrams, and steps will have to be taken, perhaps as one of the immediate lines of research, to secure a higher degree of uniformity. The last point I propose to mention is with reference to the question of symbols. Every worker on valves seems to have adopted a notation of his own. It is time that this Wireless Section settled whether they are going to keep to the k_1, k_2, etc., as adopted in this paper, or to use Dr. Eccles's notation, or to adopt the American notation. I suggest that the Wireless Sectional Committee should take the matter in hand and at any rate decide it provisionally. It is not necessary to reach a final decision, but we can come to some temporary agreement until something better is put forward. Leaving the actual subject matter of the paper, I should also like to refer to the Valve Committee. That was formed in 1918 under rather adverse conditions at a time when the supply of valves for the various Services was far from sufficient. It took up the matter of the supply of valves, and had a lot of difficulties to overcome, as there was a certain amount of opposition. But after its formation the supply of valves never actually failed, although perhaps there was not always a big reserve. The Committee did not do everything that was expected of it, but it certainly did what was wanted. The wireless branches of the different Services are indebted to that Valve Committee to no small degree.

Mr. C. C. Paterson: This paper shows how very good is the historical method of presenting any subject. The author has described all the stages of pioneer work in their chronological order up to the time when valves of all types were turned out on a production scale, but he has said very little about his own work in connection with this matter, although the results achieved were largely due to his tact and originality. As one who saw a good deal of this work from the manufacturing point of view, but who was not in any way responsible for it, I would say that this whole subject of the production of the valve from its early stages is of quite as much interest from the point of view of industrial research as it is from that of radio research. One first of all appreciates that it was only achieved by both the technical people who were responsible for the development of the valve, and the manufacturers who were responsible for its production, each appreciating the difficulties which the other found. There were many difficulties to surmount on both sides. The technical staff of the Services were being pressed hard all the time to produce something which would work. The manufacturers were up against enormous difficulties in production under war conditions. They were having to use substitutes in a large portion of their manufactures, and men on whom they depended were being taken away from them for war service. Yet, in spite of all this, this country undoubtedly led the way in development and progress in connection with thermionic valves. I think it is very much to the credit of this country, and also of those who had any share in the work, that this result was achieved. Another moral to be drawn from this is that, as Professor Fortescue has said, the development of the valve was not the result of research handed over to the manufacturer to get into production, but the fundamental research had to proceed in parallel with the actual effort to produce something. The manufacturer had to adopt the hit-or-miss method to try to get something going, but he was supported throughout by the more fundamental research which followed but seldom preceded the production of the actual result. That is the way in which, in my experience, industrial research very frequently proceeds.

Professor G. W. O. Howe: This paper emphasizes a remark that I made at a previous meeting of the Wireless Section. Many of us thought in the early days after the war how little had been done in this country compared with other countries, but the papers which have been read before this Wireless Section during the last year, and this paper to-night, show that we were in no way behind, and that an enormous amount of valuable research work was being done under very trying conditions. I should like to express my appreciation of the ingenious model which the author has prepared. There is one point about it which I think might be made a little clearer in explanation of the action of the space charge. Many people probably experience the same difficulty as I had when I first studied the subject. If the electrons are emitted from the filament into a field which tends to repel them back to the filament, one would expect that either one would get no current due to the electrons all being driven back to the filament, or else one would immediately get the saturation current. I do not think it is usually sufficiently appreciated that the value given for the velocity of the electron emitted from an incandescent filament is only an average, and that the electrons are emitted at very different velocities. The distribution of the velocities follows a well-known law, and although the electron has an average velocity of the value quoted by the author from $\frac{1}{4}$ volt to $\frac{1}{2}$ volt, some of the electrons are ejected from the filament with a much lower velocity, and some with a velocity of 4 or 5 volts. What actually happens is this: if the height of that little hill in front of the filament on the model represent $\frac{1}{4}$ volt, it is only those electrons which are emitted with a greater velocity than $\frac{1}{4}$ volt that succeed in getting over, and all those below $\frac{1}{4}$ volt fall back again. If the voltage of the grid is raised a little the height of that hill will be altered, in fact will be lowered, and now a greater proportion of the electrons emitted will be enabled to get over the hill. By altering the grid voltage we vary the height of the hillock and thus alter the proportion of the constant number of electrons emitted that are capable of getting over and thus avoiding being returned to the filament.

