duce a magnetic field, for an electric current is merely charge in motion and it is well known that currents produce magnetic fields. Goudsmit and Uhlenbeck first recognized that an electron has its own intrinsic spin and associated magnetic field or, to be more exact, its own magnetic moment. An electron has a characteristic intrinsic angular momentum or *spin* with which there is associated a magnetic moment equal to $eh/4\pi mc$, where all the symbols have their usual values and m is the mass of the electron. If we regard the proton as a spinning sphere of positive electric charge which has a definite angular momentum, then the proton should likewise have a definite magnetic moment. In effect, a proton should exhibit the magnetic behavior characteristic of a small (infinitesimal) dipole. While this picture is helpful for an elementary discussion, it is not adequate for a thorough understanding of nuclear magnetism.

TABLE VI*

NUCLEAR SPINS IN UNITS OF $h/2\pi$, AND NUCLEAR MAGNETIC MOMENTS IN UNITS OF THE NUCLEAR MAGNETON, μ_0†

Nucleus	I	μ/μ_0	Nucleus	I	μ/μ_0
${}_0N^1$	1/2	−1.910	${}_4Be^9$	3/2	−1.176
${}_1H^1$	1/2	2.7896	${}_5B^{10}$	1	0.598
${}_1H^2$	1	0.8564	${}_5B^{11}$	3/2	2.687
${}_1H^3$	1/2	2.9756	${}_6C^{12}$	0	0
${}_2He^3$	1/2	−2.131	${}_6C^{13}$	1/2	0.701
${}_2He^4$	0	0	${}_7N^{14}$	1	0.403
${}_3Li^6$	1	0.8214	${}_7N^{15}$	1/2	0.280
${}_3Li^7$	3/2	3.2535	${}_8O^{6}$	0	0

* From E. M. Purcell, *Science*, vol. 107, p. 433, 1948. The value for ${}_2He^3$ is from H. L. Anderson and A. Novick, *Phys. Rev.*, vol. 73, p. 919, 1948.
† The sign of the magnetic moment refers to the polarity of the nuclear dipole with respect to the direction of the angular-momentum vector.

In general, the magnetic moments associated with nuclei are about one thousand times smaller than that of the electron, since the magnetic moment is inversely proportional to the mass of the particle. For example, the magnetic moment of the proton is measured in units of $eh/4\pi Mc$ where M is the mass of the proton; the later expression is usually called a *nuclear magneton* and is the unit for measuring nuclear magnetic moments. Both the nuclear spin (denoted by I) and the nuclear magnetic moment are properties which are uniquely characteristic of nuclei. The spin may assume either integral or half-integral values, as is illustrated in Table VI, wherein there appear the spins and magnetic moments of several light nuclei. Certain rules exist which prescribe the spin value for a given nucleus, but as yet no consistent theory predicts the value of the magnetic moment for nuclei. Our simple picture of spinning charge brings us to despair when we note that the neutron, an uncharged particle, has an associated magnetic moment.

Duplex Tetrode UHF Power Tubes*

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***Summary*—Major factors affecting the design and development of wide-band uhf power tubes are considered and emphasis is given to the television application. A qualitative discussion of methods for obtaining the required performance is presented, and a 5-kw 300-Mc liquid-cooled, internally neutralized duplex tetrode is described.**

INTRODUCTION

IN CONSIDERING the design and development of electron tubes suitable for use as grid-modulated television power amplifiers, there are certain performance characteristics that must be attained, and others that are highly desirable. The fixed tube-performance characteristics, such as bandwidth, power output, and carrier frequency, are determined by the standards adopted for television broadcasting, and must be accepted as minimum values in the design. When the other tube characteristics, grid currents, power gain, impedance presented to the modulator, efficiency, and feedback are considered, the desired values are not all attainable in a given design, and the best compromise is sought. Attempts to satisfy requirements of bandwidth, power gain, linearity, ease of modulation, and power output at the higher carrier frequencies can be resolved into a search for means of obtaining large cathode emission-current densities, large average anode-current densities, electrodes capable of handling large power dissipation per unit area of bombarded surface, small interelectrode spacings, small electron currents to the grids, and a tube geometry and circuit-wise arrangement of tube elements that will provide adequate utilization of the aforementioned.

