RECENT DEVELOPMENTS IN MINIATURE TUBES*†

By

BERNARD SALZBERG AND D. G. BURNSIDE

RCA Radiotron Division, RCA Manufacturing Company,
Harrison, N. J.

Summary—The development of two indirectly heated miniature tubes, a triode and a sharp cut-off amplifier pentode especially suited for use at high frequencies, is described. The electrical and mechanical factors involved in the design and application of these tubes are discussed and their novel structural appearance is described.

Because of their decreased lead impedances, interelectrode capacitances, and transit times, these miniature tubes allow considerable improvement to be made in high-frequency receiving equipment. It is possible to operate the triode as an oscillator in a conventional circuit down to a wavelength of approximately 40 centimeters. The pentode can be operated as a radio-frequency amplifier down to a wavelength of approximately 70 centimeteres. It is practicable to obtain stable gains with it of from ten to fifteen at three meters, a wavelength at which standard tubes are almost entirely ineffectual. Both tubes can be used, down to much lower wavelengths, in exactly the same manner and for the same applications that the corresponding conventional tubes are used; i.e., as oscillators, amplifiers, detectors, converters, and as negative-resistance devices.

The small size of the tubes and their novel structural design allow compact and convenient receiving equipment to be built. Even at the longer wavelengths, they are applicable to a large number of uses for which their excellent characteristics, small size, and low weight make them particularly useful.

INTRODUCTION

EARLY work on the extension of the high-frequency limit of receiving equipment, which made use of conventional radio-frequency amplifier circuits built up around standard tubes, indicated that the amplifier section of the receiver became less and less effective as the signal frequency was increased and that ultimately, at frequencies of the order of one hundred megacycles, the amplifier was virtually useless. Similarly, the detector section and the oscillator section (when one was employed) of the receiver became more and more ineffectual as the frequency was raised and although they continued to operate beyond the limiting frequency of the amplifier, they too ultimately became inoperative. Improvements in the circuits proper resulted in only relatively slight improvements in the over-all performance of the receiver, so that it became apparent that the tubes themselves limited the operation of the equipment.

Recourse was then possible only to positive-grid operation of the available tubes, either in the oscillating state (Barkhausen-Kurz or

---

Gill-Morrell), or in the nonoscillating state (Hollmann or Carrara). These methods were not entirely satisfactory, however. With them, no cascaded amplification was obtainable at the carrier frequency, operation was invariably attended by high internal tube noise, over-all sensitivity was poor, careful adjustments were required, and the equipment was generally unreliable, at least for anything more than experimental use.

B. J. Thompson realized that the limitations of the conventional tubes were the result of their size. G. M. Rose, Jr. and he built small tubes and with them conclusively demonstrated that the limitations to the successful operation of vacuum tubes at the higher frequencies may be overcome by reducing the dimensions of the tubes.[1,2]

The possibilities of such tubes aroused an interest sufficiently widespread to warrant further development, and the "acorn" tubes are the present results of this development work.[3]

Factors Involved in the Design of Miniature Tubes

The essential principle upon which these tubes are based is the Model Theorem, or the Principle of Similitude. It is possible to show from the fundamental differential equations and the boundary conditions involved that if all of the linear dimensions of a tube structure are divided by a constant factor, say n, then the electrode currents, transconductance, amplification factors, and plate resistance will remain substantially constant, but the lead inductances and capacitances, the tube capacitances, and the time of passage of the electrons between the various electrodes will be divided by n. The direct-current lead resistances will be multiplied by n, but the alternating-current lead resistances will ordinarily be increased by something less than this factor. The allowable plate dissipation and the available emission of the tube, however, will be divided by n^2, and the current densities will be multiplied by n^2. The latter considerations are important in any application of this principle to power amplifier or transmitter tubes. Physically, the tube will be reduced in its over-all dimensions by a factor n, and its weight by a factor n^3.

For mechanical reasons, however, it is not feasible to reduce all of of the tube dimensions to the same degree. For example, a reduction by a factor of four of all of the linear dimensions of the type 56 tube would require grid side rods of $6\frac{1}{4}$ mils diameter, grid wire of 0.83 mil

[1] B. J. Thompson, "Tubes to fit the wavelength," *Electronics*, August,(1933).

[2] B. J. Thompson and G. M. Rose, Jr. "Vacuum tubes of small dimensions for use at extremely high frequencies," Proc. I.R.E., vol. 21, pp. 1707–1721; December, (1933).