Mr. J. St. Vincent Pletts: I was very interested in the model. The chances seem to be very much against the marble getting into the grid, but I should have thought that many more would have gone in than appears to be the case. I doubt if in that model even one in a thousand would get in.

Mr. J. Scott-Taggart: The design of valves may be classed into mechanical and electrical design, the former being almost as important as the latter. Figs. 9 and 10 show two very ingenious methods of constructing valves of high power. The problem in the case of these valves is chiefly the method of supporting the electrodes within a tube. There are two re-entrant tubes, one at each end of the bulb, and to these tubes are attached the supporting wires which hold the electrodes. Two methods are shown in this paper. One consists of metal bands which grip a stem, and in the other the anode is supported by means of springs which expand inside the tube and so hold the electrodes. There are one or two points to consider when choosing a method of supporting electrodes within the valve. The different electrodes should be so arranged that the insulation between them is exceedingly high, with a view to preventing leakage when high voltages are used. Another point is the rigidity of the electrodes. This is of special importance with valves which have to be transhipped. The rough treatment in the handling of the goods naturally requires the utmost rigidity of the internal structure of the valves. Again, in connection with the design of the valve from the structural point of view, there is the necessity of avoiding any glass-work which is liable to crack. Consequently, the ordinary arrangement whereby the supporting wires are fused into the glass stem cannot be employed on the higher-power valves, but some method must be devised

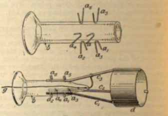


FIG. A.

