Valve Curve Diagrams

Understanding the Significance of Load and Other Lines

By "CATHODE RAY"

LAST month, in discussing cathode followers, I made use of certain valve curve diagrams. It has occurred to me that there may have been readers who quickly shied off at that stage, or, seeing the diagrams in advance, were non-starters. Others, though less easily deterred, may through unfamiliarity have found them somewhat baffling, notwithstanding the clues I scattered as freely as space permitted.

The first thing that has to be explained, perhaps, is why it is considered necessary to use up a lot of paper and drawing effort in this way instead of dealing with valve problems in a neat equation or two. The reason is that valves do not behave in ways that can be represented accurately by neat equations. They are not like resistors and capacitors and air-core inductors. Oh, I know there is such a thing as an "equivalent generator" by which certain valve calculations can be reduced to simple algebra, but (a) that method takes account only of signal currents and voltages, so is no use at all for finding the best working conditions, such as grid bias voltage, and (b) it doesn't even deal with the signal part accurately, because it ignores the curvature or non-linearity of valves. In any case, certain types of mind are more brightly illuminated by a graphical diagram than by a row of equations.

In equations, quantities such as voltage and current are represented by letters or numbers (depending on whether their values are being dealt with in general or particular). On diagrams they are represented by distances on the paper. I am assuming it is well known how two such quantities are represented by distances respectively horizontal and vertical. Even tired business men understand this, when the two quantities are such things as time and commission on sales. But while we may all understand how it applies to voltage and current (for example, anode current and grid voltage), what may not be quite so clear is how resistance, conductance and power can also be represented on the same diagram, or how several different voltages in a circuit can be shown.

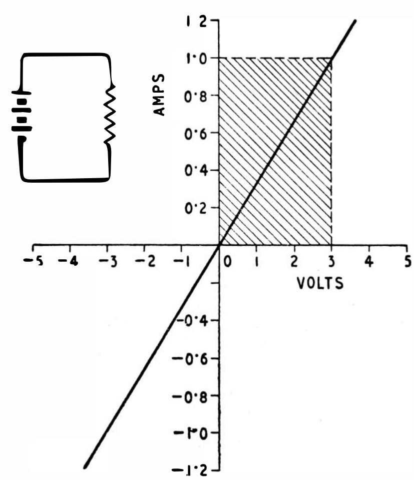


Fig. 1. Graph of current against voltage for linear resistance, represented by the diagonal line. The power used up in it when 1 amp is flowing is represented by the shaded area. Negative currents and voltages are in the reverse direction in the circuit.

If one were to repeat Ohm's original experiment, plotting the current passing through a piece of wire, against the voltage between its ends, the resulting graph would be the kind of thing shown as Fig. 1—a straight line passing through the "origin" (0). (Of course Ohm himself knew nothing about volts and amps, but we might as well make use of our modern units.) The information conveyed by this line could be presented with much less effort as an equation: $V=3I$. Except for the number, the equation would be the same for different pieces of wire; a shorter length of the same wire would give a smaller number than 3, and vice versa. If "V" is being used to denote the potential difference in volts, and "I" the current in amps, the number is the resistance in ohms. The smaller the resistance, the steeper the line in the graph. If that fact is not obvious, try one or two different lines, and consider why the slope of the line is connected with the resistance in this way. The reason, of course, is that resistance in ohms can also be regarded as volts per amp. So the resistance represented by a line on a current/voltage graph is equal to the number of volts it slopes along the voltage scale for each amp up the current scale. In other words, resistance is the ratio of voltage to current, and on a graph the slope or gradient of a line is the ratio of vertical movement to horizontal movement or in this case current to voltage.

The easiest figures for finding the resistance in this example are 3 volts and 1 amp, but because the line is straight—representing a *linear* resistance—the differences in volts and amps between *any* two points on the line would do. If the resistance were not linear, the slope of the line, and the resistance, would vary with current (or voltage).