Realizing that these requirements could not be adequately met if the limitations imposed by conventional tube design were assumed, Zworykin organized a laboratory group for research in high-power electron tubes in 1937. It was his continued interest and good counsel which made possible the development of a 50-kw tube which served as the background for the development of the smaller, higher-frequency power tube herein described.

Early in 1938 the senior author introduced a duplex tetrode with an electron-beam-forming electrode configuration and high-dissipation anodes. The initial tests

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were made in continuously pumped demountable metal envelopes. Sealed-off demountable tubes were made possible when fitted with a copper-gasket demountable seal introduced by Garner, a member of the group. Many laboratory tubes were built and tested before a tube capable of a 5-kw output at 300 Mc with a total output bandwidth of 10 Mc could be properly designed. This paper describes such a tube.

DESIGN CONSIDERATIONS

In arriving at a tube design, it is difficult to formulate a mathematical expression containing all of the factors affecting the design and to obtain the unique or the best solution. Tube design represents a compromise between conflicting factors which are individually studied to advantage, and which must be combined with care and ingenuity and with a view toward the circuit and application problems. A detailed analysis of the individual factors will not be attempted here, but only qualitative indications of the trends required for providing an improvement in the factors pertinent to the design of grid-controlled power tubes will be discussed.

The frequencies for the present commercial and experimental television channels are sufficiently high to make the electron-transit time between tube elements of importance. Many of the effects of long transit times are known, and have been observed in cathode back-bombardment, control-grid loading, and loss in efficiency and power output. Therefore, one of the present considerations is that of extending the usable frequency range of grid-controlled tubes by reducing the electron-transit time. Such a reduction in transit time is obtained by decreasing the interelectrode spacings and increasing the electron acceleration. Under conditions of space-charge-limited emission from the cathode, the increased electron acceleration is obtained only when increased cathode-current densities may be drawn. For example, the electron-transit time in a region between parallel-plane electrodes of large extent is proportional to the one-third power of the ratio of the electrode spacing to the current density when operated with space-charge-limited emission and assuming zero emission velocity. In grid-controlled high-frequency tubes, effective electrode spacings are obviously to be made as small as is practical without sacrificing mechanical rigidity of the electrode structure, and the longitudinal thermal conduction required for cooling. Large cathode-current densities are available from such surfaces as the thoria-on-tantalum cathode under steady-state conditions with a reasonable life. Since we are concerned with continuous operation, the large pulse emission-current densities from barium-strontium-oxide cathodes cannot be utilized.

An attempt to utilize large current densities increases the difficulty of providing an adequate control-electrode configuration, particularly for the high-frequency applications where close interelectrode spacings are of importance. Since grid control of the large-density electron emission is sought, it is evident that a beam-forming electrode arrangement can be used to advantage. A focusing electric field is provided in the region adjacent to the cathode surface by means of focusing elements electrically connected to the cathode, and projecting slightly beyond the cathode into the cathode-grid space. Many such focusing arrangements are possible and the details must be chosen to fit the method of construction and other tube parameters. A typical cathode and focusing-element arrangement is shown in Fig. 1.

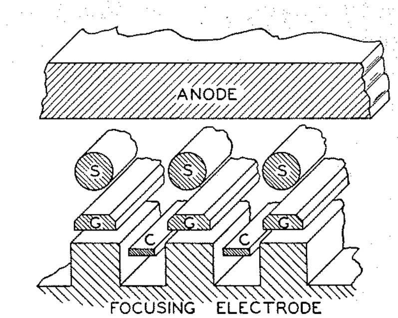

Fig. 1—A beam-forming electrode configuration. S=screen-grid element, G=control-grid element, C=electron-emitting filament.

Since the instantaneous voltages of the control grids and the anodes vary with respect to time, the electron beam focusing is not constant over the operating cycle. In a practical design, the electrode configuration and electric fields are so arranged that at the instant of maximum beam spreading the portions of the beam intercepted by the No. 1 and No. 2 grid elements are small enough to prevent excessive power dissipation at these elements. Also, the portion intercepted by the No. 1 grid should be sufficiently small to cause a negligible variation in the impedance presented to the rf driving stage and to the modulator over the modulation cycle. It is just this beam spreading and the possible formation of potential minima in the interelectrode regions that determines the values of applied voltages and the amplitude of the control-grid and anode rf voltages for a given structure. The electric fields must be sufficiently great at the maximum of the grid-voltage swing to support the large space-current densities and to maintain sufficiently narrow beams. Considerations of transit time and beam spreading determine the minimum gradients to be provided in the regions between the cathode and No. 1 grid, between the No. 1 grid and No. 2 grid, and between the No. 2 grid and the anode. Because of the gradients required in the latter region of a high-frequency power tetrode, the minimum of the instantaneous anode voltage of a high-frequency tetrode should be substantially above the screen-grid voltage to utilize in the best manner the current available in the plane of the No. 2 grid.