[3] Bernard Salzberg, "Design and use of 'acorn' tubes for ultra-high frequencies," *Electronics*, September, (1934).

diameter, a cathode sleeve of 12½ mils diameter, and a cathode coating of approximately 0.75 mil thickness. Parts of such minute dimensions would be extremely difficult to manufacture with present-day equipment. Consequently, as is usual in many engineering problems, it is necessary to arrive at a practical solution which will give the essential results.

In addition to the limitations imposed upon design by consideration of the internal structure, a number of electrical requirements must be considered in the design of such miniature tubes. For example, the tubes should not only be suitable for high-frequency work, but because their reduced size and weight are frequently advantageous at lower frequencies, it is desirable that they be suitable for practically any use to which the standard tubes can be put. They should be adaptable to either battery or alternating-current operation, and should require a minimum of heater power. Their electrode voltage and current ratings should be such as to fit, in so far as possible, existing auxiliary circuit equipment. A reasonable life expectation and good stability of characteristics during life are also essential requirements. As regards external structure, it is imperative that the basing designs be such as to permit the aging and testing operations incidental to the manufacture of the tubes to be carried out conveniently, and to allow easy insertion of the tube in circuit equipment without introducing undue losses. The lead terminals should be placed so that they permit short connections between the tubes and the associated circuits. Finally, it is desirable that the tube designs be suitable for economical production maintainable within reasonably close electrical limits.

Considerations such as these circumscribe the design of the tubes. Their static characteristics must be set by a study of the various uses to which the tubes might be put and by a careful weighing of their relative importance. For the triode, such considerations indicated the desirability of obtaining a plate resistance of the order of ten to fifteen kilohms and an amplification factor above fifteen, together with a ratio of grid-plate transconductance to plate current as high as possible. For the sharp cut-off pentode, it was desirable to obtain under amplifier operating conditions a plate resistance of over one megohm and a transconductance of at least 1000 micromhos.

To effect a significant improvement in high-frequency behavior, and yet have tubes which could be manufactured, it was decided to reduce the electrode spacings to minimum distances of the order of five mils. This reduction would extend the upper frequency limit of operation beyond that of existing commercial tubes by a factor of approximately four, and at the same time would keep the design of the tubes within the realm of attainable manufacturing technique.

To make the tubes suitable for general battery and alternating-current use, the heater voltage was set at 6.3 volts. It was decided to use a conventional cylindrical cathode of the smallest practical diameter in order to realize the minimum heater power. Its length was so chosen that the desired static characteristics could be obtained with low interelectrode capacitances. Maximum plate voltages of 180 volts for the triode and 250 volts for the pentode were chosen as consistent with the requirements of low transit time and good life performance.

To obtain short leads, low losses, suitable means for effective bypassing at the higher frequencies, and a practical form of base, it was necessary to abandon the conventional form of pinch stem and standard base assembly. Instead, the tube elements were connected to heavy leads suitably positioned and fastened to mica spacers; these leads were then sealed in and used as base pins.

Except for transit-time considerations, the actual calculations involved in the design of these tubes are similar in all respects to the usual tube structure calculations. These are of a semiempirical nature, based in part upon known derivations of the space-charge-limited current between the elements of diodes of simple geometrical shape, and in part upon approximate analyses of the electrical field of tubes of ideal configurations.[4,5,6,7] As regards the transit time between the various electrodes, it is important for our purposes to keep the distances traversed by the electrons as short as possible, and to get them moving as fast as possible (by making the effective potentials in the planes of the various electrodes as high as possible)

DESCRIPTION OF THE TUBES

The tubes are shown in Fig. 1, and their size can be judged from the size of the golf ball which is included in this group photograph. The remarkable resemblance of the triode to an acorn, both in size and shape, has resulted in the trade designation for these tubes as the "acorn" series. One of the practical difficulties which arose as a result of the small size of the tubes was the difficulty of etching the usual trade name and type number on the bulb.

[4] I. Langmuir and K. T. Compton, "Electrical discharges in gases. Part II, Fundamental phenomena in electrical discharges," *Rev. Mod. Phys.*, vol. 3, p. 191; April, (1931).

[5] F. B. Vogdes and F. R. Elder, "Formulas for the amplification constant for three-element tubes in which the diameter of grid wires is large compared to the spacing," *Phys. Rev.*, vol. 24, p. 683, (1924).

[6] Bernard Salzberg, "Application of conformal transformation to some problems in vacuum tube engineering," Thesis for M.E.E. degree, Polytechnic Institute of Brooklyn, 1933.

[7] S. Koizumi, "On the amplification constants of multi-electrode tubes," *Jour. I. E. E.* (Japan), Abstracts, vol. 10, p. 18, (1934).