So not only the value of a resistance but also whether or not it is linear, is clearly shown on a current/voltage graph.

And because conductance is the ratio of current to voltage, it is shown too; the steeper the slope the *greater* the conductance. The mutual conductance of valves is, in fact, often called slope.

Representing Power

How about power? It is current multiplied by voltage. Horizontal distance multiplied by vertical distance gives the area enclosed by the vertical and horizontal lines at each end. For example, the power released in our wire when 1 amp flows through it (i.e., 3 watts) is represented by the shaded area. With a shorter piece of wire, only 1 volt might be needed to pass 1 amp, and the corresponding area would be one-third the size, representing $1 \times 1 = 1$ watt. Equal powers in different resistances are represented by equal areas of different shapes.

Incidentally, if the voltage in Fig. 1 were doubled, from 3 to 6, the area would obviously be *four* times as big. The diagram helps the weaker brethren to visualize the fact that (with a linear resistance) the power dissipated is proportional to the *square* of the voltage (or current).

Our Fig. 1 line represents a certain resistance or conductance, but does not by itself reveal the actual current flowing in it. That depends on the voltage, which we do not know. It might be anything. What the line does show is that *if* 3 volts were applied the current would be 1 amp. Suppose we don't know the voltage applied to this 3-ohm resistance, but we do know the total voltage applied to it and another known resistance in series. With linear resistances it is a simple exercise in Ohm's law to calculate the voltage across each resistance and the current through both. With non-linear resistances, to which Ohm's law doesn't apply, we would probably be stuck—if we didn't have the graphical method to fall back on. But before taking a non-linear example, let us first try a linear one, which we can check by calculation.

Two Resistances

Suppose 8V is applied to our 3Ω in series with 10Ω. We know that the resulting state of affairs must be represented by a point *somewhere* on the resistance line in Fig. 1. It must also simultaneously be on a line representing the 10Ω. If we were to draw a 10Ω line through 0, that would be the only point common to both lines, and of course it would not represent the situation at all. The clue is the fact that the voltage applied to the 3Ω is 8V *minus* whatever is dropped in the 10Ω. The voltage dropped in the 10Ω is, then, from the point of view of the 3Ω, a negative one, beginning at 8V. So we draw the 10Ω line as shown dotted in Fig. 2. To emphasize that there is nothing wrong about putting the zero-current point at 8V, I have added a second voltage scale to apply to this resistance. The dotted line shows on this scale the voltage to be deducted from 8V to give the voltage across the rest of the circuit, whatever the current.

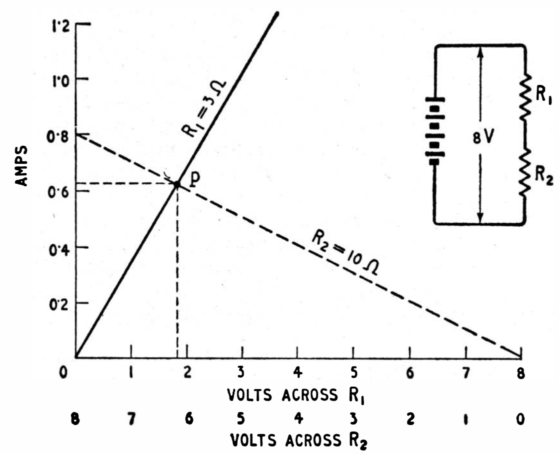


Fig. 2. A circuit with two resistances in series can be investigated by adding a second resistance line, sloping from the point representing the total voltage.

The point *p*, where the two lines cross, is the only one common to both, and indicates that the current through both must be 0.615A, the voltage across the 3Ω must be 1.85, and across the 10Ω, 6.15. Having checked this by calculation, we can have some faith in the graphical method and go on to apply it to situations where calculation fails.

