Secondary Electron Problems in Beam Tetrodes

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THE critical distance tetrode consists, in essence, of a structure a section through which is sketched in Fig. 1. Beams of electrons travel from the cathode to the anode as indicated. The beams are formed by an electron lens system which exists due to the configuration and relative potentials of the cathode, control grid and screen grid. This valve is of a type which first reached the market in 1935.[1]* Some beam tetrodes are provided with " beam forming electrodes " of cathode potential such as those indicated by the dotted lines in Fig. 1. Critical distance valves were devised by the author in 1931,[2] and came into wide use under the name of the 6L6 beam tetrode when this valve was first marketed by the R.C.A. in 1936. Beam forming electrodes were used in these 6L6 valves.

The beam tetrode operates and has a " dynatron-free " characteristic because of the effect of a potential minimum due to space charge between the screen grid and the anode. In valves of the 6L6 and similar types, the beam forming plates exercise only a slight effect in producing the beam; but have an appreciable effect in producing the retarding potential;—indeed, tubes of this type first built up by the author in 1932 were looked upon by him as hybrids and as being somewhere between the pure beam tetrode and the pentode valve in which undesirable secondary electron current is got rid of by the action of a suppressor grid of zero potential positioned between the screen grid and the anode.[11]

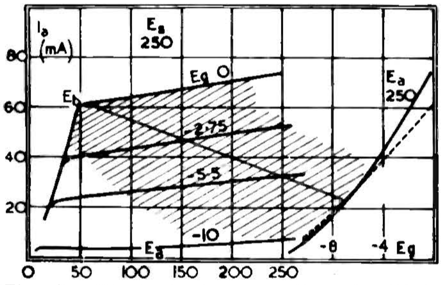

Fig. 2. Measured characteristics of critical distance tetrode.

An outline of the history of the beam tetrode has already been published.[3] Because, for instance, the Radio Corporation of America sells, at the moment, 17 receiving beam tetrode types and four transmitting types (including certain much publicised ultra-high-frequency vaves), it is not surprising that several mathematical theories have been published. Salzberg & Haeff, of the R.C.A. research staff, have published[4] one which may be taken as typical. Broadly speaking, this analysis consists of an ingenious mathematical treatment of a theoretical space charge due to primary electrons between the screen grid and the anode, and deduces (quite correctly) that there can be a potential minimum. This was done by an extension of well-known space charge theories, such as that published some years ago with respect to triodes by Gill[5] and Tonks.[6]

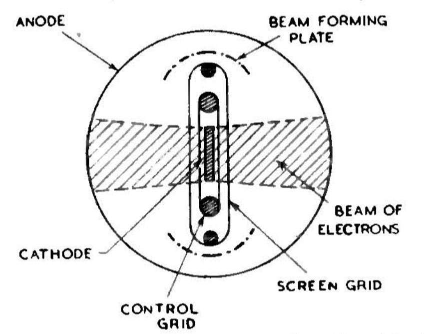

Fig. 1. Diagrammatic sketch of critical distance tetrode showing the electrode arrangement.

It will, however, be shown in the present paper that the operation of the beam tetrode has not in fact been explained at all. The values of potential minimum deduced by the published theories are quite incapable of preventing a dynatron characteristic being produced and do not fit the facts in other ways. In fact, a new approach to the problem, and one involving other factors, is required.

The Properties of Secondary Radiation

Certain facts about secondary electron emission which were published as long ago as 1922 have apparently escaped notice.

Fig. 2 shows typical anode characteristics of a critical-distance valve.

In such a beam tetrode a potential distribution may be expected somewhat similar to that sketched in Fig. 3. The potential minimum Vc corresponds to a retarding potential (1-Va/Vc), which tends to prevent the secondary radiation from travelling back from the anode to the screen grid. (It must not be forgotten, by the way, that secondary radiation of an appreciable amount may travel from the screen grid to the anode).

H. E. Farnsworth[7] published in 1922 the values of retarding potential required between the screen grid and anode to reduce the ratio of primary to secondary current to any desired amount. His method of measurement needed some slight corrections (afterwards made by him in 1928)[8] but is substantially correct.

The following table is plotted from Farnsworth's Fig. 5 of his 1928 paper,[8] and shows a typical result for iron. The results for nickel are much the same.

It is clear that a retarding potential of a very considerable amount will be necessary if, when the anode voltage is raised from the knee value E_B (Fig. 2) to a value equal to the screen voltage, the working surface (shaded) of the anode characteristic is to remain substantially flat.

TABLE

Relationship between retarding potential and secondary electron coefficient for iron.

Retarding potential (1—Vc/Va).	Secondary radiation coefficient (Is/Ip %).
0.99	6%
0.95	6.5%
0.8	8.2%
0.7	9.5%
0.6	12.0%
0.5	13.5%
0.4	16%
0.3	18.5%

Fig. 4 is drawn from Farnsworth's and other information and shows a plot of retarding potentials against secondary radiation coefficient Is/Ip, for various anode potentials.