It is well recognized that the wide-band high-frequency power tube requires large power dissipation per unit area at the anode. In order that the greatest power and bandwidth be obtained from a tube with a given anode current, the ratio of the tube output capacitance to the anode current should be small and the anode power dissipation per unit area should be large. When sufficient anode dissipation is available, the maximum tube output load impedance is determined by the required bandwidth and the tube output capacitance plus whatever effective capacitance is added by the output circuit. It is assumed that the anode voltage can be increased to the required value without failure of the tube or circuit. This assumption is reasonable for total bandwidths of 10 Mc or more, but leads to excessively high voltages for bandwidths less than 1 Mc. When the allowable anode dissipation is too low, in a given tube, the tube must be operated with a reduced anode voltage, a reduced output load impedance, and consequently a reduced efficiency and power output. At this expense, an output circuit is obtained whose bandwidth is increased beyond that required.

The requirement of large anode dissipation per unit area of bombarded surface can be met by the use of high-velocity water in cooling channels formed in a copper or silver anode body. This construction increases the area of metal in contact with the water and reduces the tendency for diversion of the cooling water by steam bubbles. Such an anode structure is shown in Fig. 6. This structure permits anode dissipations of from 500 to 1000 watts per square cm averaged over the anode face. This is to be compared with an allowable dissipation of 50 to 100 watts per square cm in conventional structures.

With an electron-beam system such that but a small portion of the beam current is collected by the No. 1 grid and such that the electron-transit-time effects are small, a large power gain can be achieved if the circuit losses are low and if there is no feedback. Small amounts of feedback from the output circuit to the input circuit give rise to assymmetric distortion of the sidebands, while larger values of feedback will produce instability and oscillation. It is common practice to add a load to the input grid circuit to minimize the effects of the feedback, even though such loading decreases the power gain. The feedback can be made small by designing the tube such that the anode and output circuit are shielded from the input by special grids, as is done in the tetrode, and somewhat similarly in the grounded-grid triode; or a neutralizing circuit may be applied. In the design of grids, the requirements for obtaining good shielding conflict with those for obtaining the desired electronic performance, and a compromise is usually made. As a result, most tetrodes and grounded-grid triodes require some neutralization for wide-band amplification at a high frequency. The selectivity of the neutralizing circuits for such application introduces an added difficulty in obtaining wide-band amplification. The selectivity of the neutralizing circuits can be decreased by making their elements very short compared to a quarter wavelength at the operating frequency. In a duplex tetrode arranged for push-pull operation, such short neutralizing elements can be located internally. This is done in the described developmental tube.

In order that the circuit losses be kept to low values to increase the power gain and to prevent mechanical failure as a result of heating, it is desirable that metal-to-glass seals be used that have low I^2R losses in the metal member. Among the seals suitable for power-tube construction, two such types are well known. These are the feather-edge copper-to-glass Housekeeper seal and the silver-plated-chrome iron-to-glass seal. The Housekeeper seal has good electrical conductivity but lacks the mechanical strength and rigidity of the kovar seal, and because of its construction is difficulty to apply in some designs. The silver-plated-chrome iron-to-glass seals are made with *rf* induction heating and require carefully controlled heating conditions. These seals use a glass with a lower softening temperature than that of the kovar sealing glasses.

The kovar-to-glass seal is widely accepted and is satisfactory, except for its high electrical resistivity, which may become troublesome in some high-frequency tubes. During the work on the described tetrodes, methods have been developed for coating the kovar with a high-conductivity film and for sealing kovar matching glasses to this film. A coating of either copper, silver, gold, or chromium is electroplated to a thickness of several mils and is bonded to the kovar. Seals made to kovar coating in this manner have an electrical conductivity 10 to 20 times that of uncoated kovar at frequencies in excess of 50 Mc, and are particularly adaptable to the structures and requirements herein described.

