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RCA RADIOTRON
DIVISION

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APPLICATION NOTE ON THE OPERATION OF THE 6L6

The 6L6 is a new type of tetrode intended for use in the power-output stage of an a-f amplifier. Unlike most existing tetrodes, the 6L6 does not exhibit any secondary-emission effects at low plate and control-grid voltages; its characteristics, therefore, resemble those of the usual power-output pentodes. Some unique features of the 6L6 are high power output, high efficiency, and high power sensitivity.

THE PENTODE SUPPRESSOR GRID

When the plate voltage of the usual tetrode is less than the screen voltage, an appreciable number of secondary electrons, which are emitted from the plate because of bombardment by primary electrons, are attracted to the screen; the plate current, therefore, is greatly reduced. For this reason, the plate voltage of the usual tetrode should not swing below the screen voltage if the output is to be substantially free from distortion. A zero-potential suppressor grid (G_3), positioned between screen (G_2) and plate (P), serves to prevent the loss of plate current due to secondary emission. Hence, in a pentode, the plate voltage (E_b) can be made less than the screen voltage (E_{c2}) without appreciable secondary-emission effects.

The manner in which a suppressor prevents loss in plate current due to secondary emission can be explained by Fig. 1A. When the suppressor is connected to cathode, the potential of the suppressor wires is zero and the potential of the spaces between the wires is positive by an amount that depends on the geometry of the tube and the voltages applied to the electrodes. Therefore, the effect of inserting a zero-potential suppressor between screen and plate is to lower the potential of all points between screen and plate. Fig. 1A shows the approximate potential distribution between the screen and the plate of a pentode for various plate voltages. When E_b is greater than a critical value (E_b'), a potential minimum (a plane of zero-potential gradient) is formed in the vicinity of the suppressor. When the difference between the plate voltage and the poten-

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tial at the suppressor ($E_b' - E_b''$) is great enough, secondary electrons from the plate are not attracted to the screen, but return to the plate. Consequently, for all values of E_b greater than E_b', there is no appreciable loss in plate current due to secondary emission. Under these conditions, the plate current is nearly independent of plate voltage.

The plate characteristic of a typical pentode is shown by the solid-line curve of Fig. 1B; the knee of the curve, though not well defined, occurs at $E_b = E_b'$. The round knee in the region of E_b', which is characteristic of the usual pentode, is due mainly to the presence of the zero-potential suppressor wires. Because of their presence, the field in the region of the suppressor is not uniform; hence, there is no definite value of E_b' at which plate current becomes substantially independent of plate voltage. Other factors that influence the roundness of the knee are: the shape and uniformity of the cathode, the shape and pitch of the control grid and screen grid, the relative distances between electrodes and grid side-rods, and the voltages applied to the electrodes. The effects of a round knee are to increase third-harmonic distortion and to decrease power output. If the knee were well defined, as shown by the dashed-line curve of Fig. 1B, the plate-current and plate-voltage swings would be increased, with a consequent increase in power output. Moreover, because of the greater uniformity of the entire plate family, the distortion would contain a smaller amount of third harmonics.

The new 6L6 does not use a physical suppressor in order to minimize secondary-emission effects. Suppression is obtained by creating a potential minimum between screen and plate by space-charge effects. The electron stream to the plate is confined to a beam whose electrons have nearly uniform path length and velocity. Such a design results in a plate characteristic that has a relatively sharp knee at a low plate voltage.

THE VIRTUAL CATHODE

Consider a hypothetical tetrode in which all the electrons that pass between the wires of the screen to the plate have uniform path length and velocity; hence, the electrons move along a path perpendicular to the axis of the cathode. Further assume that no secondary-emission effects are present. When the potential of the plate is lower than that of the screen, the electrons that pass the screen will be decelerated. Under the proper conditions, this deceleration creates a space-charge condition between screen and plate. Fig. 2A shows the potential distribution between screen and plate of the hypothetical tetrode for various screen-to-plate distances (d) and fixed electrode voltages. For distance d_1, the potential distribution at various plate voltages is shown at the left of Fig. 2B. At a certain high plate voltage, which is lower than that of the screen, the potential gradient is zero at one point (P_{min}), although the actual potential of that point is positive. Since there is no secondary emission, all the electrons reach the plate for any positive plate potential, as indicated at the right of Fig. 2B. The potential distribution for distance d_2 at various plate voltages is shown at the left of Fig. 2C. For this distance, a potential minimum (P_{min}) can occur at the plate when $E_b = 0$. Here, too, all electrons reach the plate for any positive plate potential, as shown at the right of Fig. 2C.

Fig. 2D shows that, at a certain distance (d_s), a potential minimum (M) of zero value occurs at a definite plate voltage E_b'. As E_b is made less than E_b', this point (M) recedes from the plate toward the screen for the following reason. As the plate voltage is lowered from some high value, the space charge between screen and plate increases. This increased space charge depresses the potential of (P_{min}) until it becomes zero at plate voltage E_b', as shown in Fig. 2D; (P_{min}) is then located at point M. The potential of (P_{min}) cannot become negative for a further decrease in E_b. Any tendency for the potential of (P_{min}) to become negative is offset by an increase in the number of electrons that return to the screen; thus, the space-charge density between the screen and point M increases and the point of minimum potential shifts to a new position (M'). As shown in Fig. 2D, the point of minimum potential shifts from M to M' for a change in voltage from E_b' to E_b''.

