Published in:
Proceedings of the National Electronics Conference, Vol. V
Chicago, Illinois
September 26, 27, 28 1949

THE 6BN6 GATED BEAM TUBE

Part 2. The Commercial Realization Of The 6BN6

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Abstract.—The use of sharply focused beams in grid-controlled receiving tubes represents a new departure in tube design which entails many unusual problems. Mechanical and electrical considerations in the production design are reviewed. The transfer characteristics of the 6BN6 are given and experience to date with this type, as well as plans for future types, are briefly discussed.

I. DEVELOPMENT OBJECTIVE

The initial design of the 6BN6, features of which have already been discussed by Dr. Adler, demonstrated the practical nature of a beam type tube in which a quadrature voltage can be developed by space charge coupling to yield the discriminator circuit. The inclusion of a highly efficient limiter in the form of an electron beam whose current is defined by placing an apertured slot in the beam at a region of high current density, makes the 6BN6 limiter-discriminator circuit possible.

In developing this tube, it was our objective to design a tube which would have two control elements each having essentially a step function transfer characteristic in order to realize efficient circuit operation at low input levels. Operation at low levels necessitated a design which would yield a well-defined electron beam in order to insure high input transconductance and further required that the input admittance of the tube be low so that reasonably high gain could be realized in the last i-f amplifier of the receiver. Together, these features make possible switching of the plate current between cutoff and its limited value with low input signal to the receiver. A fourth design objective was that of making a tube which would have essentially constant cathode current regardless of the control electrode potentials. This characteristic would make possible the use of a cathode resistor for developing operating bias voltage.

II. UNCONVENTIONAL NATURE

The 6BN6 as illustrated in Fig. 1 is unique from many standpoints. The electron beam in this tube takes the form of a sheet beam of varying cross section and current density. In addition, there are no focusing or intensity controls as are found in most circuits in which electron beam tubes are used. This requires accurate initial beam forming and focusing and further requires tube processing stability to retain such forming when there is dependence upon cathode emission level and contact potential. Of particular interest is the fact that low voltage electron optics are utilized which necessitates holding unusually small manufacturing tolerances. The field strengths in the lens systems are not unusually high but they are obtained by using low supply voltages and small interelectrode spacings which further must be maintained symmetrically about a central plane. Since we are interested in gating the electron beam,

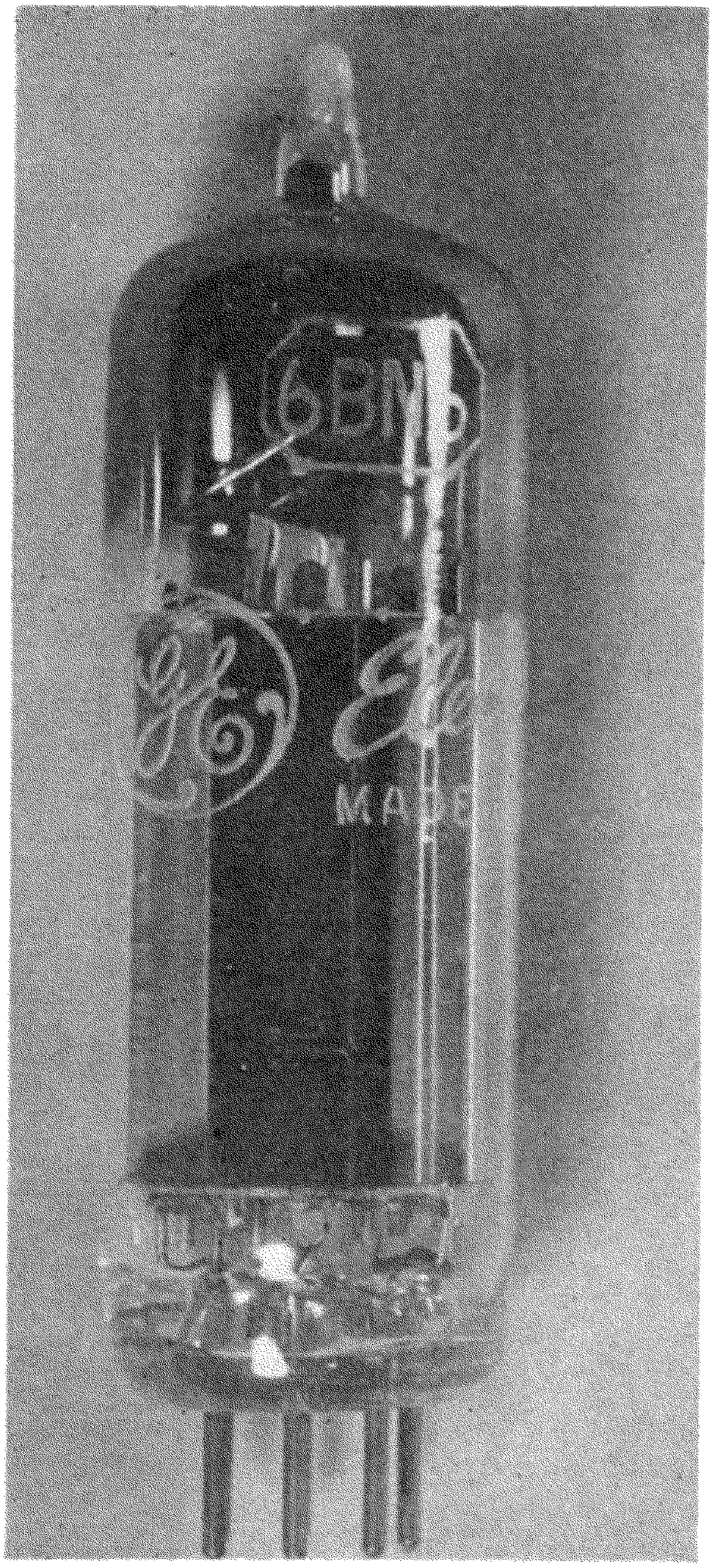


Fig. 1—The 6BN6 tube.

a third factor for consideration is that there are major changes of space charge distribution when the beam is stopped by one of the control grids. With either of the grids negative, conditions for Barkhausen-Kurtz oscillations are present and we must prevent such oscillations from occurring. Further, space charge coupling within the tube must be uni-directional if the input grid circuit is to remain unaffected by voltages appearing in the quadrature grid circuit.

Among the unusual features of the 6BN6 is that its beam creating accelerator shields the cathode from the electrostatic fields of the control grids. This serves to make the cathode current independent of control electrode potentials. Considering this, we see that with plate current cutoff biases in the order of 2-volts, voltage developed across a cathode resistor by accelerator current alone is easily capable of biasing the tube past the cutoff voltage and therefore the tube is capable of cutting off its own plate current completely. Since the beam current is of constant amplitude, switching of that current away from the plate circuit by making either of the grids negative causes the current in the accelerator circuit to increase, yielding a negative transconductance characteristics to the accelerator electrode. The constant beam current provides limited grid 1 and grid 3 currents which reach saturation at about +2 volts. The magnitude of these limited currents is dependent upon the beam density and the screening area of these electrodes.

III. MECHANICAL CONSIDERATIONS

In order to satisfy our objectives, it is necessary to provide unusually complete shielding between the input and quadrature grids as well as to provide the necessary focusing, accelerating, and electron lens components. Whenever possible, several electrodes have been combined into single mechanical structures in order to provide the minimum number of parts in the 6BN6 assembly. By making these parts in such manner that mechanical symmetry is obtained about a plane formed by the center of the plate and the vertical axis of the cathode, a symmetrical beam is generated. As was mentioned, extremely close tolerances are required not only of the individual parts, but, as is apparent, of the whole assembly. Considering that a space between electrodes of forty thousandths of an inch is used to create an electric field intensity of 800 volts per centimeter, a change in position of plus or minus two thousandths of an inch represents a change of about plus or minus 40 volts per centimeter in field strength. In the critical area between focus electrode and accelerator, a field strength of approximately 1600 volts per centimeter exists with a spacing of only .015″. The current density along the beam varies downward from 25 milliamperes per square centimeter so that the relative importance of electronic space charge within the beam varies widely along its path. These two considerations require that high mechanical uniformity be maintained from tube to tube if a uniform product is to be realized. Those components which are of particular importance in this respect are shown in Fig. 2 and are the focusing electrode which surrounds the cathode, the accelerator