In the design of a tube for application as a grid-modulated amplifier, a linear modulation characteristic is usually sought. While some curvature of the modulation characteristic is acceptable, it is important that the shape and slope of the characteristic be independent of the frequency and amplitude of the modulating voltage. Large variations in the required rf driving power with modulating voltage applied will make the modulation characteristic substantially dependent on the modulating frequency, unless the input grid circuit has a bandwidth equal to, or greater than, the tube output circuit. Such variations in the required grid driving power can be reduced by reducing the feedback, the electron current to the No. 1 grids, and the electron-transit times. These reductions will also act to make the impedance presented to the modulator more nearly constant over the modulating cycle.

The duplex tetrode tube arrangement was selected by the authors as lending itself to internal neutralization and being capable of providing an effective utilization of beam-forming electrode configurations, thoria-coated filaments, and large-dissipation anodes in a tube to be operated as a wide-band grid-modulated power amplifier in the present commercial television channels. In the duplex tetrode the two tetrode units can be placed in very close proximity and can use, in effect, common

screen-grid and cathode structures. The two screen grids are directly connected and by-passed to the cathode structure by low-impedance members, as in Fig. 4 and Fig. 5. The cathodes of the two tetrode units can be provided as the opposite legs of a "U"-shaped filament. These features permit the design of a high-gain wide-band grid-modulated high-frequency power tube that has exceptionally low feedback and good modulation characteristics.

Since a maximum of shielding is required between the input and output circuits, a metal envelope can be used to advantage to provide a convenient connection to external shielding in such a way as to make the envelope act as part of the shield. The metal envelope is also convenient when a demountable structure is desired. Two types of copper-gasketed compression joints are shown in Fig. 2. One of these uses a flat copper-ring gasket compressed between a flat and a curved surface, while the other uses two round wire rings clamped between two flat surfaces, the outer ring acting only as a support ring to prevent distortion of the clamping plates. Ground and polished clamping surfaces are used with annealed OFHC copper gaskets. These demountable joints may be baked to 450°C in the processing of the tube, and are regularly used in sealed-off tubes. The tube shown in Fig. 7 is constructed with a compression joint and metal envelope, and is operated as a sealed-off tube.

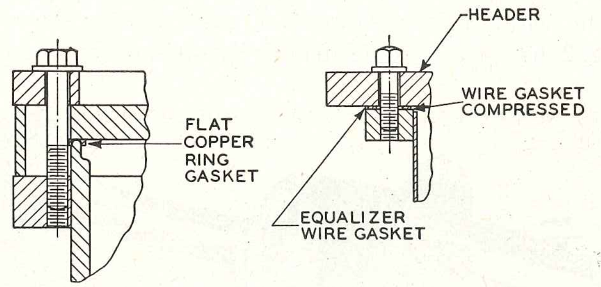

Fig. 2—Details of the copper-gasket vacuum seals.

The Duplex Tetrode

The tube described is a developmental liquid-cooled duplex tetrode arranged for push-pull operation as a grid-modulated television power amplifier, and is designed to give a power output, at the maximum of the synchronizing pulse, of 5 kw at 300 Mc, and a total output bandwidth of 16 Mc. Neutralization is provided by elements attached to the No. 1 grids and included within the vacuum envelope.

An electron-beam-forming electrode configuration is used with a thoria-coated "U"-shaped filament in the arrangement shown in Fig. 1. The opposite sides of the filament act as the cathodes for the two tetrode units. The construction of the cathode and focusing-electrode assembly is shown in Fig. 3. Each of the two focusing-electrode blocks is connected to the filament, and functions as the connection to the filament-heating supply. A mica sheet is used to insulate the two focusing-electrode blocks, which are supported and cooled by water-cooled blocks fixed to the header plate. Tantalum heat and emission shields are used, and are shown as part of the cathode assembly in Fig. 3. The electron-emitting surface of each of the two halves of the 8-strand filament is approximately 1.6 square cm in area. The filament strands are formed from tantalum sheet. A layer of thoria powder is sintered to the surface of the tantalum after the filament is formed. The filament operates at approximately 2000°K.