whereby the structure is extremely strong without employing any glass-work. Again, there is the ease and cheapness of manufacture. Still another point of importance is that the metal parts inside the valve should, during the bombardment of the electrodes, be also bombarded, so that no portions of metal which do not have the occluded gases removed should be inside the tube. When I had to design the internal structure of the valves made by the Ediswan Company, several methods occurred to me, but I found that practically all of them had already been patented by the Osram Company. I eventually thought of the arrangement shown in Fig. A herewith. The upper figure shows a glass funnel which is sealed into one end of the bulb, and it is to this funnel that the electrodes are to be attached. The method that is being used is to take a number of small U-shaped wires, as shown, made of nickel-iron alloy having the same coefficient of expansion as glass, and dip them just below the surface of the glass. Being arranged in the manner shown, the supporting wires, which should preferably be of channel cross-section, are then slipped in between the wires. The two ends of each wire are then twisted together and thus firmly tie the supporting wire to the glass. The completed stem showing an anode mounted is seen in the bottom figure. This construction has been found extremely strong, much stronger than would appear from the diagram, and, moreover, the chances of cracking are extremely remote. Out of hundreds of these valves that have been manufactured there have been no cases of cracking of the glass, and no particular precautions for annealing are necessary. Another advantage of this arrangement is that the anode is very securely attached. There is no fear of its slipping round, and no complicated arrangements are necessary. Another point is that there are no metal bands or large surfaces of metal which do not actually come under the influence of the electron bombardment. There is only a short distance which is not actually exposed to the influence of the electron bombardment, and consequently a higher degree of exhaustion is possible, or, alternatively, the same precautions are not necessary in the manufacture of a valve designed on this principle. The lantern slide illustrates an arrangement whereby the filament of a valve may be supported. This is a very difficult problem in a valve, and the usual arrangement has been to support the top end of the filament from the other end of the tube. This necessitates a rather more difficult method of manufacture, and at the same time there is a liability of leakage from the top end round to the electrode which is attached to the stem at that end. In this arrangement I have used a supporting wire tied to the glass stem which holds the filament wires, thus producing a very strong and efficient method of supporting filaments for rectifiers and high-power three-electrode valves. It is to be noted that this supporting wire is usually of nickel, while at the very top I use a small piece of molybdenum wire to prevent damage to the filament when the latter is incandescent. Another slide shows a small-power rectifier capable of dissipating about 250 watts. It will be seen that the anode and filament are mounted at the same end of the bulb. The anode is attached to the stem before the latter is sealed into the bulb. Consequently, the manufacture is very much cheaper and it is quite suitable up to comparatively high voltages. The danger is that sparking may take place through the glass between the anode supports and the filament wires. To prevent that, the filament wires are covered with very thick glass tubing, and this arrangement has been found very much cheaper to construct than the usual type in which the anode is mounted at the other end of the bulb. Mention has been made of the difficulty of manufacturing the V24 valve designed by Captain Round. This difficulty, I think, has been very largely exaggerated. This type of valve is, from the point of view of the manufacturer, probably one of the best that has been produced, and the breakage is exceedingly small. The valve is extremely light, and if dropped suffers very little. The connections are made at the sides of the tube, and so there is an infinite resistance between the anode and filament and between the grid and filament. This is a most important point in valve construction, and a considerable number of valves of the four-pin type, and also of the Air Force "C" and the Navy "R5" types, are rejected at the works on account of leakage between the different electrodes, not inside the bulbs but between the leads outside. The caps used are attached by means of cement, which is naturally moisture-absorbing, and after a time the insulation is liable to deteriorate. Another advantage is that the capacity of the electrodes is probably less than in any other type of valve. The leads are taken direct to the outside and do not run parallel, as is the case in other types. A further slide shows a valve (known as the RV30) somewhat on the lines of the V24, which possesses all the advantages due to the absence of leakage and to minimum capacity of the electrodes. There are one or two points of interest. First, the anode support is fixed to a glass cup by means of the tie-on construction which I have explained. Another point is the nature of the glass cup, which provides a very long leakage path between the anode to the filament and between the grid to the filament. The leakage path between the grid and anode is also long. Turning to the original paper, there are one or two features in some of the designs which could be improved. The supporting of the filament of R5 valves is inadequate. The thin spring wire gets heated throughout its whole length and loses its elasticity. During the manufacture of these valves, this lack of efficient filament springing causes a considerable amount of breakage when on the pumps. If the spring is too tight the filament on shrinking is liable to snap; if too loose, the filament is liable to touch the grid; in each case, valves are spoilt. The tension on the R5 filament appears to be too critical. As the end of the spring wire is pulled down the tension increases. If, however, the flat spring wire is given a double loop and thus made about twice as long, the tension on the filament is less dependent on the adjustment of the spring during manufacture. A trial of 200 valves with such filament springs showed a saving of 15 per cent in filament breakage. It was also found on other valves that an additional spring wire at the bottom still further reduced the breakage during manufacture and also in transit. With regard to the grid of the R5 valve, it appears to be of a smaller diameter than necessary. Decreasing the grid diameter may even lower the amplification factor, and certainly does increase the cost of manufacture, as does also the asymmetrical placing of the grid and anode with respect to the filament. The backlash test for vacuum is not infallible. The current to the grid is the algebraic sum of the electrons and positive ions striking the grid. A "hard" valve in which the electron current to the grid was below normal might thus be considered "soft." It is to be regretted that in this paper no mention has been made of rectifying three-electrode valves. From the title of the paper one would have expected some description of the design of valves for purposes other than amplification.