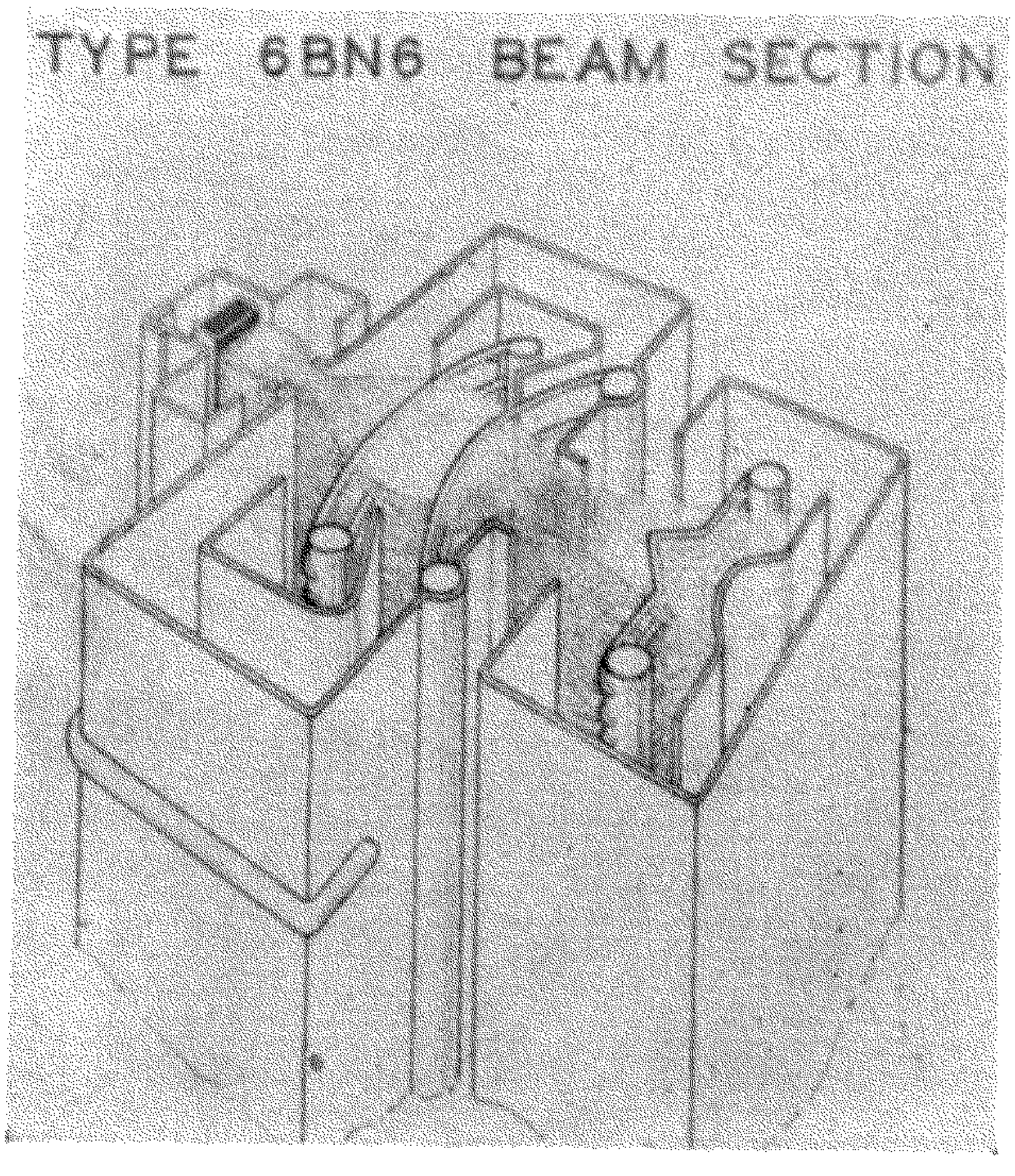


Fig. 2—Type 6BN6 beam section.

slot close to the cathode, the lens which surrounds the first grid, and the accelerator grid-accelerator region which is just behind the lens. As can be seen, half grids are used to gate the beam and act to shape the return paths of electrons reflected from these elements when they are negative. The lens structure not only forms the beam but also acts as a shield to reduce the inter-electrode capacitance from the input grid to the quadrature grid. The last shield structure which surrounds the quadrature grid and plate serves the same function with respect to inter-electrode capacitance and helps to define the effective cathode of this system and confine the paths of reflected electrons to a definite pattern. By preventing the electron beam from striking the side rods of these grid systems, it is possible to limit the grid currents to maximum values in the order of several hundred microamperes. A factor of some importance regarding the transfer of the beam from the cathode to the plate is that of maintaining low vertical dispersion of the beam. When the beam is passed through the input grid, the increased charge density between grid laterals is such as to cause the beam to disperse vertically after it has passed through them. While the effects of this dispersion cancel at the center of the grid, the end effects are not negligible and can result in some loss of plate current. Since this loss in general appears as additional accelerator current, and it is desired to keep the ratio of accelerator to plate current as low as possible, the 6BN6 has been designed to reduce the effect of such vertical dispersion. In addition, the concentration of space charge between the grid laterals can become high enough to reflect some electrons approaching the grid, resulting in a net loss of plate current when the grid voltage is low. This property is, of course, useful when cutting off plate current.

In the 6BN6 design, the convergent lens formed by the focus electrode and the accelerator lips, and the divergent lens between the apertured slot and the input grid when that electrode is at low or slightly negative potentials, cause the beam to spread as it approaches the input grid. This action increases the beam area and hence reduces the relative space charge density between grid laterals. The beam is reconverged by passing it through an electro-static field which is shaped between the lens and the accelerator grid to bring the electrons to a focus in the region in front of the quadrature grid. The quadrature grid is shaped to give an extended depth of grid control so that

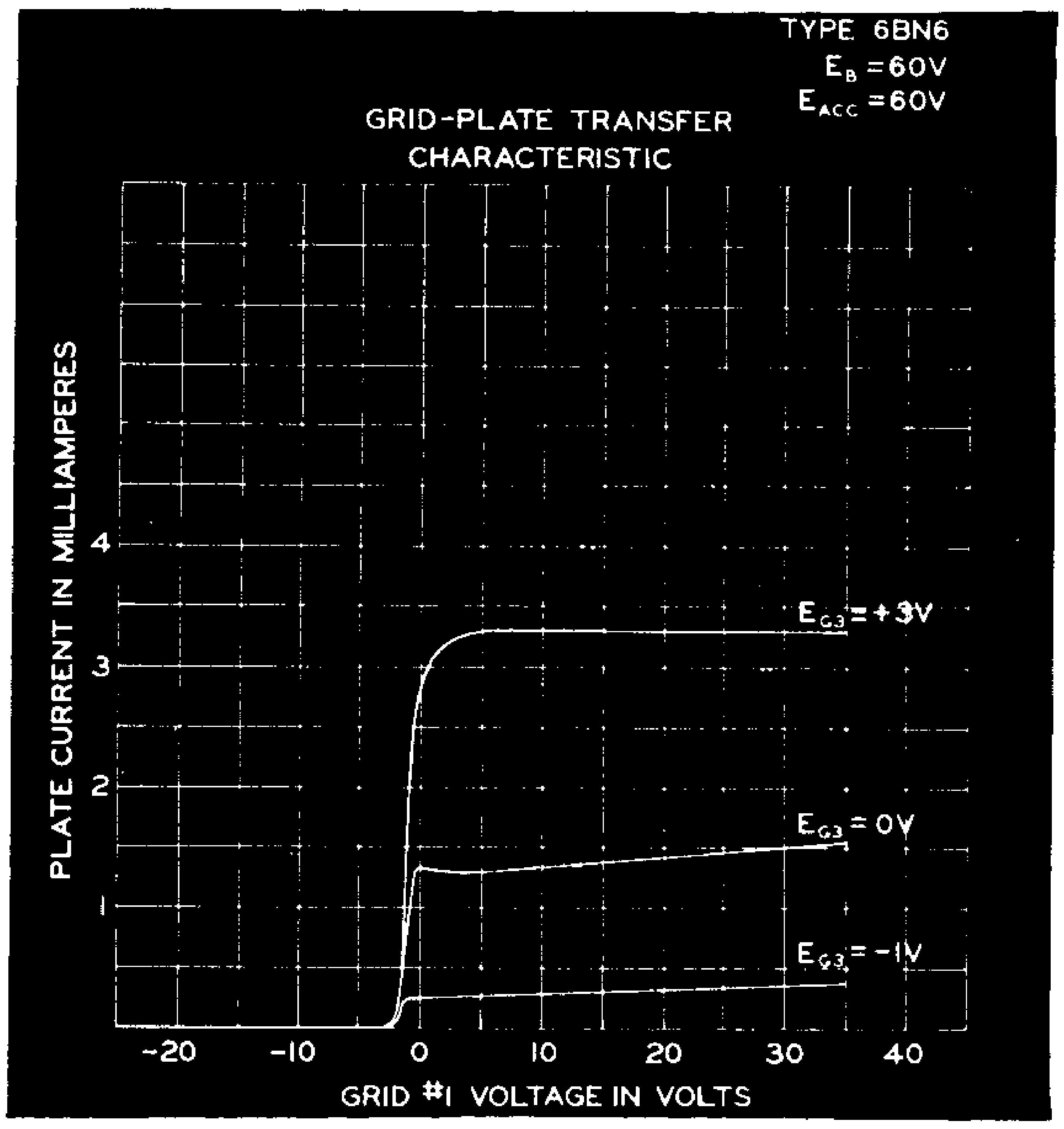


Fig. 3—Grid-Plate Transfer characteristic.