A point at which the potential gradient and the absolute potential are zero has the properties of a cathode; hence, it is called a "virtual cathode." The characteristics of a virtual cathode and plate (a "virtual diode") are similar to those of a physical diode; the plate current is space-charge limited for values of E_b from 0 to E_b'; when E_b is greater than E_b', the virtual diode is saturated, a potential minimum of positive value is formed, and the plate current remains substantially constant for further increase in plate voltage. This characteristic for the hypothetical tube is shown at the right of Fig. 2D. A potential minimum between screen and plate is necessary to return secondary electrons to the plate. With the correct screen-to-plate distance, the potential of (P_{min}) can be made just enough to suppress secondary-emission effects.

If the screen voltage is made less positive or if the control-grid voltage is made more negative, the current to the screen and plate decreases, the space charge between screen and plate decreases, and the virtual diode saturates at a lower value of plate voltage. Thus, the position of the knee of an E_b - I_b characteristic depends on the screen voltage and the control-grid bias. This is illustrated in the case of the 6L6 by the plate families of Figs. 4, 5, and 6.

THE 6L6

In order for a practical tube to approach the ideal conditions assumed in this Note, it is necessary to confine the electron paths to the plate so that the end effects of the control grid and screen grid are avoided. In the 6L6, this is accomplished by placing two "beam-forming plates" in the plane of the virtual cathode, as shown in Fig. 3; these plates are electrically connected to the real cathode inside the tube. In this manner, the electron paths to the plate are very nearly perpendicular to the axis of the cathode after passing the screen.

In order that the design of the 6L6 further approach the ideal, its control grid and screen grid have the same pitch and corresponding turns of each grid lie in the same plane. When the grids are aligned in this manner, the control grid focuses the electron stream from the cathode between the screen wires; the electrons then emerge from the screen in the form of "sheets." Due to the dispersion of the beam beyond the screen, the potential of the virtual cathode is nearly uniform throughout its length. This action is shown in the sketch. Due to alignment of the grids in this manner and due to the proper spacing between grids, the screen current is maintained at a low value. These features increase the overall efficiency of the tube as a power amplifier.

In the 6L6, secondary-emission effects are suppressed by creating planes of proper minimum potential between screen and plate. The well-defined knee of the 6L6 at a low plate voltage is due to the geometry of the tube elements, the careful alignment of the control and screen grids, the confinement of the electron stream by means of beam-forming plates, and the elimination of a physical suppressor grid.

OPERATION OF THE 6L6

Table I lists a number of fixed- and self-bias operating conditions for the 6L6. The subscript (1) used with the designations Class A and Class AB indicates that grid current does not flow during any part of the input-voltage cycle. The subscript (2) indicates that grid current flows during part of the input-voltage cycle.

Single-Tube Operation - Class A_1

Condition 1. With 375 volts on the plate, 125 volts on the screen, and a bias of -9 volts, the power output of the 6L6 is approximately 4 watts for either fixed- or self-bias operation; the distortion, which is mainly second harmonic, is 9 per cent. This operating condition is especially desirable when high power sensitivity is desired. For example, in a radio receiver, the 6L6 may be driven to full output by a type 6H6 diode detector without the use of an intermediate a-f amplifier stage. With this connection, the control grid should not draw current during any part of the input-voltage cycle; hence, the least-negative instantaneous grid voltage should not be less than approximately -1.0 volt. Because of low plate and screen currents, this operating condition is also desirable when a 6L6 is to be used with a high-voltage, low-current source of power.

Condition 2. Approximately 4 watts output can also be obtained from a single 6L6 when 200 volts are applied to both plate and screen, as indicated in Table I. However, because the plate current is comparatively high, this operating condition should be used only when a low-voltage, high-current source of power is available. Although the power outputs for conditions 1 and 2 are approximately equal, the load, bias, and peak signal voltage for negligible control-grid current are different.

Conditions 3 and 4. Two operating conditions are recommended when an output of approximately 6.5 watts is desired from a single 6L6. With 300 volts on the plate and 200 volts on the screen, a peak signal of 12.5 volts is required for full output. With 250 volts applied to both plate and screen, a peak signal of 14 volts is required for full output. The most desirable operating condition depends on the voltage-current capabilities of the power-supply source and the importance of having high power sensitivity.

Fig. 7 shows the variation in power output and harmonic distortion with load resistance for the 250-volt condition. As the load resistance is increased from a low value, the second-harmonic distortion decreases and the power output increases; however, the third harmonic, which is more objectionable to the ear than the second harmonic, also increases. The output with a 2500-ohm load resistance, which is recommended for the operating condition, is nearly maximum and its distortion is mainly second harmonic. The curves of Fig. 8 show the relation between distortion and power output for the recommended 250-volt operating condition; the relation between signal voltage and power output is also shown.