Dr. W. H. Eccles: One of the most noteworthy of the numerous details of information in the paper is the formula for the voltage factor. I have myself worked out a formula for another type of grid and this formula is identical with the one in the paper, when Maxwell's analysis of the plane problem is extended to determine an undetermined constant in my formula. It is to be hoped that the method of obtaining the formula in the paper will be divulged some day. In answer to a question by one of the speakers, I might mention that the Wireless Sectional Committee have several times had under consideration the possibility of doing something towards standardizing notation and symbols. It is, however, a difficult problem. The fact is that wireless telegraphy and telephony are developing so rapidly that any nomenclature suggested might soon become obsolete. We have seen that happen in the history of other electrical ap aratus. The present chaos is a kind of preliminary stage, but in another few years I believe we shall have a better chance of getting agreement between the people who have to use these symbols. I think that is the view of the Wireless Committee. For my own part I think it would be lost labour to go far at present. As an instance of the difficulty of persuading people to use standard symbols, the authors of English textbooks and papers use the letter " m " to stand for metre, or milli, or micro-, or mega-, indiscriminately. We often see microfarads written " mfds," contrary to the recommendations of the International Electrotechnical Commission. The same author in the next line will write " mhy " for millihenry, " m " in one line standing for " micro-," and in the next for " milli." I suggest that " wireless " authors might begin disciplining themselves by using the International Electrotechnical Commission's recommendations. Meanwhile the Committee will keep the matter before them and decide when the time is ripe for action.

Mr. H. M. Dowsett (*communicated*) : Having regard to the series of processes to which the gas atoms are subjected in a " soft " valve, it is a noteworthy achievement to have developed the theory of this valve to such a point that it is possible to predetermine the characteristics of a given design. To enumerate these processes : (1) There is first of all the break-up of the neutral molecule and the surrender by it of as many electrons as correspond to the atomic number of the element concerned. (2) The bombardment of the anode by the negative ions and the passage towards the filament of the positive ions. (3) The entry of the positive ions into the space charge and their reaction on it. (4) The bombardment of the filament by these atoms and their reflection from it as negative ions towards the anode or the walls of the valve. There are two of these states which call for some further remark. It is an accepted fact that the positive ion is able to neutralize much of the effect of the space charge. How it does so is a moot point. As the atom is travelling towards the filament it is probable that it fails to hold any electrons which are proceeding towards the anode, but they stream through it until it strikes the filament. At the same time, as the axis of the atomic magnetic field corresponds to its axis of translation, the space-charge electrons which are moving erratically and not towards the anode will be caused to whirl in spirals round the atom, forming a funnel up the centre of which the newly expelled electrons from the filament will find an unimpeded path. After the atom has struck the filament and its direction has been reversed, it will take up its full complement of electrons or an excess depending on the space potential, as it will now be proceeding in the same direction as the electrons, and in this way it will tend to reduce the space charge. All these electrostatic and magnetic effects are fortunately proportional to the atomic weight or the atomic number, and this must be held to explain why predetermination is not a more difficult matter.