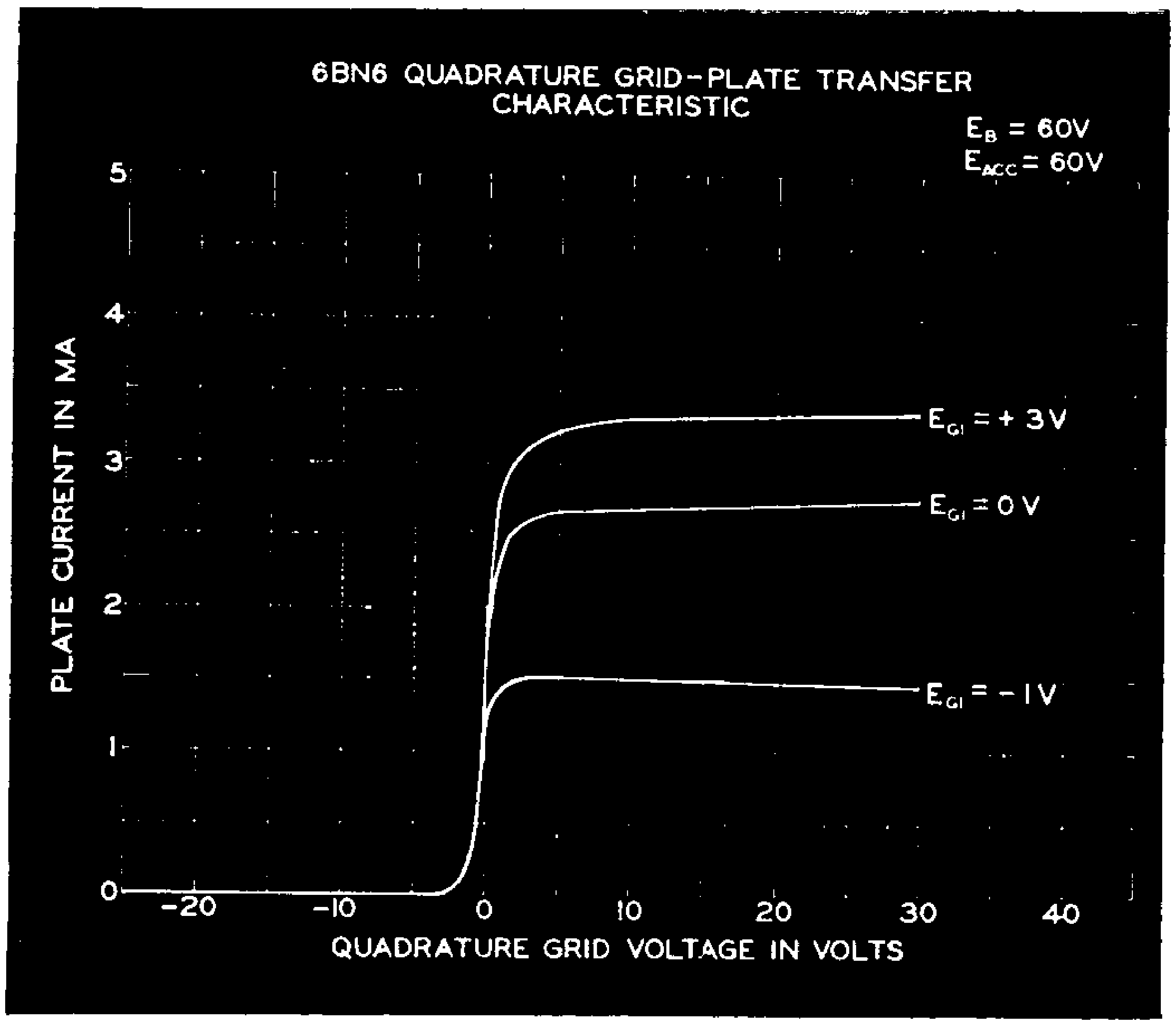


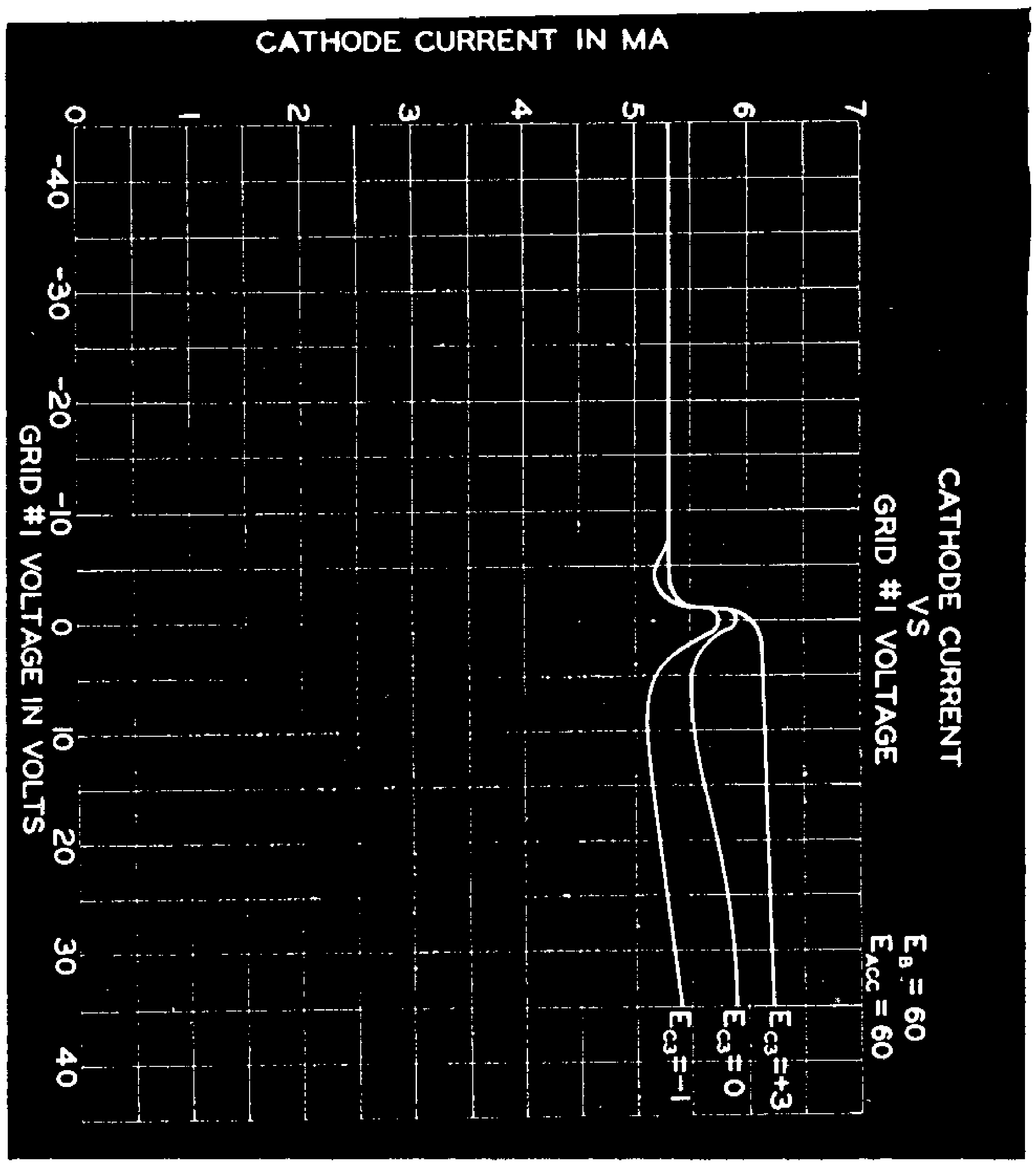
Fig. 4—Quadrature grid-plate transfer characteristic.

constant transconductance is obtained despite the movements of the effective cathode of this triode section as the potential of the input grid is changed. The plate structure is formed to obtain constant amplification factor for the triode section.

IV. TUBE CHARACTERISTICS

The extent to which the 6BN6 approaches the step function transfer characteristic can be seen in Fig. 3. For values of quadrature grid voltage in excess of +2 volts, the plate current is essentially constant. For lower grid voltages, the plate current is as indicated on the transfer characteristic curve. Note that this characteristic is essentially linear regardless of the potential of the No. 1 grid for any given value of quadrature grid potential. As has been indicated, two step function characteristics are required for discriminator operation. The quadrature grid-plate transfer characteristic is shown in Fig. 4, and approaches the step function reasonably well. The transconductance of the No. 1 grid is approximately 3,000 microhms at a plate current of .75 milliamperes. The transconductance of the quadrature grid under the same conditions of operation is approximately 1,500 microhms or a transconductance-to-plate current ratio of approximately 4,000 microhms per milliampere for the input grid and 2,000 microhms per milliampere for the quadrature grid. Considering this information, we see that the transfer functions satisfy our objectives reasonably well.