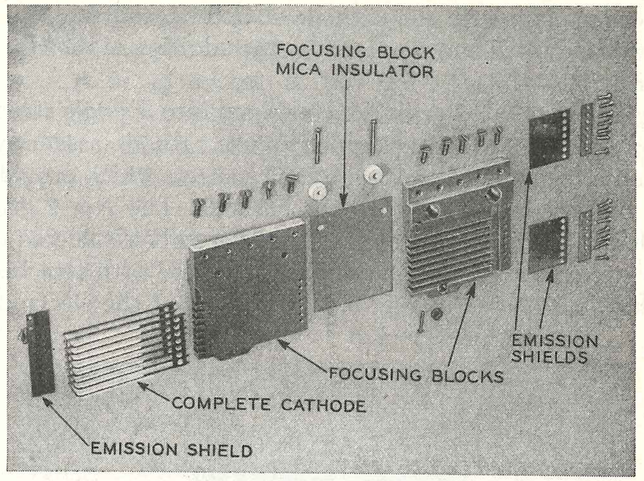

Fig. 3—The filament, filament shields, and focusing blocks.

The No. 1 grids consist of molybdenum bars silver-soldered to water-cooled tubes which also carry the neutralizing elements. These grids are supported by the glass of the metal-to-glass vacuum seal mounted in the header plates as shown in Fig. 4. This figure shows the

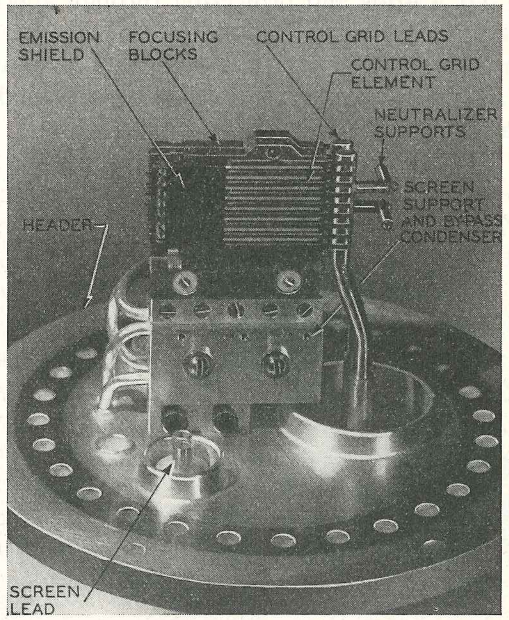

Fig. 4—The header with filament, filament shields, No. 2 mounting blocks, and No. 1 grids mounted.

header plate with the cathode structure, and the No. 1 grids mounted and prepared for the addition of the No. 2 grids.

The two No. 2 grids are combined into a single structure which is rigidly clamped to the cathode assembly, and is insulated therefrom by mica sheets which provide a by-pass capacitance to the cathode. The No. 2 grid elements are molybdenum rods and are silver-soldered to water-cooled copper plates. This structure with attached shields is shown in Fig. 5. The cooling of the electrode

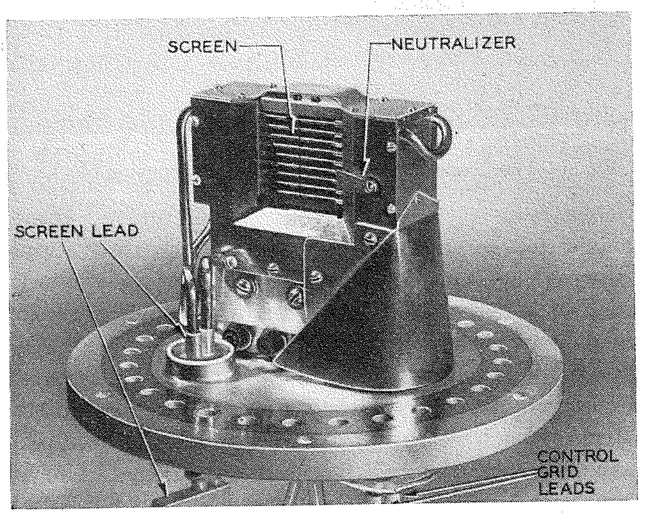

Fig. 5—A completed header assembly showing No. 2 grids and neutralizers mounted.

elements is obtained by thermal conduction along the length of the elements to the cooled supporting copper plates.

The complete header assembly containing all of the electrodes excepting the anodes is shown in Fig. 5. The neutralizing tabs are shown mounted on elements fixed to the No. 1 grids and projecting through apertures in the No. 2 grid blocks. This use of a header for mounting the close-spaced electrodes permits accurate electrode alignment and inspection before the anode dome is mounted.