Captain H. J. Round (*communicated*) : The author has brought together in this paper a very large amount of information on the details of design and construction of valves which has been in the last few years both secret and scattered. Although a few of us have had access to some of the work recorded in the paper a great deal of it is quite new to me, particularly the splendid series of soft-valve characteristics. The paper, in fact, records such a mass of work that a satisfactory discussion of it would take up much more space than the paper itself. I find that I have had to concentrate on one or two parts of the paper and leave the rest for reference when the subjects referred to become of interest. I think it is rather a pity that any space at all is given to the American ultraudion circuit. To synthesize a good circuit is far more useful than to analyse and patch up such an arrangement. In connection with this ultraudion circuit, E. A. Armstrong gave a similar analysis of it in a communication to the *Radio Institute Journal* about two years ago. Mr. Gossling's paper teems with characteristics of various valves, but the relation of these to circuits, and an indication why such and such characteristics are valuable, would add to the completeness of the paper. Perhaps I am asking too much, as I am aware that the paper was written with the idea that it is generally known what characteristics are wanted. How these characteristics were obtained by theory and experiment and reproduced on a manufacturing scale is the author's special province. I think we are waiting for our Chairman or another to collect together into one comprehensive book or paper all the specialist papers on valves and valve circuits. The collected work on soft valves is a very valuable contribution, and most of it is quite new to me. I should like to know to what extent the static characteristics are relevant in high-frequency work. The paper still leaves me in doubt as to whether magnification by ionization is possible, and up to what order of frequency, and whether it occurs to any practical extent in soft valves. One can feel fairly sure that with frequencies such as 50,000 ∿ per second hard valves obey the static characteristic laws, but is this true with soft valves ? I am strongly of the opinion that practically all the advantages of a soft valve are obtained, due to the neutralization of the space charge and the consequent lowering of the resistance of the valves. Static characteristics would, by showing the sum of the negative and positive currents, give a false idea of the operating characteristic. Wherein lies the value of a soft valve ? This question of course introduces the additional question : For what use do we require the valve—as a rectifier or a magnifier ? I can answer the last part of the question by making the practical statement that a soft valve has nearly all the properties of a bank of hard valves in parallel. In other words, the soft valve has for its " *m* " value a very low resistance compared with the hard valve. The "*m*" value of a valve can be defined as the maximum voltage amplification possible when using a resistance-drop amplifier, when the resistance and the plate voltage are both infinite. If we replace the resistance by a resonant circuit and consider the voltage amplification when using frequencies exactly in tune with this circuit, we can say that the "*m*" value is now the voltage amplification when the damping of the circuit is zero. The plate potential now of course need not be infinite. Suppose, however, that damping is now applied to the circuit; the actual "*m*" value is then less than the maximum by a factor depending upon this damping and upon the resistance of the valve. In general, the lower the resistance of the valve, if its maximum "*m*" value is kept constant, the nearer the practical "*m*" approaches the maximum "*m*." The value of damping in the plate resonant circuit is well known in "quasi-aperiodic" amplifiers. Again, in "quasi-aperiodic" low-frequency magnifiers where a ratio transformer is used to the next valve grid, the lower the resistance of the valve the higher is the ratio of step-up transformation that can be used—depending on the effective losses in these transformers. All these advantages are of course dependent upon the fact that the internal capacities of the valves do not exhibit such low impedances that applied voltages on grids, for instance, are appreciably lowered. The real point in the soft valve is this: that at reasonable plate voltages high practical magnifying power can be obtained. The actual working capacities of soft valves do not seem to have been determined, but there is probably a considerable increase over the static capacities of the tubes. General consensus of opinion seems to indicate that with hard valves the working capacity is not appreciably different from the static capacity. Recent work has enabled us to obtain with the four-electrode hard valve all the advantages of the soft valve with the dimensions, filament and plate voltages, and filament current of the V24 valve. One set of hard valves which we are now manufacturing and shortly intend to place on the market has the same internal resistances as a V24, but with an "*m*" value of 30 instead of 6 as in the V24. The benefit of this on a cascade resistance-drop amplifier can be at once seen. The capacities of these valves are still small compared with those of clips, leads, and windings. I should like to note that in the use of Sir J. J. Thomson's formula for the "*m*" value it is usually sufficient to use a value $\pi d n$, where d is the grid diameter, and n = no. of turns per cm. length; or, in the case of a square mesh, $2 \pi d n$; providing always that the diameter of the wire is small compared with the spaces. This value is obviously the amount of wire per cm. length of grid. Further correction is best done experimentally by testing a number of valves.