Fig. 5 indicates a typical distribution of velocity of secondary electron emission from a metal target. It will be observed that there is a peak of emission at a velocity almost equal to the primary impact velocity. It has been shown by Farnsworth and by other workers[9] that this peak gets relatively less in magnitude as the anode voltage (impact energy on the anode) is increased from a small value up to the order of at least 250 volts.

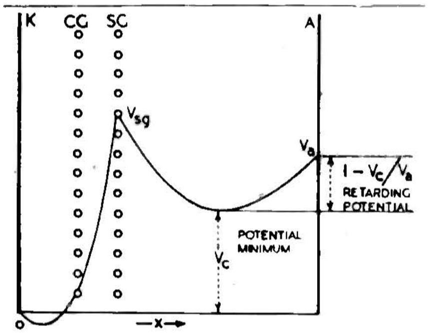

Fig. 3. The potential gradients in the critical distance tetrode. The arrangement of the electrodes is only diagrammatic.

The radiation coefficient Is/Ip for all secondary electrons (disregarding their relative velocities) increases, in the case of a clean nickel anode, from a value of about 0.4 at an anode potential of 50 volts to about unity at an anode potential of 250 volts.

Davisson and Kunsman[9b, 9c] and Tate[9d] show that secondary emission from a plate anode travels almost entirely in the direction from which the primary electrons arrive.

It is clear that unless the retarding potential in a beam tetrode is very considerable (so that the operation is well to the left hand of Fig. 4), as the anode

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*Figures refer to bibliography at end of article.

potential increases from a knee value up to a value towards the screen voltage, the secondary electron current will increase rapidly and a dynatron characteristic will be found. For instance, if the knee of the anode characteristic is imagined to be at 50 anode volts, and if the retarding potential averages about 0.2, then the order of about 30 per cent. secondary radiation current will flow from the anode to the screen grid at anode potentials intermediate between the knee and screen voltage. The result will be a very pronounced dynatron type dip in the characteristic. The only way in which linear characteristics can be explained is by a comparatively complicated mechanism involving the use of retarding potentials of fairly high values at the left-hand end of Fig. 4. A theory of this kind is in course of preparation.

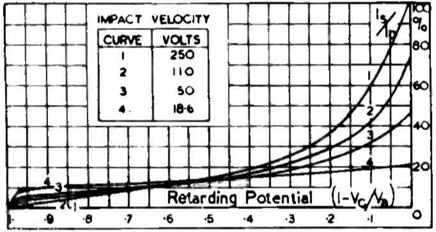

Fig. 4. Relationship between secondary radiation coefficient Is/Ip and retarding potential for various impact velocities on the anode. Impact velocities are expressed in terms of anode volts (after Farnsworth and others).

The problem is not merely one of preventing the passage of secondary radiation at one particular value of anode current, anode voltage and screen voltage. It is, on the contrary, that of maintaining a flat working surface to the characteristic over wide variations of these quantities.

The previous analyses, if quantitatively applied, produce a result such that, even if the potential minimum is sufficient at the knee voltage E_B (in Fig. 2), it is hopelessly insufficient when the operating locus travels down the load line in the direction of the arrow, the anode current drops and the anode voltage rises.

Referring quantitatively to the previous theories (of which that due to Salzberg & Haeff is taken as typical), these workers published a graph (their Fig. 7) which shows the values of potential minimum for various values of a dimensionless parameter P_a. P_a includes in itself such factors as the square root of the anode current and the reciprocal of the 3/2 power of the screen grid voltage. The anode current is therefore proportional to P_a^2. It is possible from this information to plot quantitatively the anode current characteristics predicted by the Salzberg & Haeff theory. This has been done in Fig. 6 of the present paper. In the author's opinion, it is difficult to see any resemblance between these predicted characteristics and those of an actual beam tetrode. The very large hysteresis loop effects are not found in the beam tetrode. For instance, at $P_a = 2$, two "knee values" exist at $V_a/V_g = 1$, and at $V_a/V_g = 0.35$. Apart altogether, however, from this discrepancy, it is clear that for any "knee" to exist at a value of V_a/V_g, much less than unity (*i.e.*, for a beam tetrode type characteristic to exist at all), P_a cannot be much greater than say 1.7 to 1.8 or so.

Moreover, again utilising Salzberg & Haeff's Fig. 7, it is possible to draw Fig. 7 of the present paper. This graph shows retarding potential plotted against V_a/V_g for various values of Pa which give knees that are below the screen voltage. Excepting for the left-hand end of the $P_a =$ curve (which is instable and therefore useless) the retarding potential does not exceed about $0.15\ V_a$. A reference to Fig. 4 of the present paper shows that there is no possibility of the valve giving anything else than a pronounced dynatron characteristic. Apart, however, from this point, Salzberg & Haeff's theory fails in another way, because it is clear that, even if at some particular point (such as X on Fig. 7 of the present paper) a certain amount of secondary radiation could be stopped, the slightest change of anode current or anode voltage would upset these conditions completely.