But before we do that, let us see how Fig. 2 can be used to answer different kinds of questions. If we knew the value of the current but not R_2, it could tell us what R_2 would have to be. Try it for $R_1 = 3$ and $I = 0.5$. In this case the point on the R_1 line is fixed by the fact that $I = 0.5$, so what we have to do is lower the slope of the R_2 line to make it pass through that point and then find what resistance it represents.

Or suppose we are told to find the value of R_2 that results in 2 watts being dissipated in R_1. That means

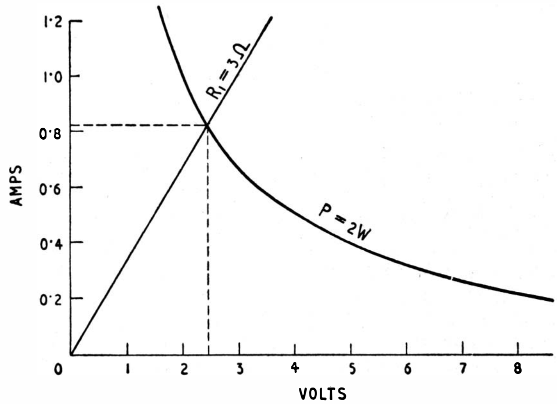


Fig. 3. The top right-hand corners of all the rectangles representing a given power (2 watts in this case) trace out a curve like this.

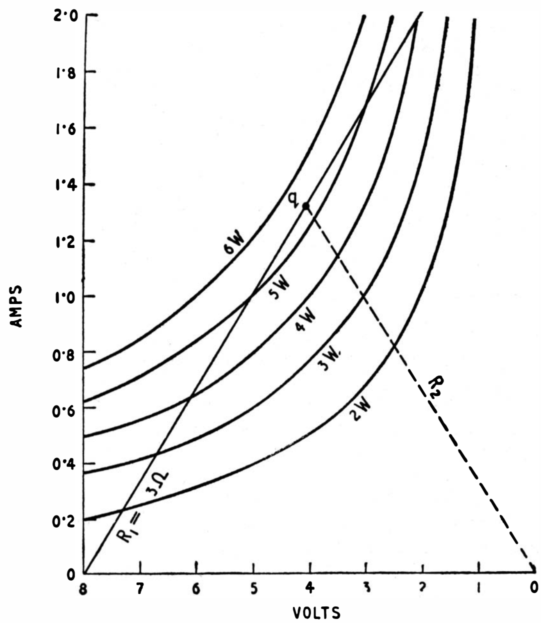


Fig. 4. Power curves can be used to find the value of R_2 receiving maximum power in the series circuit.

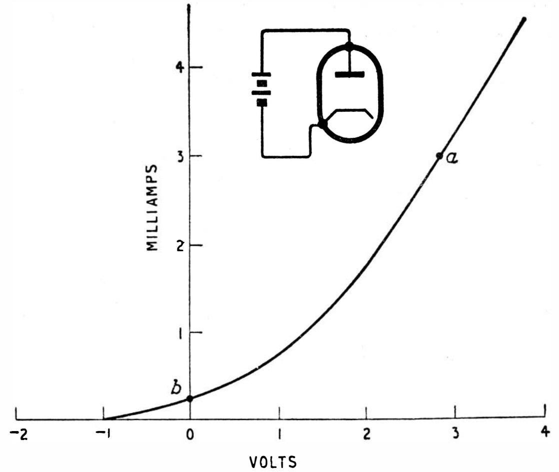


Fig. 5. Graph of a non-linear resistance—that of a diode valve.