Condition 5. The maximum operating condition for a single 6L6 is given in Column 5 of Table I. With 375 volts on the plate, 250 volts on the screen, and -17.5 volts bias, the power output is approximately 11.5 watts. Although the total harmonic distortion is 14.5 per cent, it is mainly second harmonic. Because of plate dissipation requirements, a corresponding operating condition with self-bias for 375 volts on the plate and 250 volts on the screen is not recommended. For the load resistance shown in Column 5, the d-c plate current rises with power output. Consequently, the zero-signal bias should be less than the maximum-signal bias in order that optimum conditions exist at maximum output. When the zero-signal bias, however, is less than -17.5 volts, the maximum dissipation rating of the tube is exceeded. It is possible to use a higher load resistance than that recommended for fixed-bias operation in order to minimize second-harmonic distortion and the attendant rise in d-c plate current. With this condition, electrode voltages indicated in Column 5 may be used for self-bias operation; however, the distortion will be mainly third harmonic.

The second-harmonic distortion and the attendant rise in d-c plate current in a single-tube can be made small when a resistance-coupled circuit is used between the 6L6 and the previous a-f amplifier tube. If strong even harmonics are generated in the pre-amplifier, the phase of these harmonics will be opposite to those generated by the 6L6 with the recommended load resistance. Therefore, the overall even-harmonic distortion will be small; the odd harmonics from both stages add. Even-order harmonics of proper phase can be generated in the pre-amplifier by over-biasing the control grid or by using a low value of plate load. Cancellation of even harmonics may be obtained with transformer coupling when the transformer is phased correctly.

Push-Pull Operation - Class A_1

Condition 6. Two type 6L6 tubes may be connected in push-pull when high output at low distortion is desired. As shown in Column 6, Table I, approximately 14 watts at 2 per cent total distortion can be obtained with this connection when 250 volts is applied to plates and screens. Since the bias and plate-to-plate load have been selected for a small rise in d-c plate current, it is advisable to use these operating conditions when the regulation of the power-supply source is comparatively high.

Push-Pull Operation Class AB_1

Condition 7. When connected in push-pull and driven to the grid-current point, two 6L6 tubes with 400 volts on the plates and 250 volts on the screens will give approximately 25 watts at 2 per cent distortion. Since the data given in Column 7 obtain for operation without grid current, high-resistance grid circuits may be used. The rise in d-c plate current with the signal voltage is appreciable with fixed bias; therefore, a power supply having good regulation should be used in order to approach the power output shown in the Table. (The effect of plate regulation on power output and distortion will be discussed in a future Application Note.)

Condition 8. With 400 volts on the plates and 300 volts on the screens, two 6L6's will give more than 30 watts where the circuit is designed for zero grid current at maximum signal, as shown by the data of Column 8.

Push-Pull Operation - Class AB_2

Condition 9. When approximately 40 watts output is desired from type 6L6 tubes with 400 volts applied to the plates and 250 volts to the two screens, it is necessary to draw grid current during part of the input-voltage cycle. The conditions for this service are shown in Column 9, Table I. At 40 watts output, the total plate-circuit distortion does not exceed 2 per cent. However, grid-circuit distortion, which is due to the resistance and leakage inductance of the driver transformer and to the impedance of the driver tube, should be considered when evaluating the overall distortion. For low grid-circuit distortion, it is necessary to use a low-impedance driver tube and the input-coupling transformer should have low resistance and small leakage inductance. Because the rise in the d-c plate current is appreciable, it is necessary to use a well-regulated power supply in order to approach the power output shown in the Table. The power output at the grid-current point is 20 watts at 1 per cent distortion.

Condition 10. With 400 volts applied to the plates and 300 volts to the screens of the two type 6L6 tubes, outputs up to 60 watts can be obtained, as shown in Column 10. The power output at the grid-current point is 23 watts at 0.6 per cent distortion.

POWER SENSITIVITY OF THE 6L6

The large oval-shaped cathode, aligned grids, and close grid-to-cathode spacing are largely responsible for the high power sensitivity of the 6L6. The power sensitivities shown in Table I have been calculated from the relation:

$$\rho = \text{Power Sensitivity} = P/E^2$$

where P is the power output and E is the r-m-s signal voltage. When tubes are connected in parallel or in push-pull, P is the total power output delivered to the load and E is the total r-m-s signal voltage applied to the input. Thus, if a push-pull amplifier furnishes twice the power output of a single-tube amplifier when the same signal voltage is applied to the grid of each tube in both amplifiers, the power sensitivity of the single-tube amplifier will be twice that of the push-pull amplifier. When the two tubes are connected in parallel, the power sensitivity is four times that of the push-pull amplifier. The power sensitivities shown in Table I were computed on this basis and are expressed in milliwatts/volt^2.

EFFICIENCY OF THE 6L6

The efficiency (ε) of a power-output tube is defined as the ratio of the power output to the power input. In a tetrode or pentode, the power input is the sum of the powers supplied to plate and screen. The efficiencies for the ratings shown in Table I have been computed in accordance with this definition.

For a given power dissipation in the plate and screen of a pentode or tetrode, only a fraction of the power supplied to the plate circuit is converted into useful power output. Because of the inherently small screen current in the 6L6, a very large percentage of the plate and screen power is supplied to the plate; consequently, high power output and efficiency are possible. The recommended maximum plate and screen dissipation of the 6L6 is 24 watts; the recommended maximum screen dissipation is 3.5 watts. For Condition No.10, which represents optimum tube performance, the plate-circuit power with maximum signal is 400 x 0.23 = 92 watts; the screen power is 300 x 0.02 = 6 watts. The total input power is 98 watts; the power output is 60 watts. The efficiency, therefore, is 60/98 = 61 per cent. The power supplied to plate and screen is 98-60 = 38 watts for two tubes. With no signal applied, the power input to plate and screen is 400 x 0.102 + 300 x 0.006 = 42.6 watts for two tubes, which is slightly less than the recommended maximum rating.