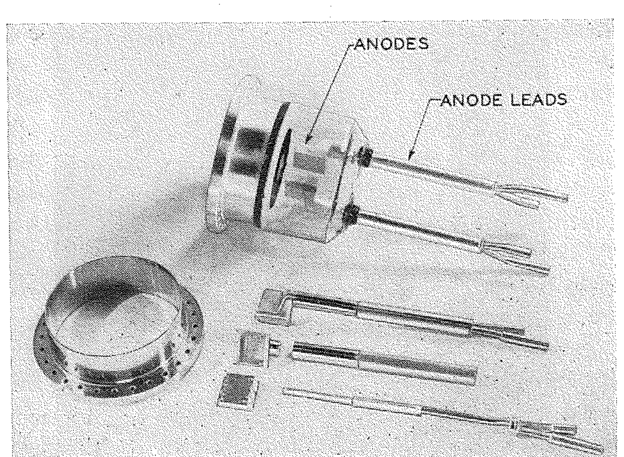

Fig. 6—The anode dome assembly, anode parts, and leads.

The anode dome and the details of the anode construction are shown in Fig. 6. The anode face has an area of 6.5 square cm., and is cooled by water circulated in the channels shown. Since the anode cooling water is carried by the anode supporting tube which functions as an element of the output tank circuit, the anode glass seals are water cooled. This cooling is adequate to permit the use of kovar at 300 Mc, if a high-conductivity coating is applied to kovar as previously described. With cooling water at a pressure of 60 pounds per square inch, these anodes have been operated without failure to a dissipation of 6 kw per anode.

The final step in assembly of this tube is the bolting of the anode dome to the header; this compresses the two copper-ring gaskets and provides the final vacuum closure of the envelope. The anodes, anode leads, and anode dome ring can be electroplated, cleaned, and washed before this operation, and are not subjected to any glass-working fires or other heating in making the final vacuum closure. The copper-ring gaskets are made from wire. This compression gasket seal, shown in Fig. 2, has proved to be an entirely satisfactory vacuum-

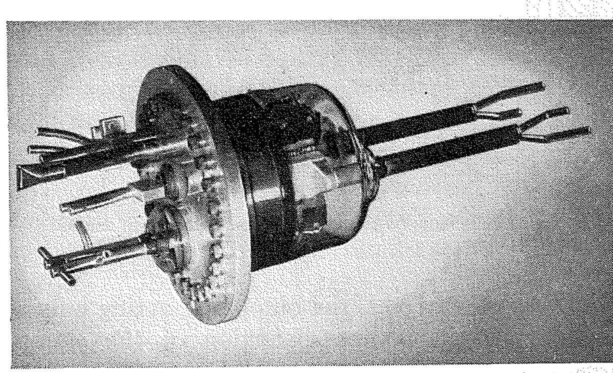

Fig. 7—The duplex tetrode.

Tube Data[1]

Direct interelectrode capacitance (each unit):

Grid No. 1 to anode	0.12 $\mu\mu$f
Input	24 $\mu\mu$f
Output	5 $\mu\mu$f
Grid No. 2 by-pass (approximate)	200 $\mu\mu$f
Grid No. 1 to anode feedback with neutralization	0.01 $\mu\mu$f

Filament—3.9 volts—105 amperes single phase

Electrode dissipation (maximum operating values):

Anodes	8 kilowatts total
No. 2 grids	400 watts total
No. 1 grids	50 watts total

Typical operating voltages:

Anode	5000–6000 volts dc
No. 2 grid	700 volts dc
No. 1 grid (cutoff bias)	—180 volts dc

Cooling water flow at 60 pounds per square inch pressure:

Anode of each unit	0.6 gallons per minute
Filament blocks in series	0.25 gallons per minute
No. 2 grid	0.3 gallons per minute
No. 1 grids in series	0.25 gallons per minute

[1] In the 8D21, or commercial model, some changes in these data were found necessary because of manufacturing techniques.

tight joint which can be used both in demountable and in sealed-off tubes.

A completely processed tube is shown in the operating position in Fig. 7. This position is determined by the filament, which must hang vertically to prevent distortion and sagging. The tube is supported by the header plate rim, which acts as a flange, and which when installed is bolted to the shield wall separating the input and output circuits.