Mr. B. S. Gossling (*in reply, communicated*): More than one contributor to the discussion has remarked upon the general characteristics of research in such subjects as that with which the paper deals. It is a fact that the greater part of the work there recorded is of a nature essentially analytical. Here is an instrument which works—sometimes at least—in such and such a manner. What is really going on? The attempt to answer such a question is a necessary part of the work of institutions, such as H.M.S. "Vernon," to which inventions are referred, and, again, as Mr. Paterson says, such work is more often subsequent than precedent to actual manufacture. In both cases it is the hand which has been dealt that has to be played, and the unexpected usually happens. What methods will be necessary, and into what fields of knowledge it will be necessary to make excursion, it is difficult to predict. Professor Fortescue will agree that a conscientious analysis of the commonest of phenomena is liable somewhere to touch the confines of knowledge. Encyclopædic minds being too rare to count upon, and usually otherwise engaged, the most promising course is for a number of specialists who cover between them all likely fields to agree to pick one anothers' brains. Such collaboration was one of the commonplaces of the war. The cultivation of the surviving relics of this spirit is a present-day problem. The analytical nature of the work recorded is well shown by the fact that, although many fundamental physical principles underlying the behaviour of valves there become recognized, no new principle not operative in one or other of the valves of 1914 has been enlisted during the period covered. However, one is entitled to hope that the analytical work of the past, besides leading up to rational standardization and deliberate design, may have resulted also in an enlargement of the opportunity for work of a different order.

Synthetic research in applied science (if I may borrow Captain Round's wording) requires a wide knowledge of the art in question such as comes slowly and to few, although direct and preferably untrammelled contact, alike with operators, manufacturers, and inventors, is an invaluable aid and a never-failing stimulus to the imagination. The synthetic attitude of mind is not quite that of the inventor, as the analytical is not quite that of the consultant, but the distinction is at least of the same order. The purely scientific equipment required may be the same in both cases, just as the possession of a common language has its uses, but the differences are differences of method and object, and more may be heard of them in the future, when a precise definition of the nature of professional research work is attempted.

The symbols employed in the paper are the same as those used by Professor Fortescue in his own published work. I do not doubt that we are equally aware of their drawbacks, but I gather that he, like myself, has felt, in the absence of an authoritative pronouncement, transcription would be wasted labour. Adoption of recognized conventions may call for some additional alternatives to standard symbols. For instance, the chief expression in the theory of the distribution of electron velocities involves the "exponential e," the electronic charge, and a symbol representing volts. For work in this field each of these quantities must have a different symbol. Which is to be called "e"?

The lack of uniformity amongst different specimens of small valves of the same design can be ascribed in large measure to variations in contact potential, which result in the field experienced by the electron near an electrode being different from that which would be expected from the indications of a voltmeter connected to that electrode. These effects usually show themselves as a bodily movement of the current/voltage characteristics without change of form, and in diagrams of the type of Fig. 32 by motion of the indicating dots towards or away from the origin. The use of a gridleak largely compensates such variations. Research on so important a point is certainly needed, more particularly as the subject of contact potential is still in the same nebulous state as were thermionics at the time when valves were first invented.

The point about the space-charge raised by Professor Howe is of vital importance. The reason why currents are observed which are less than the saturation current is to be sought in the fact that the electrons possess inertia and therefore require time for their transit, however great the attraction to which they are subjected. At any instant, therefore, between the present position and the ultimate goal of an electron which has but just left the filament there will be found a number of other electrons which have preceded it but have not yet completed their path. The first electron is subject to repulsive forces due to these preceding electrons in addition to the attraction of the anode, and the greater the space-current the greater will be the number of electrons in transit and the less the resultant attraction on those near the filament. If the attractive field is brought right down to a zero value in this way, as at the summit of the little hill to which he refers, the condition will have become stable, and the current will not increase further even though it has not reached its saturation value, unless conditions are changed by increasing the potential of the anode so that more current has to flow to counterbalance the increased attraction. This is the main effect responsible for the form of the characteristics of a high-vacuum valve, and it holds even when the applied voltages are such that the velocity of emission of the electrons is quite negligible. Professor Howe's account is a true explanation of the origin of the parts of the characteristic curve nearest the foot, where the currents are so small that the field due to the space-charge is unimportant compared with the velocities of emission. The anode voltage is then so low that the reverse slope of the little hill extends right out to the anode, and the space-current consists of those few electrons which start with sufficient speed to surmount it. As he says, there are some to which a potential difference of 4 or 5 volts does not present an unsurmountable obstacle.