CONCLUSION

Because the 6L6 can furnish high output with little distortion, it is well suited for use in high quality output systems. Moreover, these high outputs can be obtained with relatively small input-signal voltages and at low power-supply cost. A single 6L6 can furnish outputs up to 11.5 watts; the second-harmonic distortion can be reduced by generating second harmonics in the pre-amplifier. The high power sensitivity of the 6L6 permits its use in a number of circuits which avoid the troublesome effects of loudspeaker resonance and variable load impedance. The characteristics of such circuits will be discussed in a future Note.

TABLE 1

SUMMARY OF OPERATING CONDITIONS FOR THE 6L6

	SINGLE-TUBE OPERATION									PUSH-PULL OPERATION							
Condition	No.1		No.2		No.3		No.4		No.5	No.6		No.7		No.8		No.9	No.10
Class of Operation*	A_1		A_1		A_1		A_1		A_1	A_1		AB_1		AB_1		AB_2	AB_2
Kind of Bias	*Fixed*	*Self*	*Fixed*	*Self*	*Fixed*	*Self*	*Fixed*	*Self*	*Fixed*	*Fixed*	*Self*	*Fixed*	*Self*	*Fixed*	*Self*	*Fixed*	*Fixed*
Heater Volts[1]	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
Plate Volts	375	375	200	200	300	300	250	250	375	250	250	400	400	400	400	400	400
Screen Volts	125	125	200	200	200	200	250	250	250	250	250	250	250	300	300	250	300
D-C Grid Volts[2]	–9	–9[3]	–11.5	–11[3]	–12.5	–11.8[3]	–14	–13.5[3]	–17.5	–16	–16[3]	–20	–19[3]	–25	–23.5[3]	–20	–25
Peak A-F Grid Volts	8	8.5	11.5	11.5	12.5	12.5	14	14	17.5	32[4]	35.6[4]	40[4]	43.8[4]	50[4]	57[4]	57[4]	80[4]
Zero-Sig. D-C Plate Current (Ma.)	24	24	52	55	48	51	72	75	57	120	120	88	96	102	112	88	102
Max.-Sig. D-C Plate Current (Ma.)	26	24.3	57	56	55	54.5	79	78	67	140	130	124	110	152	128	168	230
Zero-Sig. D-C Screen Current (Ma.)	0.7	0.7	3.5	4.2	2.5	3	5	5.4	2.5	10	10	4	4.6	6	7	4	6
Max.-Sig. D-C Screen Current (Ma.)	2	1.8	5.7	5.6	4.7	4.6	7.3	7.2	6	16	15	12	10.8	17	16	13	20
Load Resistance (Ohms)	14000	14000	3000	3000	4500	4500	2500	2500	4000	5000[5]	5000[5]	8500[5]	8500[5]	6600[5]	6600[5]	6000[5]	3800[5]
Distortion – Total %	9	9	9	9	11	11	10	10	14.5	2	2	2	2	2	2	**	**
– 2nd Har. %	8	8	8.7	8.7	10.7	10.7	9.7	9.7	11.5	–	–	–	–	–	–	–	–
– 3rd Har. %	4	4	2.5	2.5	2.5	2.5	2.5	2.5	4.2	2	2	2	2	2	2	**	**
Max.-Signal Power Output (Watts)	4.2	4	4	4	6.5	6.5	6.5	6.5	11.5	14.5	13.8	26.5	24	34	32	40 #	60 ##
Power Sensitivity (Milliwatts/volt[2])	131	111	60.6	60.6	83.3	83.3	66	66	75.1	28.4	21.8	33.1	25	27.2	19.7	24.6	18.8
Efficiency (%)	42	42.8	32	32.5	37.3	37.7	30	30.6	43.2	37.2	38.3	50	52	51.6	58	56.8	61.2
Peak Grid-Input Power (Mw.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	180[6]	350[6]
Bias Resistor (Ohms)	–	365	–	185	–	220	–	170	–	–	125	–	190	–	200	–	–

* Subscript (1) indicates that grid current does not flow during any part of input-voltage cycle. Subscript (2) indicates that grid current flows during some part of input-voltage cycle.

** With zero-impedance driver and perfect regulation, plate-circuit distortion does not exceed 2%. In practice, plate-voltage regulation, screen-voltage regulation, and grid-bias regulation should be not greater than 5%, 5%, and 3%, respectively.

\# An output of 20 watts can be obtained at the grid-current point of Condition 9.

\#\# An output of 23 watts can be obtained at the grid-current point of Condition 10.

[1] When the 6L6 is operated at maximum ratings, the heater voltage should not exceed 7 volts.

[2] Maximum resistance in the grid circuit should not exceed 0.1 megohm for fixed-bias operation nor 0.5 megohm for self-bias operation.

[3] No signal.

[4] Grid to grid.

[5] Plate to plate.