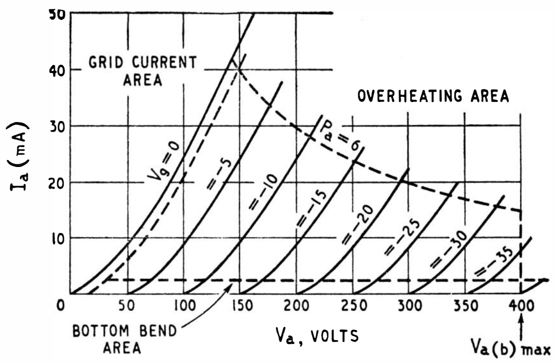


Fig. 6. Typical set of anode-current/anode-voltage curves for a small power triode, showing the areas that for various reasons are out of bounds.

drawing a constant-power line. A power of 2W can be made up of 2V, 1A, or 4V, 0.5A, or 5V, 0.4A, or 8V, 0.25A, and any number of such combinations. The 2-W line can be obtained by plotting a few of them and drawing the smoothest curve through the points, as in Fig. 3. This fixes a point on R_1, through which the R_2 line can be drawn to the applied voltage mark on the voltage scale as before, and the value of R_2 follows. Alternatively, if R_2 is known, a line of the corresponding slope is drawn through the R_1-P intersection, and where it crosses the $I=0$ axis it indicates the total voltage that has to be used.

A rather more difficult problem would be: Given R_1 and the total voltage, find the value of R_2 in which maximum power is developed. One way of doing this is to draw several different power curves for R_2. This means that they have to be drawn with reference to the "volts across R_2" scale, as in Fig. 4. The point on the R_1 line corresponding to the highest power is *q*, somewhere between 5 and 6 watts (actually $5\frac{1}{3}$), and if the diagram has been drawn well enough it will tell us that R_2 for this condition is 3Ω. As we probably knew all the time, it would invariably be equal to R_1, whatever that was, because a well-known and important circuit theorem says so (the Maximum Power or Load Matching theorem).

Diode Characteristic

I should think that's about enough for linear resistances, for all the problems so far (except possibly the last) can be solved more easily and neatly without graphs. A diode valve is a simple example of non-linear resistance. As Fig. 5 shows, regarded as a resistor it has several features not according to Ohm. First, a negative voltage does not cause a negative current; i.e., one in the opposite direction to that which flows with a positive voltage. (This is not strictly true, but one has to have a very super-sensitive micro-ammeter to discover it.) On the contrary, the current when the negative voltage is small is positive. Next, the slope of the line (which is visually, as well as mathematically, a curve) increases as the voltage increases positively, which means that the resistance decreases. Near zero it decreases very rapidly from infinity, but at higher voltages than shown here it is practically linear and therefore constant.

This is where the new boy may get confused. The ordinary "d.c." way of reckoning resistance is the ratio of applied voltage to current flowing. At point *a*, the voltage is 2.8 and the current 3mA, so the resistance is $2.8/0.003=930\Omega$. This resistance is equal to that represented by a straight line joining *a* to 0. It is not equal to the resistance represented by the slope of the valve curve at *a*. This slope resistance is sometimes called the a.c. resistance, being the resistance to small alternating currents superimposed on the steady 3mA at *a*. The reason they are supposed to be small is that the bit of curve involved by them should then be as near straight as makes no matter. Both these kinds of resistance are significant; the d.c. kind when considering the "working point" of a valve (anode voltage, bias, and so forth), and the a.c. kind when considering signals being handled by it. At *a* there is not a great deal of difference between them, but at *b* the d.c. resistance is zero, whereas the a.c. resistance is far greater than at *a*.

A diode is normally used as a rectifier, and rectifiers are always more difficult than you think, so despite the apparent simplicity of the diode I am going to hurry past it to the triode. The anode current in a triode depends simultaneously on two voltages—anode and grid—so really needs a three-dimensional diagram, for the making of which one would have to employ a sculptor, and the Editor would object to the expense. So, although a triode's current/voltage characteristic is really a 3D surface, for economy and convenience it is usual to make do with a series of cross-sections of this surface in two dimensions. Which two depends on what one wants to show most clearly. Sometimes they are anode current (I_a) and grid voltage (V_g), at a number of evenly-spaced values of anode voltage (V_a); and sometimes I_a and V_a at values of V_g. The latter (Fig. 6) are the more generally useful.