Figure 5 shows how cathode current varies with grid 1 and grid 2 potentials. It can be seen that the cathode current is, within reason, constant regardless of the grid signal levels and consequently a cathode resistor can be used to develop the necessary operating bias. Another transfer characteristic of particular interest is that shown in Fig. 6. Here we see that as the input grid is made more positive, switching the plate current from the cutoff to the limited value, the accelerator current varies from a maximum value downward to a relatively constant value yielding a negative trans-



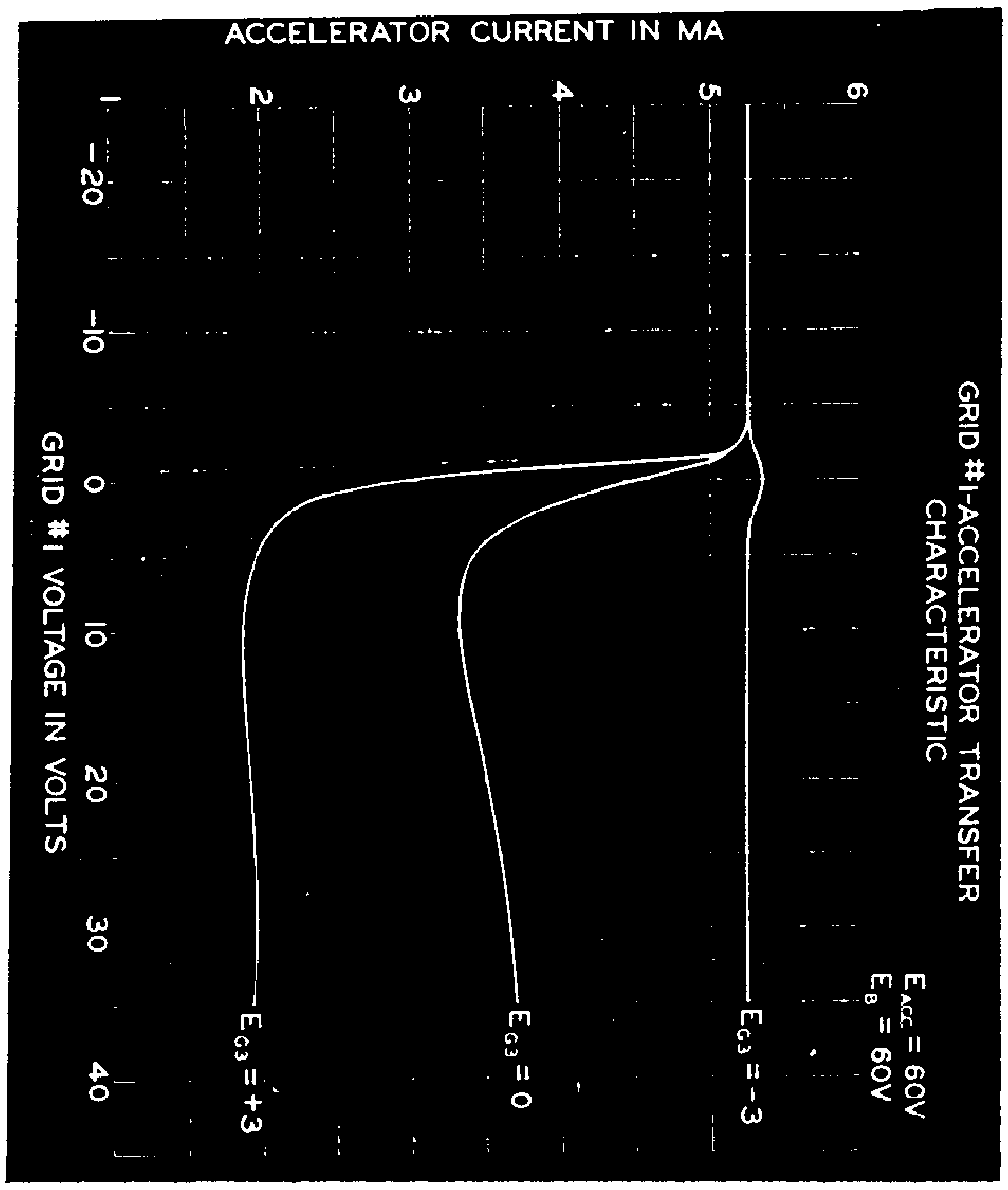


Fig. 5—Cathode Current vs. grid No. 1 voltage. Fig. 6—Grid No. 1-Accelerator transfer characteristic.