[6] Driver stage should be capable of supplying this power to the grids of the 6L6's at low distortion. The effective resistance per grid circuit of the Class AB stage should be kept below 500 ohms and the effective impedance at the highest desired frequency should not exceed 700 ohms.

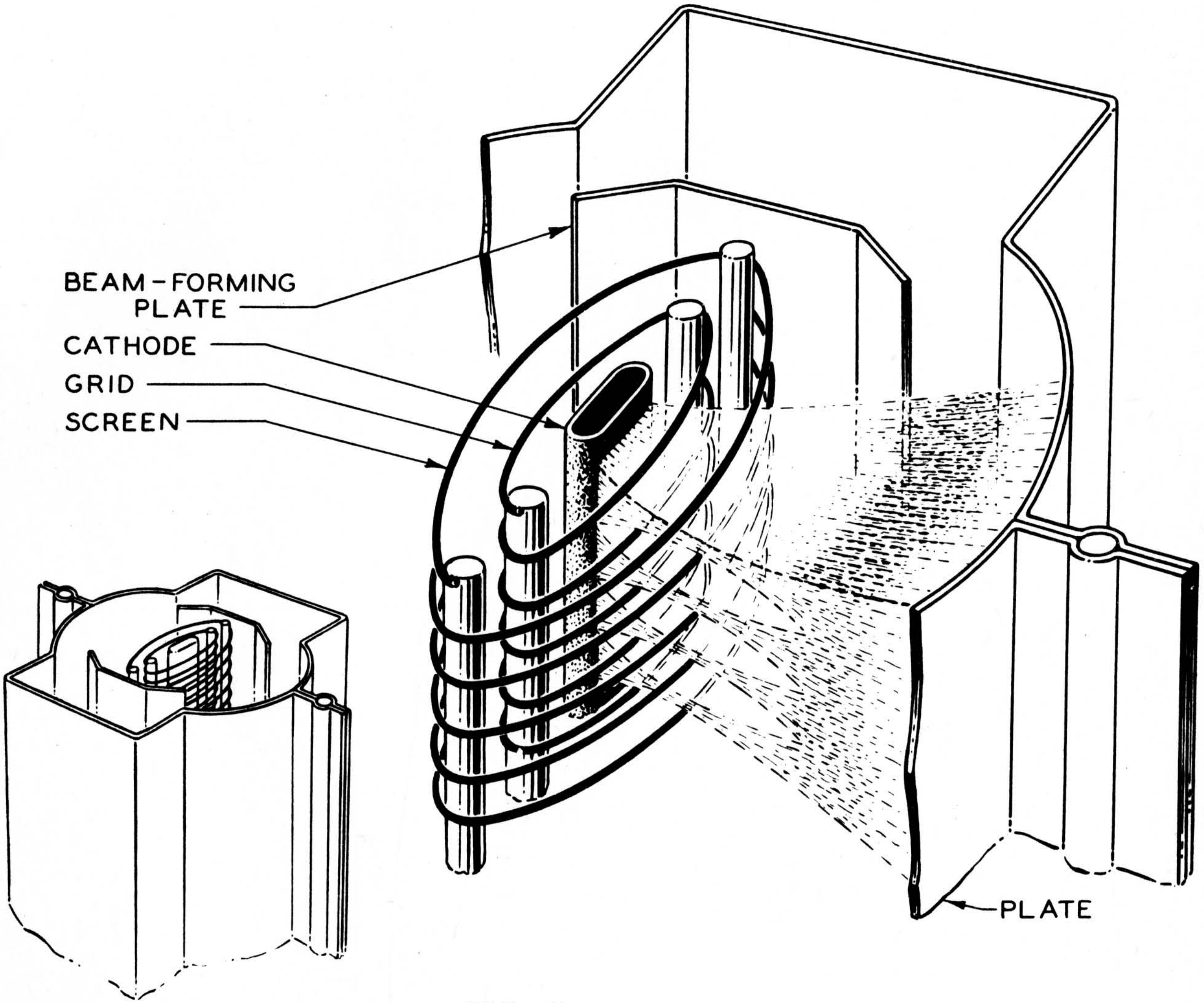

FIG. 3

SKETCH SHOWING FORMATION BY GRID WIRES OF BEAM SHEETS

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AVERAGE PLATE CHARACTERISTICS
WITH E_{C2} AS VARIABLE

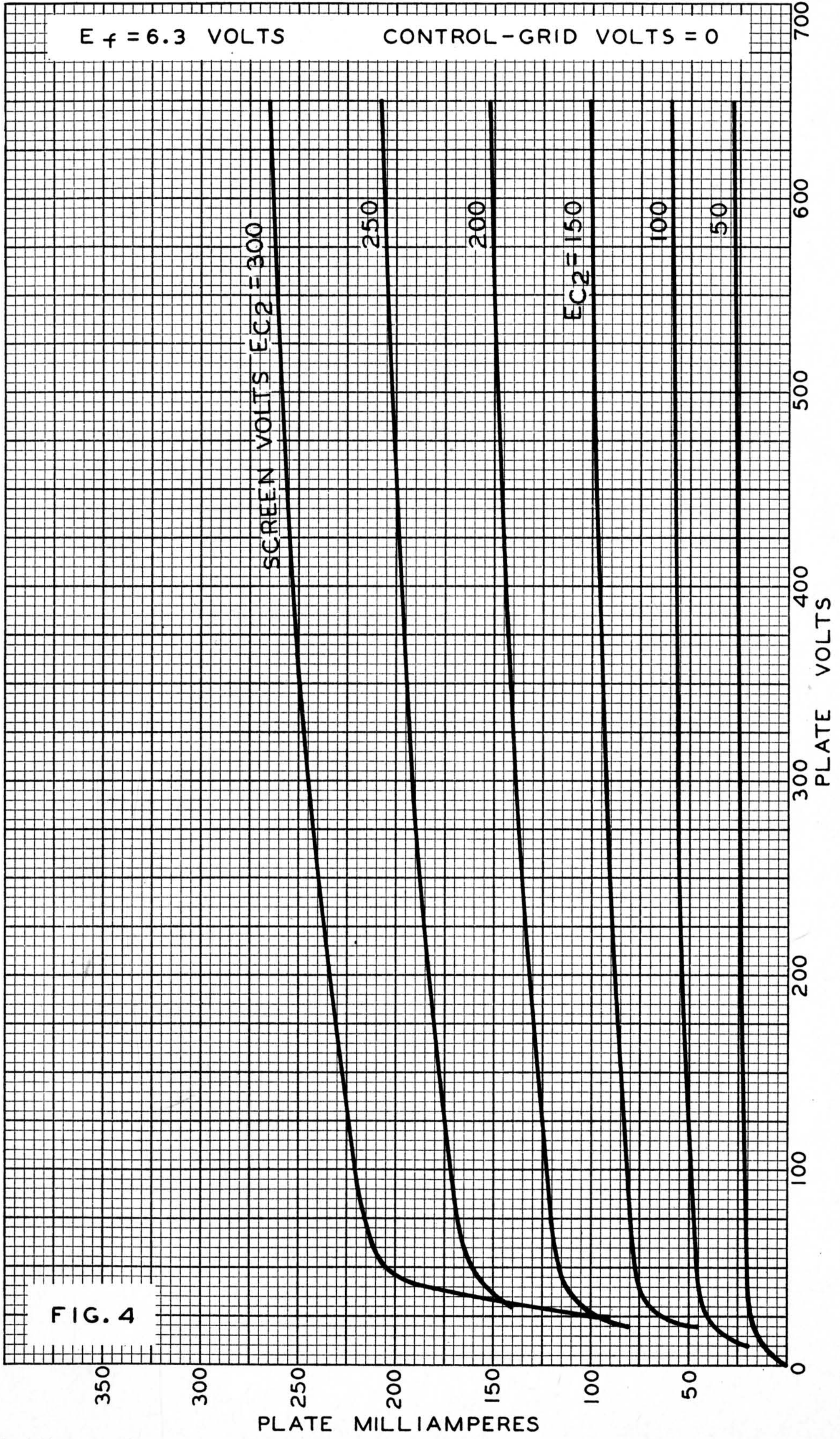

FIG. 4