The internal structures of the tubes are shown in Figs. 2 and 3. Both tubes are provided with a cylindrical cathode, inside of which is inserted a folded type of insulated heater. Fig. 4 illustrates the relative dimensions of this heater-cathode assembly and a common variety of pin. This gives some idea of the size of the parts and the precision and care required in the fabrication of such tubes. The No. 1 grids are elliptical in order to reduce the otherwise severe control effects of the side rods. The suppressor grid of the pentode is particularly useful in reducing the reaction between control grid and plate. The various elements are spaced very closely along the minor axis of the grids— where the cathode emission is most useful—in order to reduce the
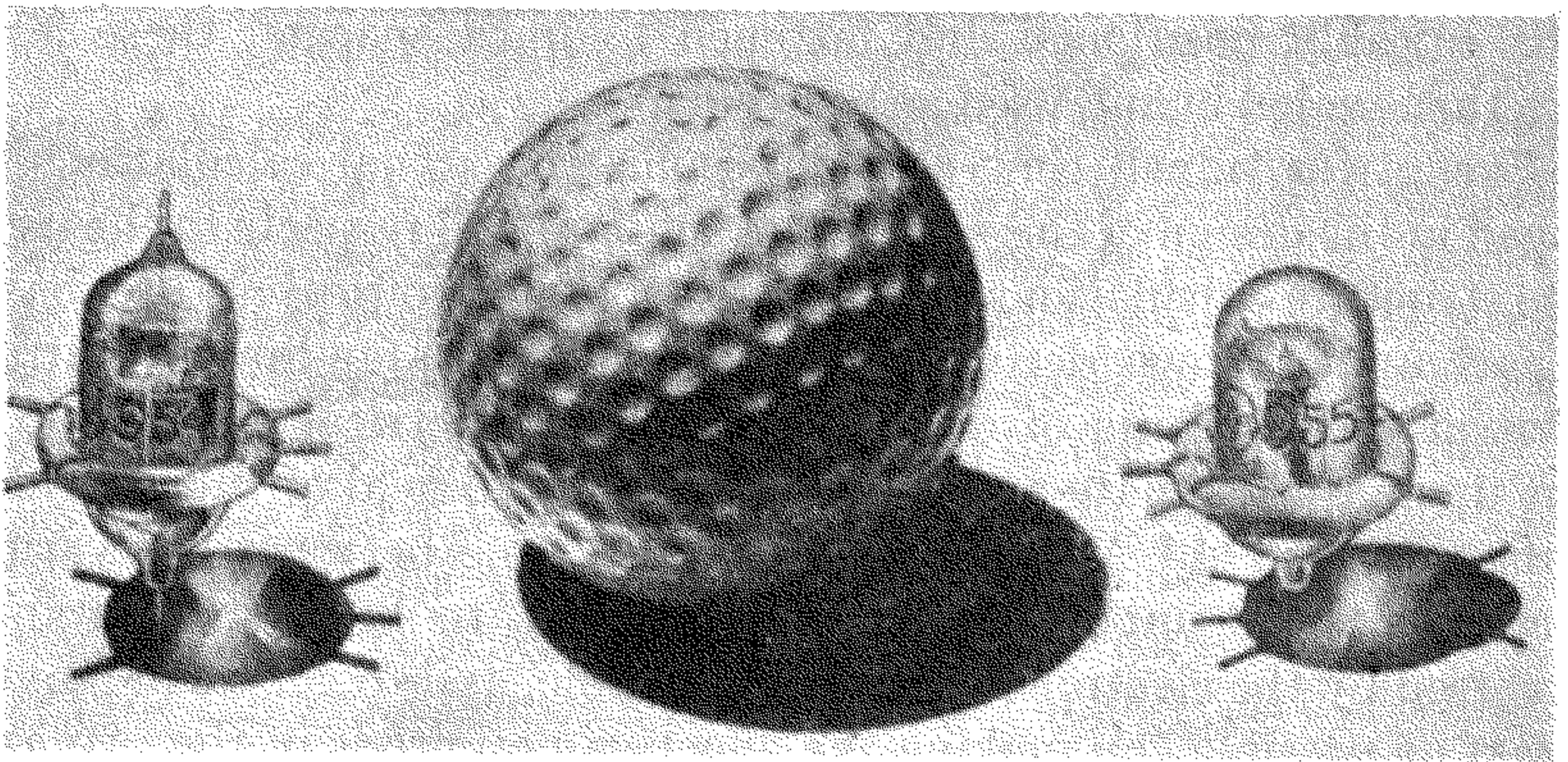
Fig. 1—Miniature triode and pentode compared with golf ball.

transit time and increase the transconductance, and somewhat less closely along the major axis in order to decrease the capacitances and increase the structural strength.