Forbidden Areas

The shape of the I_a/V_a curves is very like the diode one. The effect of making the grid negative is, roughly, to push the curve bodily along to the right. What the effect of making the grid positive is, one does not usually bother to find out for ordinary receiving valves, because grid current flows and greatly complicates the situation, as well as spoiling the valve for most of its uses. So the whole of the area to the left of the "$V_g=0$" curve is reckoned as out of bounds. In fact, as Fig. 5 shows (for the grid and cathode of a triode together equal a diode) the forbidden area may have to extend to $V_g=-1V$, or even a little farther, to make sure that no appreciable grid current flows.

Next, again assuming that distortionless amplification is wanted, it is advisable to fence off the sharply curved part at the foot of the diagram, marked "Bottom Bend Area." The remaining parts of the curves are not dead straight, but are tolerably so, and can be made much straighter by negative feedback, as we saw last month.

The ceiling is imposed by the valve makers' "maximum anode dissipation"—the maximum power, $V_a \times I_a$, that it is safe to inflict on the anode. Suppose in this case it is 6 watts. Then we draw a 6W curve on the diagram as shown, to rule off what can be called the Overheating Area.

Lastly, the valve maker usually specifies a maximum anode supply voltage ($V_{a(b)\,max}$). This must not be confused with the maximum anode working voltage ($V_{a,max}$) which is the voltage between anode and cathode when no signal is coming through, or the average when it is. When there is a resistance coupling, this anode voltage is less than the supply voltage —by the amount dropped in the resistance. But it is a voltage that is liable to get at the anode occasionally, at signal peaks or while the cathode is heating up. A vertical line should be drawn at this voltage (say 400 for example) to close up the remaining gap in the boundary.

Power into the Load

We now have a clearly defined area in which to play. But we should remember that there may be a section of it on the right that is only allowed for transient occupation—not for lingering in. That is, if there is a $V_{a,max}$ lower than the $V_{a(b)\,max}$. On the other hand, momentary trespassing across the "overheating" boundary is permitted, so long as the working point itself is not outside.

If we were aiming at the maximum power output from this valve we would put the working point actually on the 6W boundary at $V_{a,max}$, which (let

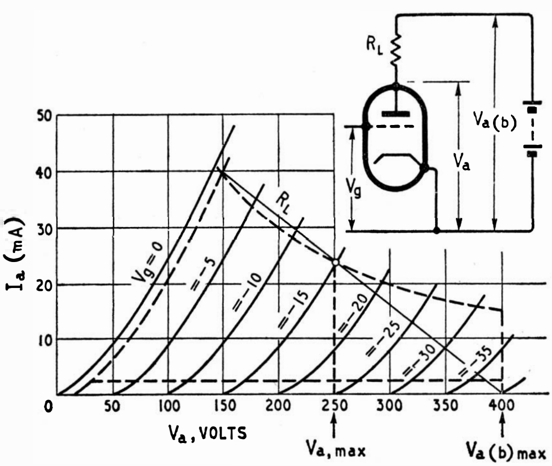


Fig. 7. The Fig. 6 curve sheet with load line added, through the working point (encircled).

us say) is 250V. And if the load were to be a resistance, fed from the maximum supply voltage (400) it would be represented by the sloping line through O and 400V 0mA, as in Fig. 7. From its slope we find it is 6,250Ω. We note that the working point is on the "$V_g=-15$" curve, so that is the grid bias. And if we allow the signal input to swing the grid right up to 0 and down to -30, the load line shows that the corresponding V_a swing is between 140 and 350 (= 210 peak-to-peak) and I_a is 41.6 and 8 (=33.6 peak-to-peak). The voltage amplification is therefore 210/30 =7. The power output (into the resistance) is equal to the r.m.s. signal voltage multiplied by the r.m.s. signal current, and since an r.m.s. value is $1/\sqrt{2}$ times a peak value, which in turn is half the peak-to-peak value, this power is equal to peak-to-peak $V_a \times I_a$, divided twice by $2\sqrt{2}$, that is to say by 8. So it is $(210 \times 0.0336)/8=0.88$W.