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AVERAGE PLATE CHARACTERISTICS
WITH E_{C1} AS VARIABLE

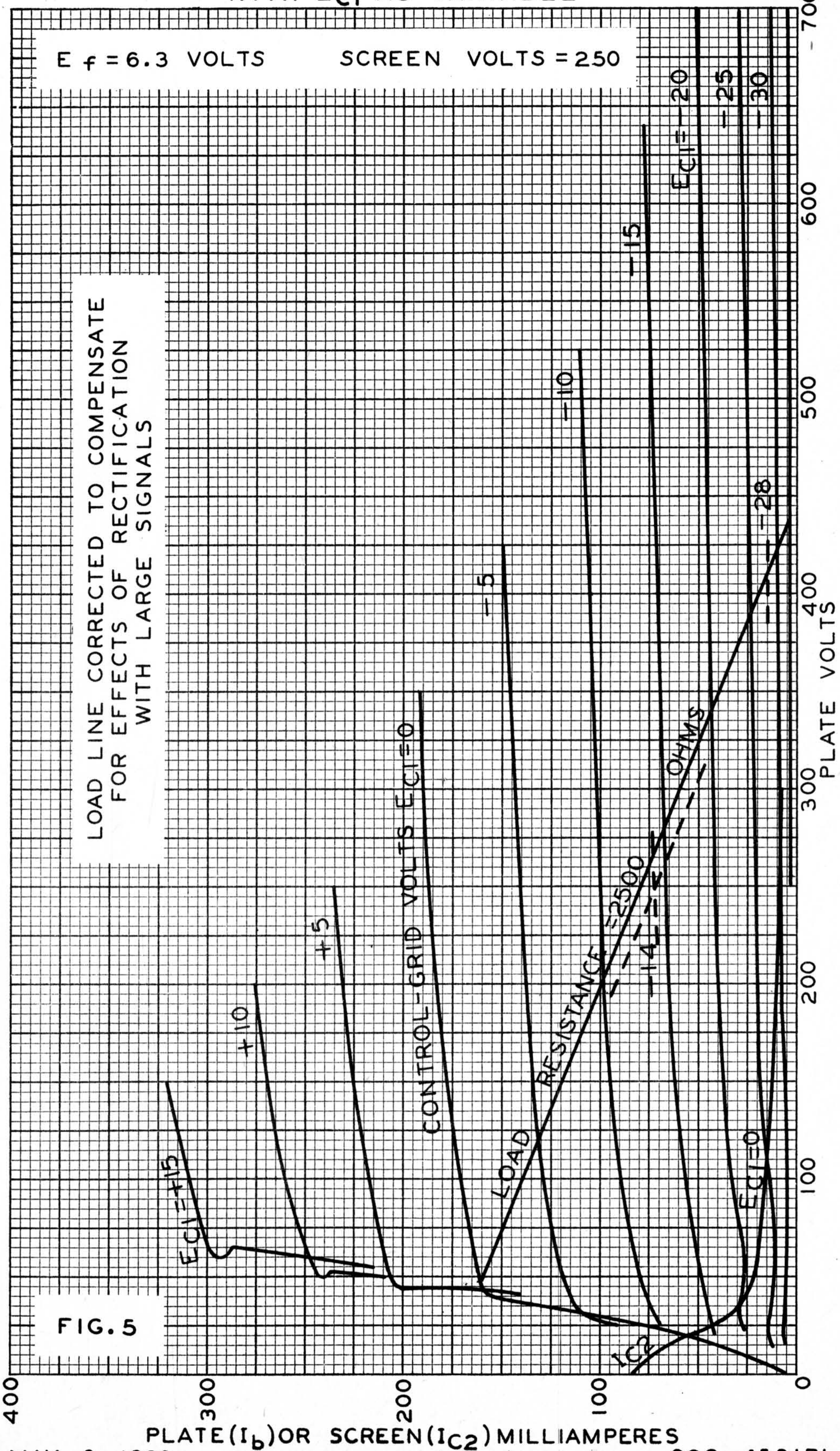

FIG. 5

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AVERAGE PLATE CHARACTERISTICS
WITH E_{C1} AS VARIABLE

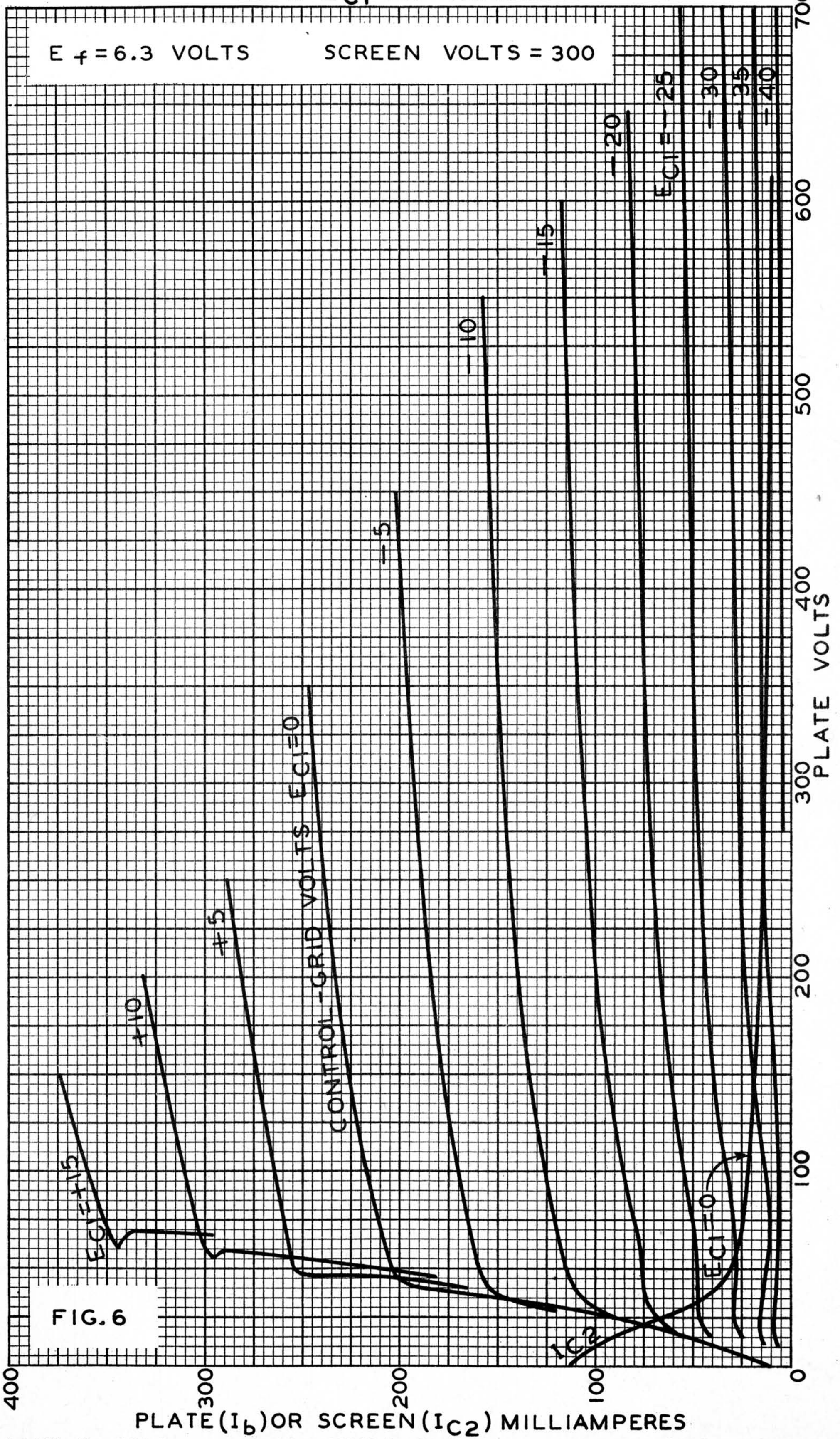

FIG. 6