conductance to the accelerator electrode. This change in accelerator current represents a negative transconductance of 1,500 micromhos. Application of such a characteristic to oscillatory and "flip-flop" circuits is, of course, possible.

V. LIMITER-DISCRIMINATOR CIRCUIT

Figure 7 shows the limiter-discriminator circuit designed for operation in a-c, d-c receivers. At the standard f-m intermediate frequency of 10.7 megacycles, the output voltage for 75 kc deviation is approximately 4.5 volts rms. The a-m rejection, defined as the ratio of a-m output voltage to f-m output voltage taken with 30% a-m and 30% f-m simultaneously, can be optimized to approximately −35 db. The a-m rejection characteristic with respect to input signal level is irregular but is such that at least 20 db of a-m rejection is realized at input voltages of 1 volt, and 15 to 30 db of a-m

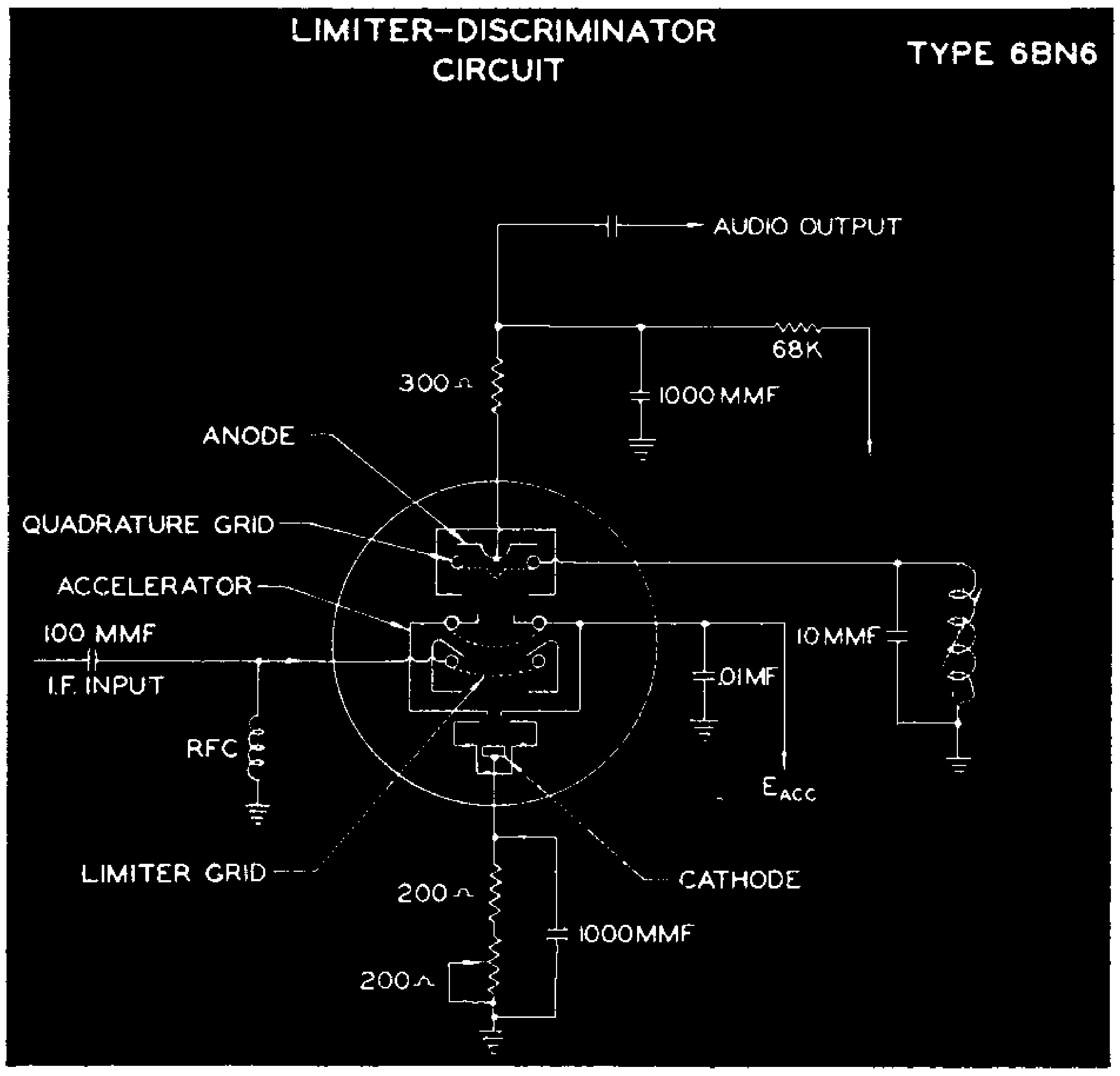
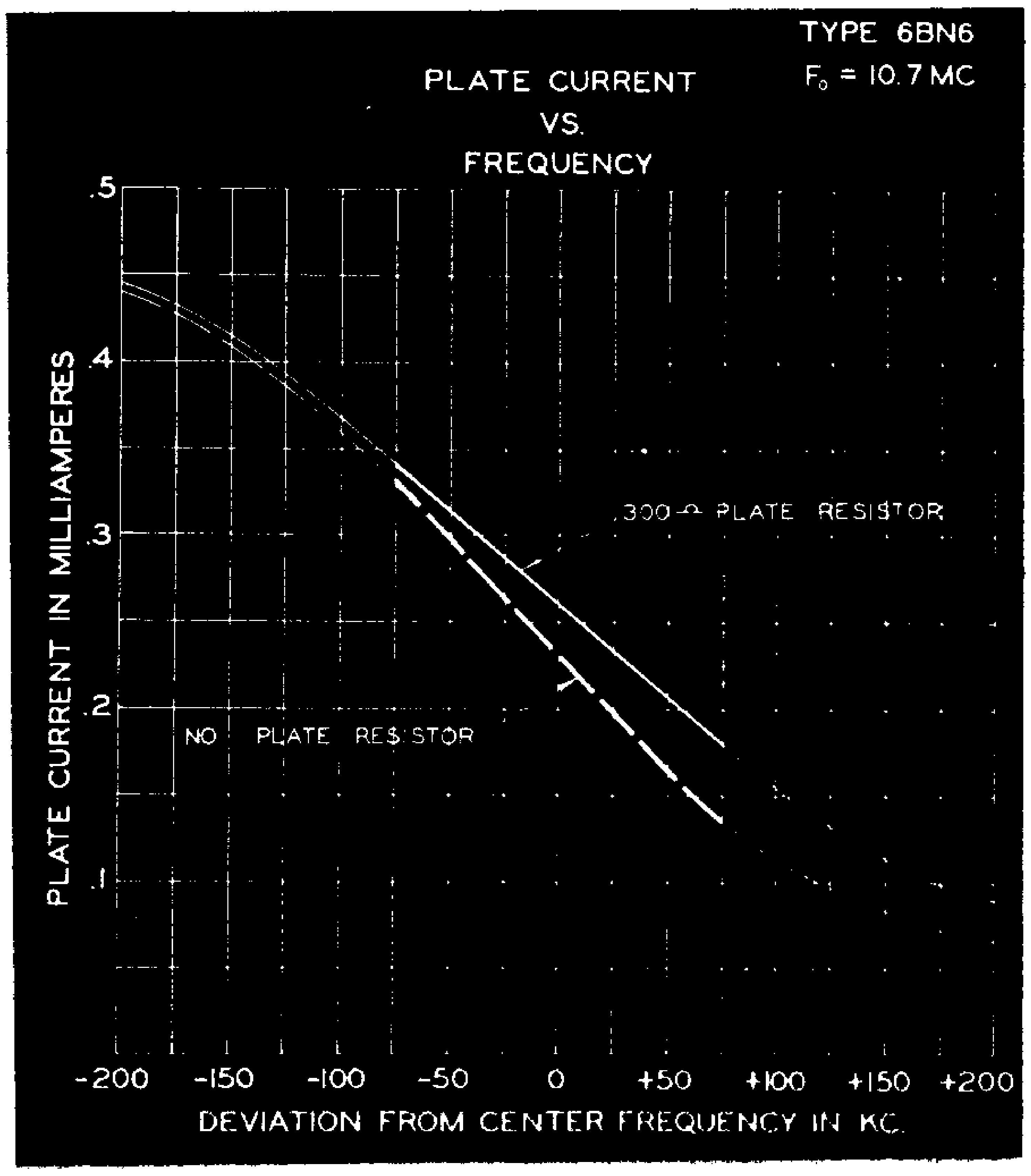