The impression which the model has given to Mr. Pletts is not at all incorrect. In actual fact it is very common for a grid current of 1 micro-ampere to correspond to an anode current of 1 milliampere, a state of affairs where only one electron in a thousand does succeed in reaching the grid.

The bulk of Mr. Scott-Taggart's remarks, though interesting, concerns recent work which I have had to consider outside the scope of the paper. I agree that filament-springing is a very important point in small valves, and we cannot be content until a solution has been found as satisfactory as the normal practice in metal-filament lamps, in some of which the filaments are very much finer than those at present used in valves. The system adopted in the V24 valve is unsatisfactory owing to the loading of the free end of the spring with a sprung mass far greater than that of the filament to be supported; this results in transverse strains on the filament of a type which it is peculiarly unfitted to withstand. The small diameter of the R5 grid favours the short, steep characteristic which enables that valve to work on a 4-volt filament accumulator, an advantage which certainly had to be bought at a price. By a suitable readjustment of the grid spacing the amplification factor can always be restored to the desired value after a change in the grid diameter. In interpreting "backlash" observations as indicating the degree of evacuation it must be borne in mind that the electronic component of the grid current decreases as the grid is made negative far more rapidly than the positive ionic component which bears a roughly constant proportion to the anode current. Mr. Scott-Taggart's criticism would therefore apply only to observations on that side of the maximum of reverse grid current on which the electronic component is gaining on the ionic, and specifications must be so drafted as to rule out such observations. Rectification at the grid of a high-vacuum triode is considered in the paper in the paragraphs preceding and following Fig. 15. For the less common case of rectification at the lower corner of the anode curve (Fig. 22, curve 6), the physical principles involved are the same; the statement as to the fixity of the form of the curve below the 20-micro-ampere point applies to grid and anode curves alike. The upper corner of the anode curve can be treated, though somewhat roughly, by the method illustrated in Fig. 30; but the treatment for the rectifying property, while fully as cumbrous as that for the amplifying, is more seriously affected by the imperfect or gradual saturation which occurs in practice. As regards the grid characteristics of soft valves, however, I share Mr. Scott-Taggart's disappointment. The difficulty here is that one can by no means neglect the probability that a given ion, after missing one grid wire, will ultimately strike another and so make a contribution to the grid current, and yet this probability would be extremely difficult to compute.

The whole field of valve research at the present time seems to be strewn with cases of discovery and re-discovery such as that of the formula for the voltage factor or amplification constant remarked upon by Dr. Eccles. Captain Round mentions another. I have always understood that Sir J. J. Thomson's expression is obtainable by a method similar to that employed by Maxwell for the plane case, but is actually simpler owing to the higher symmetry of the cylindrical arrangement of the electrodes.

The neutralization of the space-charge, as the term is used in the paper, is a matter of electrostatics, or "pith-ball electricity," rather than, as some of Mr. Dowsett's remarks seem to imply, of the inner physics of the atom. It is effected, not by any close contact of positive and negative ions, but by the interpenetration of a cloud of negative electrons by a cloud of positive ions. Taking the simple case of an ion situated between two electrons, the presence of a positive charge so placed will necessarily reduce the repulsion between the two negatives, i.e. will tend to "neutralize the space-charge."