Voltage Amplification Line

From a practical point of view all this is rather absurd. Is it voltage amplification or power output we are trying to get? We have adopted a usual method for voltage amplification—a resistance coupling—but the valve is clearly unsuitable for this and is intended for power amplification. However, what we are really out for just now is a quick understanding of graphical technique for valves, and I hope I haven't confused you by explaining two things at once. The procedure just described, if applied to a suitable high-mu valve, is correct for *voltage* amplification. One would not actually bother about a maximum power curve, however; the aim would be to slope the line as little as possible, even perhaps into the bottom-bend area, so long as the resistance was not so high as to be shunted too much by stray capacitance at the top signal frequency. The working point would be fixed where it gave equal positive and negative grid swings within reasonable limits of distortion.

For a power amplifier, on the other hand, one wants to get the power out into some external load, such as a loudspeaker, not waste it all in a resistance coupling. The coupling is done by a transformer, which has very little—perhaps negligible—d.c. resistance, but considerable signal-frequency resistance. The usual procedure would be to place the working point as already done in Fig. 7, and then draw from it to the voltage scale a line representing the d.c. resistance of the transformer or choke coupling. Being such a low resistance, the line would be almost vertical, and the resulting $V_{a(b)}$ indicated by where it cut the V_a scale would be only slightly more than the working V_a.

The *a.c.* load line need not touch the V_a scale at any particular point such as $V_{a(b)\,max}$; it should be swung round O as a pivot until it indicates the maximum output. The output power is represented by one-eighth of the area of the rectangle of which the load line is a diagonal. If the load line slopes too little, this rectangle is too flat to have much area; if the line slopes too steeply the rectangle is too narrow. The length of the load line diagonal must be equal in both directions from its pivot at O, and must not go beyond the grid-current or bottom-bend boundaries. The 6,250Ω line in Fig. 7 is unlikely to give the largest area because an input signal limited at its positive peak by grid current leaves quite a lot of useful space between its negative peak and the bend boundary. A more promising line would be steeper, indicating a lower load resistance; drawn, in fact, from the point where "$V_g = -30$" cuts the bottom-bend boundary.

In practical design there is vastly more to it than this; all I have been attempting to do is show what the various lines and things on this kind of diagram mean, and how it is that they mean them. If I have succeeded in making this clear, then perhaps you would like to turn back to last month's treatise and note how the ordinary valve curves can be used to derive another set of much straighter curves that represent the behaviour of a valve combined with negative feedback. Then, of course, there are pentodes. Their curves have quite different shapes, but except in detail the methods are the same.

At least one whole book* has been written on the subject, and the uses included in the *Radio Designer's Handbook* would almost make another book. So there is plenty of scope for follow-up.

* *Graphical Constructions for Vacuum Tube Circuits,* by A. Preisman. (McGraw Hill.)

Manufacturers' Products: NEW EQUIPMENT AND ACCESSORIES

Ground-to-Air Transmitter

A NEW v.h.f. transmitter for ground-to-air communications, rated at 20 W output, has recently been introduced by Ekco Electronics to replace an earlier model. The new set, Type CE91, can be operated on any crystal-controlled spot frequency in the band 100 to 156 Mc/s, channel changing being effected by fitting the appropriate crystal and realigning the circuits. All the controls are readily accessible from the front panel but protected against accidental misalignment by easily removable cover plates.

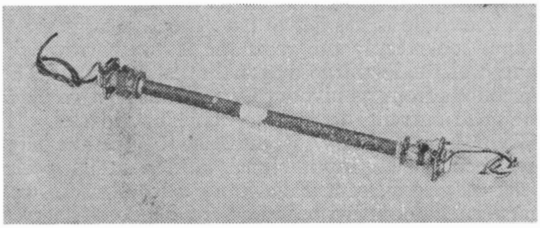
New Ekco ground-to-air v.h.f. transmitter, Type CE91.