Fig. 7—Limiter-Discriminator circuit.



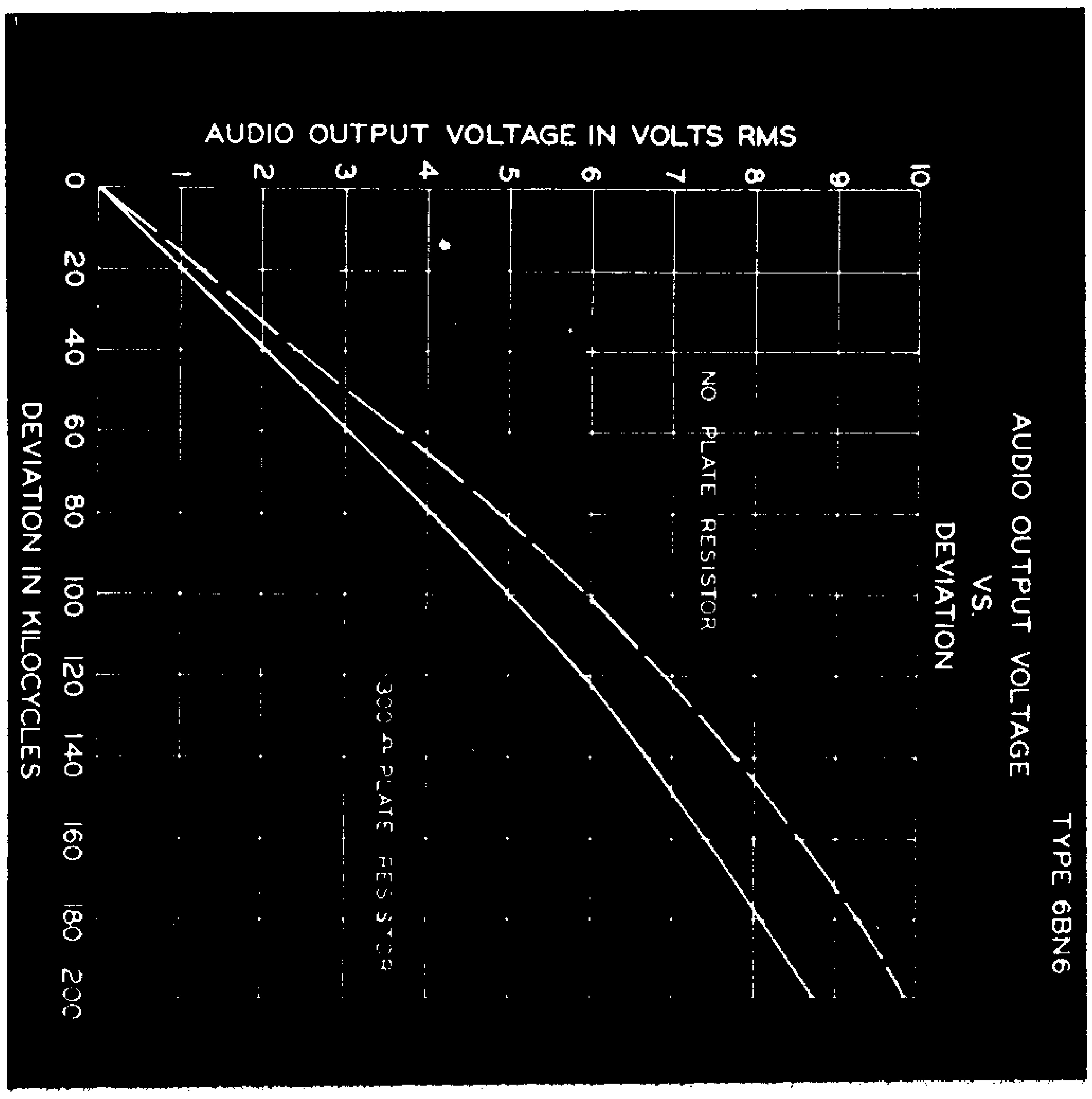


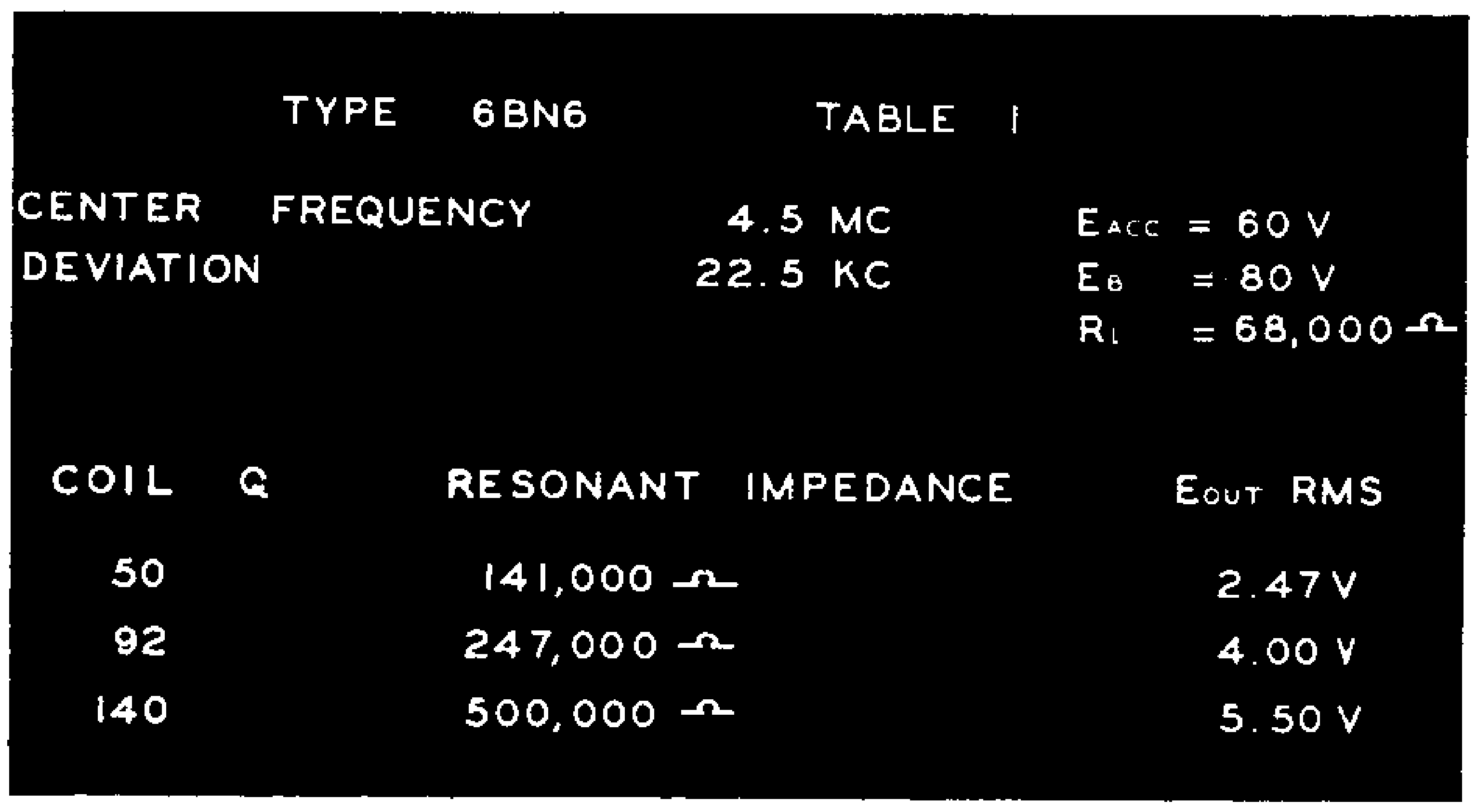
Fig. 8—Plate current vs. frequency.

Fig. 9—Audio output voltage vs. deviation.

rejection is realized at signal voltages above the optimized level of 1.25 volts rms. Figure 8 shows the remarkably wide and linear variations of plate current with instantaneous frequency and indicates as well the effect of the 300 ohm series plate resistor upon this characteristic. Figure 9 shows the relationship between audio output voltage and deviation. This figure also indicates the effect that the series plate resistor has on both output and linearity. It should be noted that an increase in output voltage from 3.75 to 4.5 volts rms is realized by the omission of the series plate resistor. However, in receivers in which it is desired to keep harmonic distortion to a minimum, the use of the plate resistor will give output with less than 1% distortion whereas omitting the resistor will give somewhat greater output at approximately 3% distortion. The output voltages shown are obtained using accelerator voltage of 60 volts and plate supply voltage of 80 volts. Higher accelerator and plate voltages and a correspondingly higher plate load resistor yields audio output of 15 volts rms for 75 kc deviation.

The application of the 6BN6 limiter-discriminator to intercarrier television receivers is of particular interest. The intercarrier frequency of 4.5 megacycles allows operation of this circuit at a frequency at which a high impedance quadrature grid tank circuit can be obtained and utilized since the undesired external coupling reactance due to capacitance between the input grid and the quadrature grid is in the order of 3.5 megohms. The dependence of the output voltage upon the Q of the quadrature grid tank is indicated in Table 1 in which variations of parallel resonant impedance of the quadrature grid tank from 141,000 ohms to 500,000 ohms yielded variations in output voltage from 2.47 to 5.5 volts rms at 22½ kc deviation. These output voltages were obtained with low supply voltages for the plate and accelerator electrodes. One application of the 6BN6 in an intercarrier television chassis where higher plate supply voltage and load resistance are used yields 15 volts rms at 25 kc deviation with an input signal of 1.25 volts. This output voltage is sufficient to drive the power amplifier tube directly and so eliminates one audio amplifier stage completely.

TABLE I



TYPE 6BN6 TABLE I

CENTER FREQUENCY 4.5 MC
DEVIATION 22.5 KC

E_{ACC} = 60 V
E_B = 80 V
R_L = 68,000 Ω

COIL Q	RESONANT IMPEDANCE	E_{OUT} RMS
50	141,000 Ω	2.47 V
92	247,000 Ω	4.00 V
140	500,000 Ω	5.50 V

Operation of the 6BN6 at 21.5 megacycles has been realized but only when considerable care was taken to shield the input and quadrature grid circuits from each other. At this frequency, with 10 kc deviation and 30% a-m, output voltage of .55 volts rms and a-m rejection of about 20 db was obtained.

At all frequencies at which tests were made, the input voltage was varied from less than 1 volt to 40 volts rms so that the full range input signals which we could expect to find in receiver applications was covered.

A comparison between the performance of the 6BN6 limiter-discriminator and an Armstrong system, i. e., limiter and Foster-Seeley discriminator has been made using a now obsolete f-m receiver made by one of the well-known receiver manufacturers. Figure 10 shows the a-m rejection characteristic vs. input to the antenna terminals of the receiver. In this case, 30 microvolts represents an input signal to the limiter-discriminator of approximately 2 volts and the receiver gain is reasonably linear to the 1,000 microvolt value. It can be seen that the 6BN6 yields superior performance in the low input voltage regions, is very slightly inferior to the Armstrong system at intermediate inputs, and approaches the a-m rejection of the Armstrong system quite well at high input levels. The performance of the limiter-discriminator, comparing audio output voltage with the input voltage to the antenna terminals, is shown in Fig. 11. Here again the 6BN6 performance is considerably better than that of the limiter and Foster-Seeley discriminator. The audio voltage reaches a maximum with about 1 volt rms signal at the input of the 6BN6 and remains essentially constant over the range of input voltages normally covered. In addition to these desirable characteristics, the limiter has associated with it no RC time constants of importance at the operating frequency and hence can respond at a rate limited only by the inertia of the electron beam. This means that ignition noise and other similar pulse noise is rejected to a degree previously unobtainable even when cascade limiter stages are used. Such response of the limiter circuit makes possible the effective reduction of common channel interference of both the beat note and cross-modulation type. The discriminator does not utilize separate cathodes as is the case in most of the other popular discriminator circuits, and hence unbalance due to variations in the aging characteristics of cathodes as the receiver is operated do not appear as a factor in discriminator performance. As has been indicated, the band-pass characteristic of this discriminator is not dependent upon transformer coupling and tuning and is linear over an unusually wide frequency range. Consequently, the discriminator accepts the full band over which modulation energy is distributed and yields low output distortion.