Captain Round's summary criticism of the ultraudion circuit carries one back in a flash to the days when most circuits merited a similar description. Nevertheless they did work in their several ways. It may fairly be contended, however, that the severe simplicity, both theoretical and practical, of the circuit of Fig. 5 was the result of intelligent pruning rather than improvised patchings. The question of the reliability at radio frequencies of statically determined characteristics is a matter of present-day interest and worthy of special research. It is perhaps because the available evidence is somewhat indirect that Captain Round sets his limiting frequency for the hard valve so low as 50,000 ∿ per second. He no doubt knows of many cases like that of the simple Lieben circuit of Fig. 1 in which variations of the resistance of the oscillation circuit agree with the corresponding variations in the critical slope of the characteristic with some approach to numerical accuracy at much higher frequencies. Again, observations of correlation between statical characteristics and circuit performances on the lines of Fig. 33, but relating to radio frequencies, are available. However, the question has never been thoroughly answered, and in some minds the characteristics are still suspect. Considering the internal physics of the valve, I am inclined to go very much further than Captain Round. With one exception, the various phenomena which it is necessary to take into consideration in accounting for the characteristics of low-voltage valves are instantaneous in comparison with periods longer than the very brief time of flight of an electron across the valve. The exception is the contact potential. This is dependent on the condition of the electrode surfaces, and the formation of surface layers is not instantaneous. But on following up Captain Round's query as to the soft valve one finds a very different story. The time of flight of an electron between plane electrodes 5 mm. apart and at 50 volts potential difference is 2×10^{-9} second, which is the time-period of a cycle at a wave-length of only $\frac{3}{5}$ metre. The movement of the positive component of the space curent will, however, be much more sluggish for positive ions are thousands of times heavier than electrons, and for atomic hydrogen, helium, and mercury respectively the critical wave-lengths will be in the proportion of 30, 60, and 400 on the same scale as before, the time of flight when, as here, the forces are equal, being proportional to the square roots of the masses. As the positive ions cannot be allowed as much as a full cycle for their motion, the effects of their slowness may well become pronounced at wave-lengths of 150, 300 and 1,000 metres for the three gases mentioned, and it should therefore be possible to observe differences between valves filled with equivalent atmospheres of helium and mercury. The effect on the characteristics of a proportion of positive ions sufficient to produce neutralization of the negative space-charge is certainly very pronounced, although their direct contribution to the total space current may be quite negligible, and it is possible that there is little further advantage to be gained by producing ions and electrons from the gas in number comparable with the primary electrons emitted from the filament. Figs. 18 and 6 (*a*) illustrate the two cases. The reverse grid-current shows approximately the number of positive ions and the corresponding anode current shows the number of electrons. The secondary electrons from the gas will be equal in number to the positive ions, and it will be seen that in Fig. 6 (*a*), where the saturated emission from the filament is only about 200 micro-amperes, they make a contribution of one-third to the anode current, whereas in Fig. 18 they are relatively negligible.

Soft valves are in general better rectifiers than the corresponding hard valves. For amplifying purposes it would certainly be possible, and indeed it would be no novelty, to make a reliable soft valve having the characteristics of Captain Round's four-electrode valve. Incidentally, might not this latter be called a "tetrode" according to Dr. Eccles's euphonious nomenclature?

On what evidence the internal capacities of soft valves when working are expected to be high I do not know, but some soft valves were included in the determinations mentioned at the end of Section 8, and showed a particularly marked decrease in the effective capacity between their electrodes on incandescing the filament. In making such observations it is essential to ensure that the effect is not masked by any increase in the damping of the resonant circuit, and, in the light of this discussion, not to employ frequencies too high for the positive ions to follow.

As regards the relations between characteristics and circuits I regret that I am unable to add to what has already been written on this subject. Systematic work on the verification of these relations was not undertaken until late in the period considered, and naturally so, because it does in fact represent a climax both in valve making and in the study of circuits, requiring, on the one hand, a sufficient selection of suitable valves, and, on the other, access to sufficient information as to the true action of the circuits in which they are used.

As long, however, as the terminals of the valve are so many boundary posts between the students of its internal action on the one hand and those of its external capabilities on the other, so long will the characteristics be the accustomed meeting-point of the two schools.