Particular attention has been given to the suppression of spurious emission, a matter of some importance now that the 200-Mc/s band is likely to become a highly populated one before long. The inclusion of bandpass and lowpass filters in the circuit contribute, no doubt, to the "clean" performance claimed for this transmitter.

The set, including the power supply, weighs 75 lb and fits into the standard 19-in rack. It is made by Ekco Electronics, Ltd., Southend-on-Sea, Essex.

Ferrite Rod Aerials

TWO directional rod aerials are now available from the Teletron Co., Ltd., 266, Nightingale Lane, London, N.9.



"Teletron" Type FRD ferrite rod aerial.

In Type FRM, which is 4in long, a single wave-wound coil at one end, of 165 μH inductance, covers 180-550 metres when tuned by a 500-pF variable condenser. The Q at 1 Mc/s is stated to be 205.

Type FRD has an additional winding at the other end of the rod giving a combined inductance of 2.2 mH to cover wavelengths up to 2000 metres. The length of this rod is 8in.

Rubber grommets are provided for mounting, and a fibre disc, secured to each coil former, facilitates adjustment when moving the coil on the "Ferroxcube" rod core.

The price of Type FRM is 8s 9d and of Type FRD 12s 9d.

Commercial Literature

Marine V.H.F. Radiotelephones, a range of six models giving 10 watts output and covering 40-185 Mc/s with 10 or 20 channels. Available for a.m., f.m. or combined a.m./f.m. Brochure from Redifon, Broomhill Road, London, S.W.18.

Soldering Irons by Hydrel of Switzerland with pointed or hammer-shaped copper bits claimed to withstand oxidation. Elements from 45 to 500 watts, lengths 12½in to 17¾in, weights 7 oz to 2½ lb. Leaflet from the sole distributors, A. B. Hobbs & Co., 214, Hatfield Road, St. Albans, Herts.

Overtone Quartz Crystals, 17 Mc/s to 36 Mc/s, listed in a new easy-reference catalogue of Salford crystals from the General Electric Co., Magnet House, Kingsway, London, W.C.2. Also a booklet on selenium rectifiers, giving performance figures and curves for various circuits, and a leaflet on Gecalloy micropowder permanent magnets.

Waveguide Components and test instruments for centimetre and millimetre waves, with notes on automatic measuring instruments suitable for production testing. Illustrated catalogue from Elliott Brothers (London), Century Works, Lewisham, London, S.E.13.

High-voltage Control Valve, triode Type TV501. With 70 kV on the anode, the anode current (max. 1.5 A) can be cut off to 100 μA by application of -400 V to the grid. Details and characteristics in a brochure from Solus Electronic Tubes, 15-18, Clipstone Street, London, W.1.

Microwave Frequency Meter, 2,400 to 10,200 Mc/s, and other waveguide components and test instruments described in an illustrated catalogue from the Narda Corporation, 66, Main Street, Mineola, N.Y., U.S.A.

Selenium Rectifier Stacks for domestic sound and television receivers. A booklet with information on ratings, coding and polarity markings, dimensions, weights, and 45 pages of performance curves. From Standard Telephones and Cables, Rectifier Division, Edinburgh Way, Harlow, Essex.

Radio Control of Models. Ex-Government equipment for this and other purposes listed in a new mail order catalogue (No. 12) from Arthur Sallis Radio Control, 93, North Road, Brighton, Sussex; price 1s 6d including postage.

Mobile Television Units in motor vans for outside broadcasting, with cameras, control equipment, centimetre-wave transmitters, etc. Diagrams and photographs showing facilities available in a booklet from Marconi's Wireless Telegraph Company, Marconi House, Chelmsford, Essex.