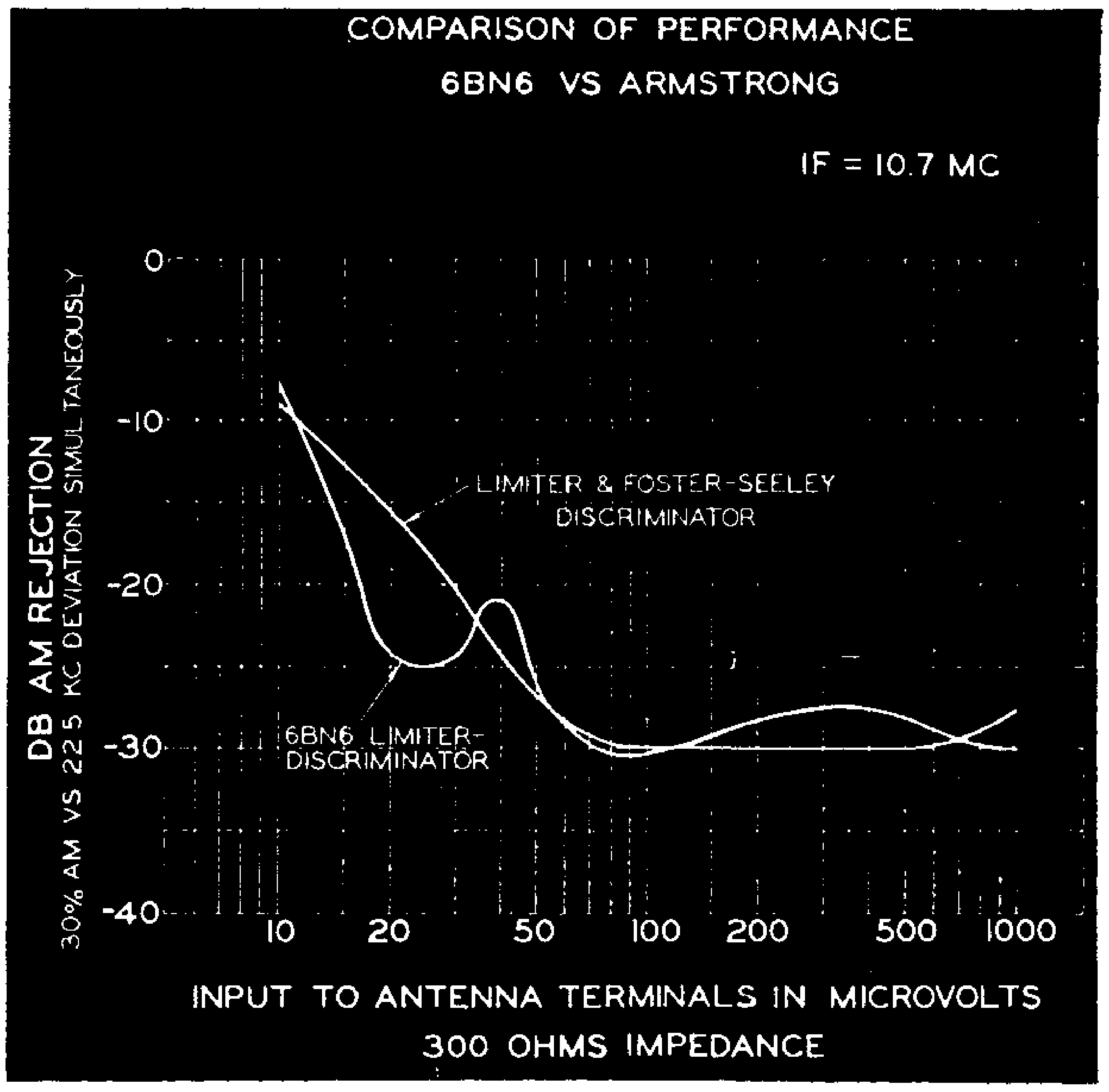


Fig. 10—AM rejection performance 6BN6 vs. Armstrong.

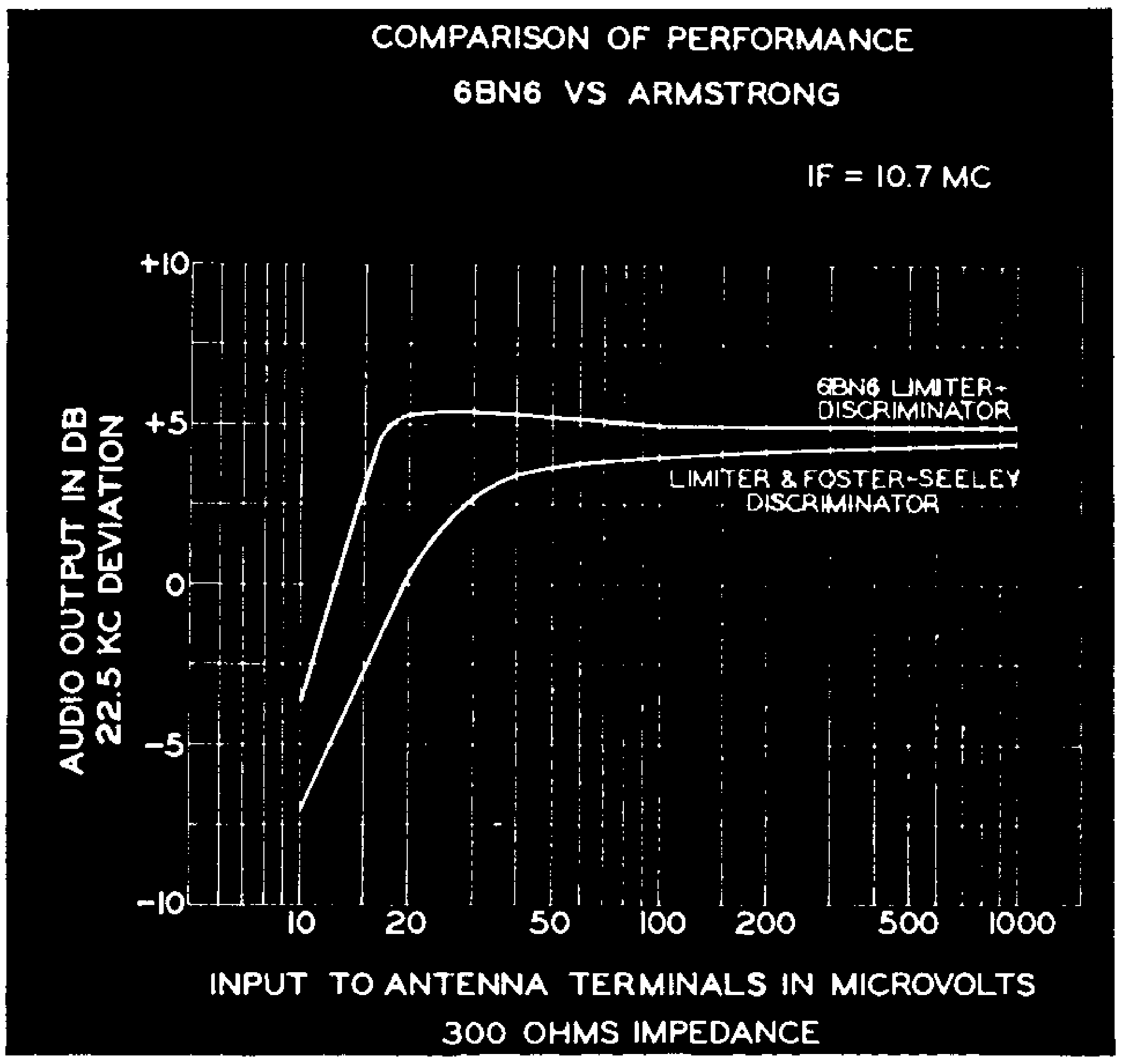


Fig. 11—Audio output performance 6BN6 vs. Armstrong.

The plate current vs. plate voltage family with the voltage of the No. 1 signal grid as parameter has a characteristic similar to that of a pentode and is quite usual in every respect. This curve is shown in Fig. 12, while Fig. 13 shows the same plate current—plate voltage family where the quadrature grid voltage is used as parameter.

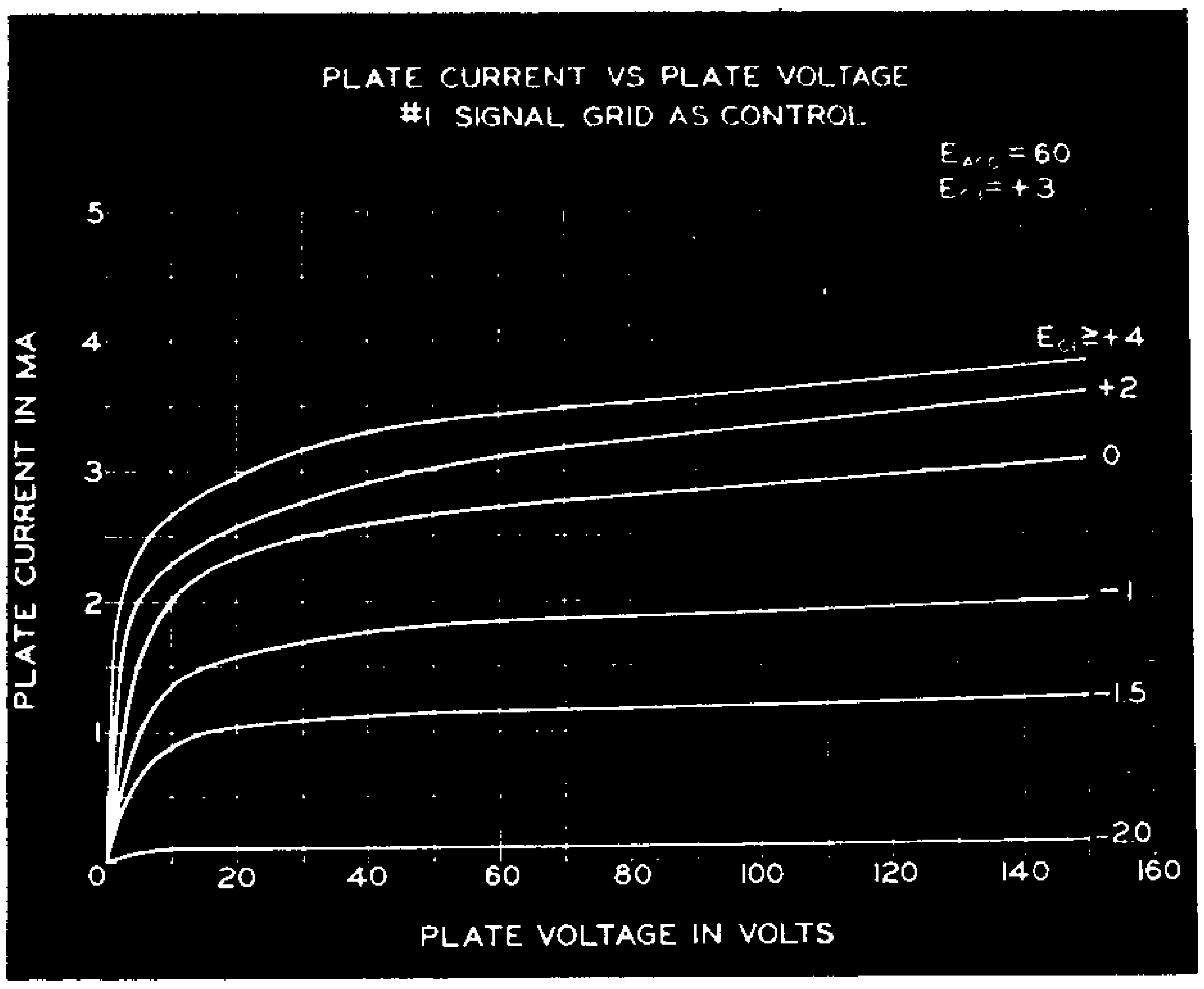


Fig. 12—Plate current vs. plate voltage No. 1 grid parameter.