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OPERATION CHARACTERISTICS

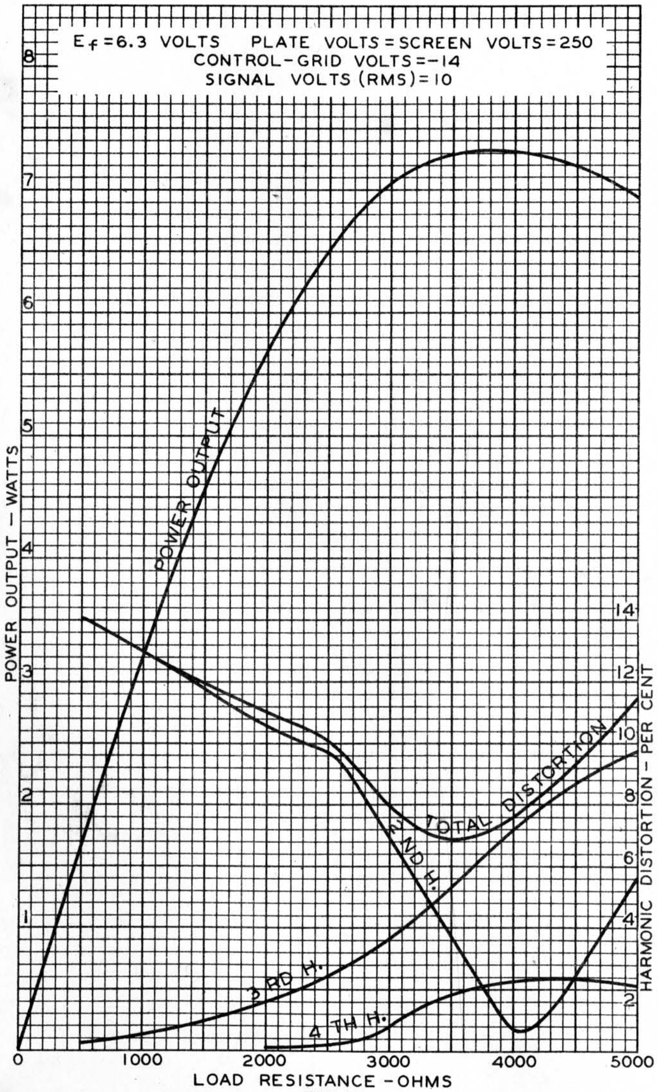

FIG.7

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OPERATION CHARACTERISTICS

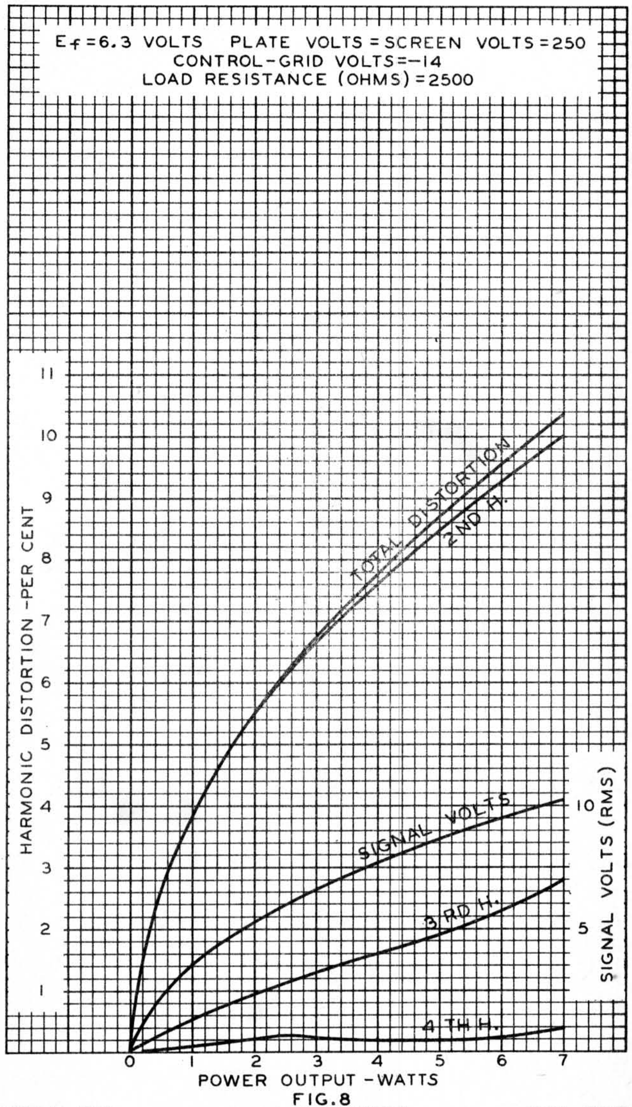

FIG.8

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