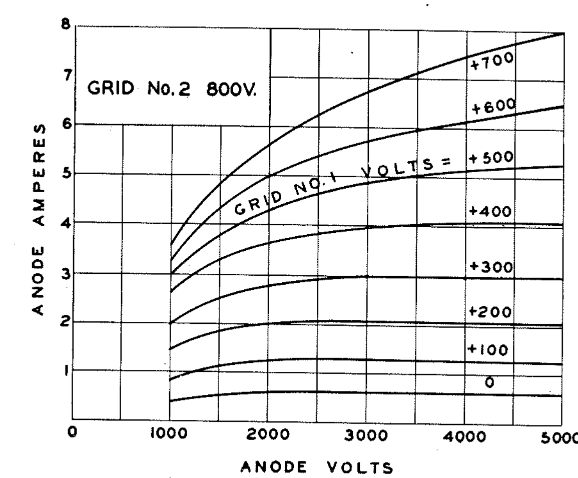

Fig. 8—Anode characteristics for each unit.

The static characteristics are given in Figs. 8, 9, and 10. A modulation characteristic, shown in Fig. 11, was obtained at 288 Mc with a total output bandwidth of 16 Mc. A maximum power output of 10 kw was obtained at an efficiency of 60 per cent. The instantaneous bias at this point was 100 volts positive with respect to

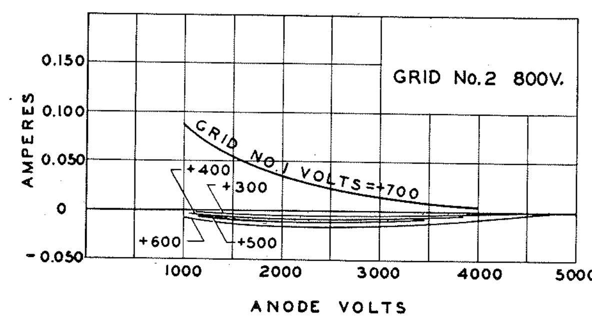

Fig. 9—No. 1 grid characteristics for each unit.

the cathode. In the television application the bias at the maximum of the synchronizing pulse may be reduced to zero or made positive to reduce the amplitude of the rf grid driving voltage. This does not substantially change the required modulating voltage.

Under power output and bandwidth conditions as given above, a power gain at maximum power output of 25 to 30 is obtained. The driving power in these tests was approximately 350 watts. When the tube is used as a 5-kw amplifier with a bandwidth less than 1 Mc, power gains in excess of 100 are obtainable. These power gains for either application are not obtainable at 300 Mc, unless low-loss grid seals such as described in this paper are used.

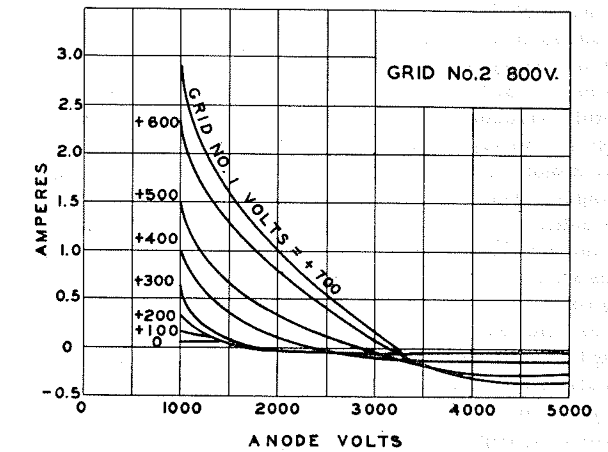

Fig. 10—No. 2 grid characteristics for each unit.

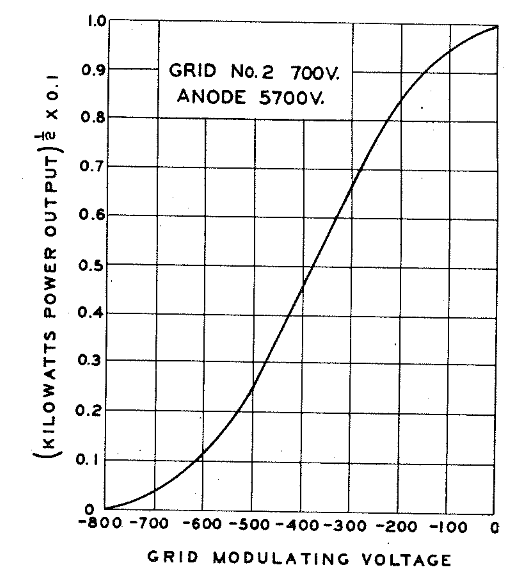

Fig. 11—Modulation characteristic.

Acknowledgment

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