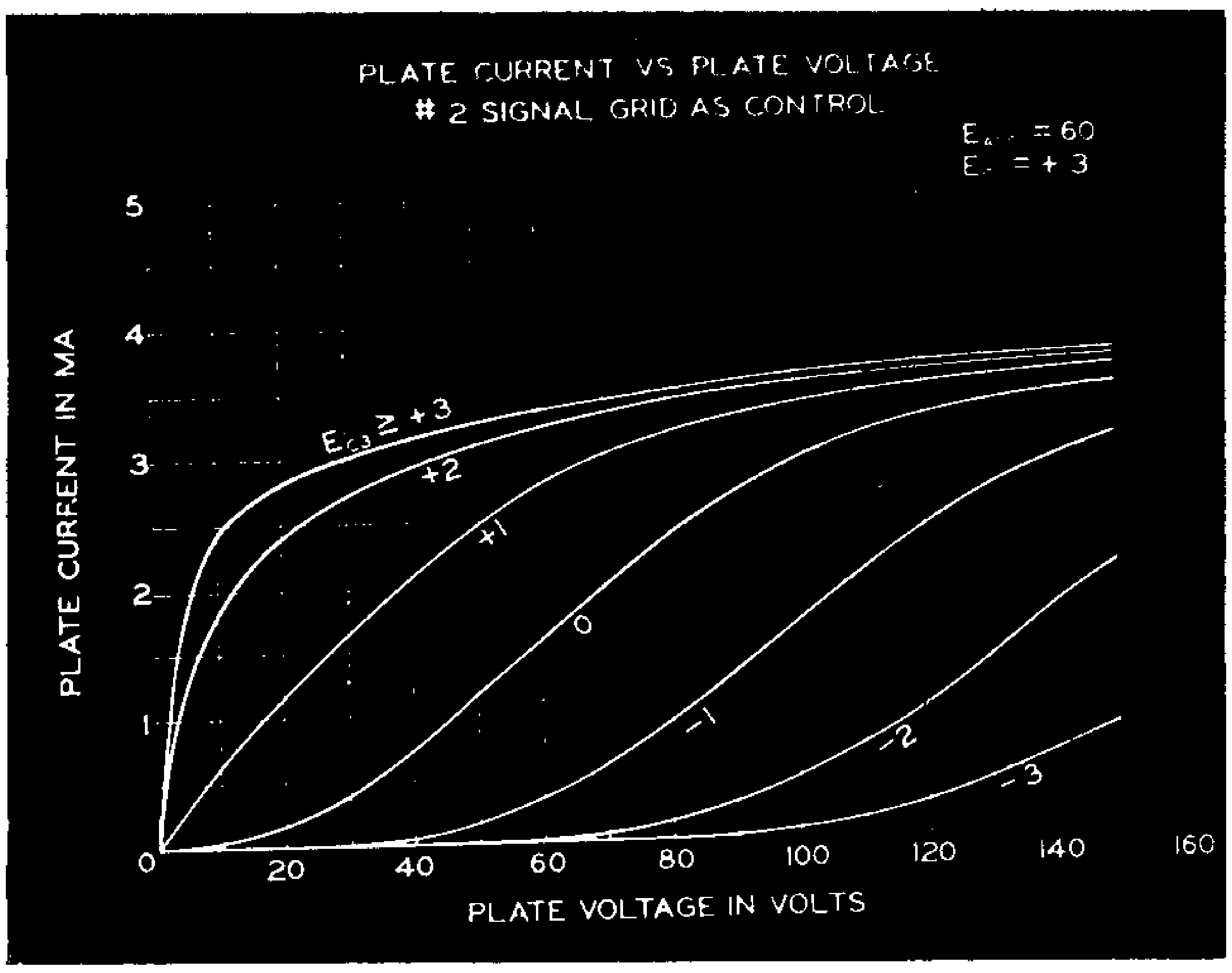


Fig. 13—Plate current vs. plate voltage No. 2 grid parameter.

In this instance, we have a very unique characteristic since the plate current is limited by the beam and the system utilizes an effective cathode whose density is determined to a large extent by the potential of the quadrature grid. When the quadrature grid is negative, the characteristic triode plate family is seen with a plate current limit due to beam limits. As the voltage on this grid is made positive, the characteristic shifts to become similar to that of a pentode. Considering these factors, we see that plate current is essentially independent of plate voltage in the case of the input grid and for the quadrature grid varies from a dependence upon plate voltage similar to a triode, to that of a pentode. By applying proper biases to the two signal grids in the limiter-discriminator circuit, it is possible to optimize a-m rejection and to obtain a ratio of plate current with signal to plate current with no signal to the input grid, which is very close to unity. This means that the over-all tuning characteristic of the f-m receiver using the 6BN6 limiter-discriminator would be characterized by a broad region of smooth tuning with noisy regions on either side due to slope detection in the i-f stages. This is a distinct advantage by comparison with the ratio detector and other systems in which the band-pass characteristic yields multiple tuning points for a single station. In this respect, the input signal level is not of great importance to the tuning characteristic since the discriminator output is very low in regions where slope detection in the i-f system occurs.

The objective of obtaining low input conductance with the input grid positive has been achieved quite well in the 6BN6 design. The limited input grid current is approximately 500 microamperes and the limited quadrature grid current is about 200 microamperes with both grids positive under static operating conditions.

VI. OTHER APPLICATIONS

The 6BN6 can, of course, be used as a plain limiter where it is desired to remove ignition or pulse-type noises from a-m signals or amplitude variations of any sort from f-m signals.

Since two step, function control characteristics are available, the tube would also find application wherever coincidence counting is desired and where such coincidence can be indicated in terms of several volts of signal.

A third application is that of a square wave generator where the input voltage may be of any frequency up to approximately 30 megacycles.

By using the two control grids, pulse-time modulation may be obtained directly from the output circuit of the 6BN6 stage.

A sync clipper circuit has been designed which, due to the limiting of grid current, yields a uniform sync pulse despite noise modulation of the incoming signal.

The 6BN6 has been used as an efficient speech amplifier-clipper for communications type audio equipment in which it is desired to maintain high modulation levels.

Considering power circuits, the 6BN6 finds application as a phase measuring device in such manner that power-factor can be metered directly or as a synchroscope type of instrument in which the relative phase angle and frequencies of alternators or alternator and line is indicated directly.

It has been found that the unique characteristic of the 6BN6 which allows generation of cathode bias sufficient to cut off plate current completely can be utilized to form a highly efficient frequency multiplier which requires little driving power and so makes possible high multiplication in cascade stages without generation of sidebands due to amplitude variation associated with conventional multipliers.

The 6BN6 has also been used in "flip-flop" circuits and as one-kick and free-running multivibrators.

Use of the tube as a self-contained oscillator to which load can be coupled either directly or through the electron stream where isolation is desired, should be possible due to its accelerator's negative transconductance. Since the output of such an oscillator can be controlled in both phase and amplitude by the quadrature grid and plate circuits, another variation of its limiter-discriminator application is that of obtaining phase modulated output from the plate circuit or obtaining four voltage vectors displaced 90° in phase from each other.

VII. CONCLUSIONS

The original objective of developing an improved limiter discriminator for f-m and television applications has been realized in the completion of the 6BN6 development. Many circuit components are eliminated completely and several are simplified to an extent. The alignment problem is simplified by the elimination of the discriminator transformer and, in the case of 4.5 mc operation, audio output voltage is sufficient to drive the power amplifier stage directly. All of these factors combine to make a very desirable performance to price balance for the manufacturer of electronic equipment. The research and development work which preceded the announcement of this type covered several years' time and has resulted in a tube which places a new tool in the hands of circuit designers. Vacuum tube characteristics which have never before been available to the industry are now a reality and should find widespread application not only in radio receiving and transmitting equipment but in industrial control circuits and laboratory instruments as well. Some of the applications mentioned have already been reduced to practice and many others should be possible.

ACKNOWLEDGMENTS

The author wishes to acknowledge the contributions of the Zenith Radio Corporation, and the assistance of Messrs. W. T. Millis, J. R. Somerville, and R. R. W. Lacy of the General Electric Company's Tube Division, and R. B. Dome of General Electric Company's Receiver Division in the design, development and testing of the tube described in this paper.