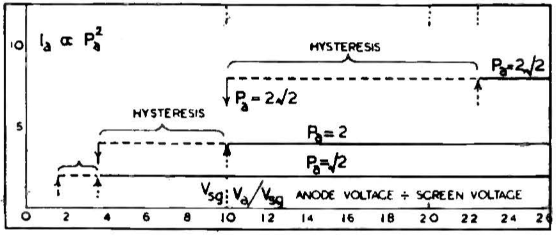

Fig. 6. Anode characteristics according to previous theory Plotted from Fig. 7 of Salzberg and Haeff.

In other words, the Salzberg & Haeff theory shows a hysteresis effect which is not found in actual beam tetrodes; an insufficient retarding potential to prevent the occurrence of a dynatron characteristic, and, finally, no range of anode current and voltage over which suitable values of retarding potential are maintained to produce the very large area of substantially flat working characteristic existing in actual valves (*see* the shaded area in Fig. 2). A large working area is really the principal justification for the existence of the beam tetrode as a commercial device. It will be remembered that this valve was originally put forward,[1, 10] because it possessed a flatter working area of anode characteristic than other multi-grid valves, and therefore had a lower level of distortion for a given power output.

It is an experimental result that no satisfactory beam tetrode critical distance effect (*i.e.*, dynatron-free characteristics) can be produced without the electrons being formed into a beam. (Fig. 1). The use of a focused beam for this purpose was first suggested by the author[2]. It is noticeable that the beam becomes narrower and the electrons more bunched when the control grid is made more negative. This is a very important factor in maintaining the potential minimum when the anode current is reduced in value during operation.

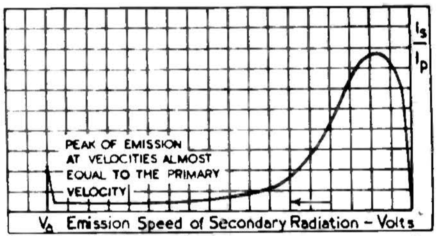

Fig. 5. Typical velocity distribution curve for secondary radiation. Impact velocity indicated by Vp.

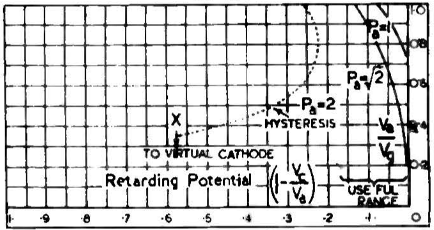

Fig. 7. Retarding potential according to previous theory. Plotted from Fig. 7 of Salzberg and Haeff.

In this paper the author has confined himself to pointing out certain information about secondary radiation which is apparently not too well known; and to a purely destructive criticism of the existing theories of the critical distance beam tetrode. What is hoped will prove to be an adequate theory is in course of preparation.

Bibliography.

[1] Harries, *Wireless World*, August 2nd, 1935.

[2] Harries, British Patents 380429 and 385968/1931, and *Wireless Engineer*, April, 1936, Vol. 13, pp. 190-199.

[3] Harries, *Wireless Engineer*, April, 1938, Vol. 15, p. 212.

[4] Salzberg and Haeff, *R.C.A. Review*, Vol. II, No. 3, January, 1938, pp. 336-374; Dow, "Fundamentals of Engineering Electronics," Chapman and Hall.

[5] Gill, *Phil. Mag.*, May, 1925, pp. 993 to 1,005.

[6] Tonks, *Phys. Rev.*, October, 1927, pp. 501 to 511.

[7] Farnsworth, *Phys. Rev.*, 1922, pp. 358 to 374.

[8] Farnsworth, *Phys. Rev.*, March, 1928, Vol. 31, pp. 405-413.

[9] (*a*) Haworth, *Phys. Rev.*, July 1st, 1935; (*b*) Davisson and Kunsman, *Phys. Rev.*, Vol. 22, No. 3, September, 1923, pp. 242 and 256; (*c*) Davisson and Kunsman, *Science*, Vol. 54, No. 1,404, November 25th, 1921, p.p. 522 to 524; (*d*) Tate, *Phys. Rev.*, Vol. 17, Series 2, No. 3, March, 1921, pp. 394 to 395. (*e*) Sharman (Communication by Professor Sir E. Rutherford), *Proc. Cam. Phil. Soc.*, Vol. 23, Part 5, January, 1927, pp. 523 to 530.

[10] Harries, *Wireless Engineer*, February, 1937, Vol. 14, No. 161, p. 63.

[11] Telleghen, British Patent 287958**.