In both tubes, two accurately punched mica spacers serve to hold the elements in position. In the triode, the whole assembly is fastened in place by means of small lugs which are bent out from the ends of the plate. In the pentode, an additional mica spacer is used to insulate the plate lugs from the shielding structure, the latter being held in place by means of two support rods. In both tubes, one of the mica spacers is used as a sort of a stem, the heavy base pins and the lighter leads to the electrodes being fastened around its periphery. The "getter" material is enclosed within a flat tab welded, in the triode, to one of the plate lugs, and in the pentode, to the shielding structure.

The mount, in each case, is placed within a bulb which consists initially of two cup-shaped heavy preformed glass sections, the shallower one of which has an exhaust pipe attached to it. The main seal,
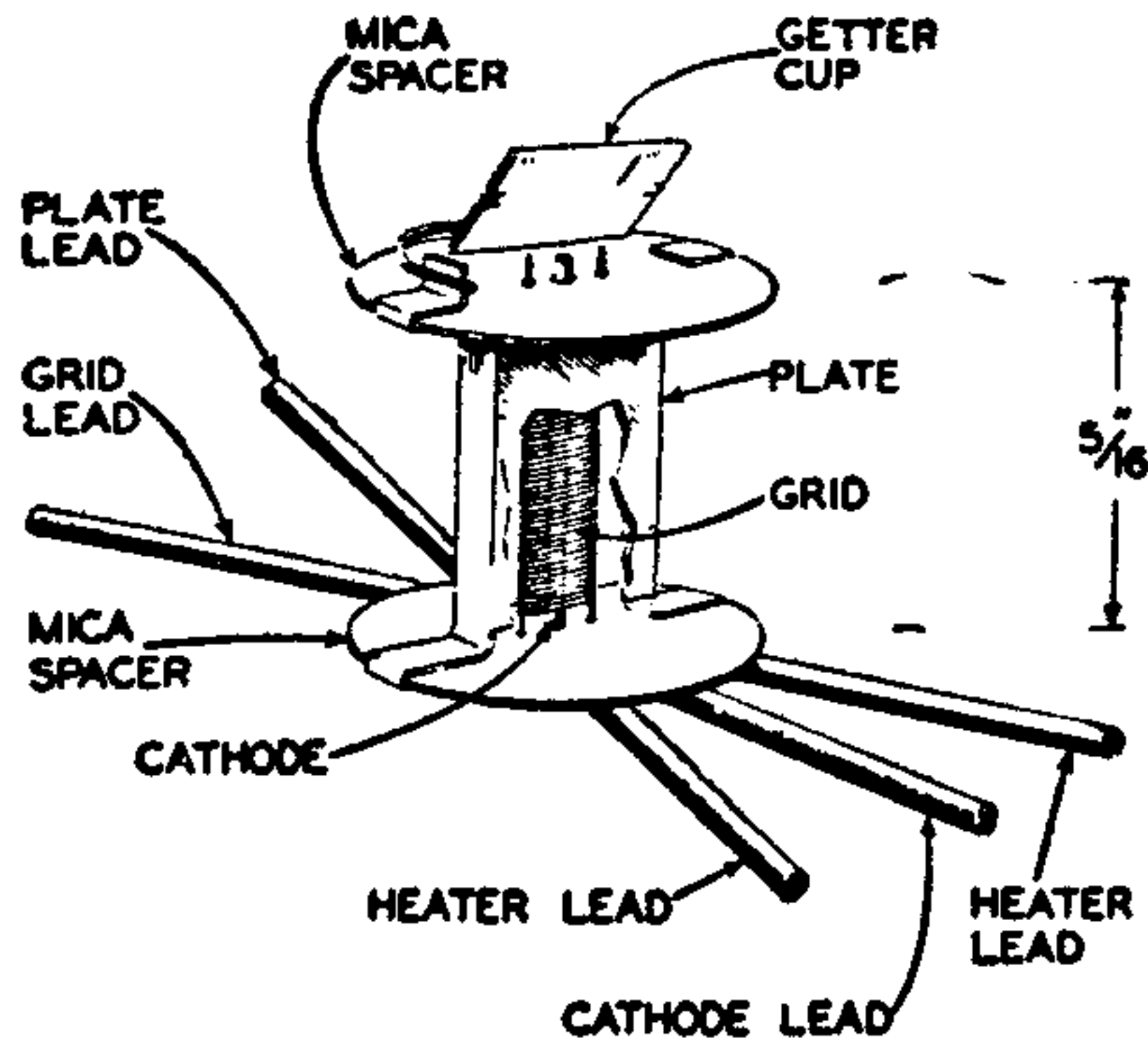
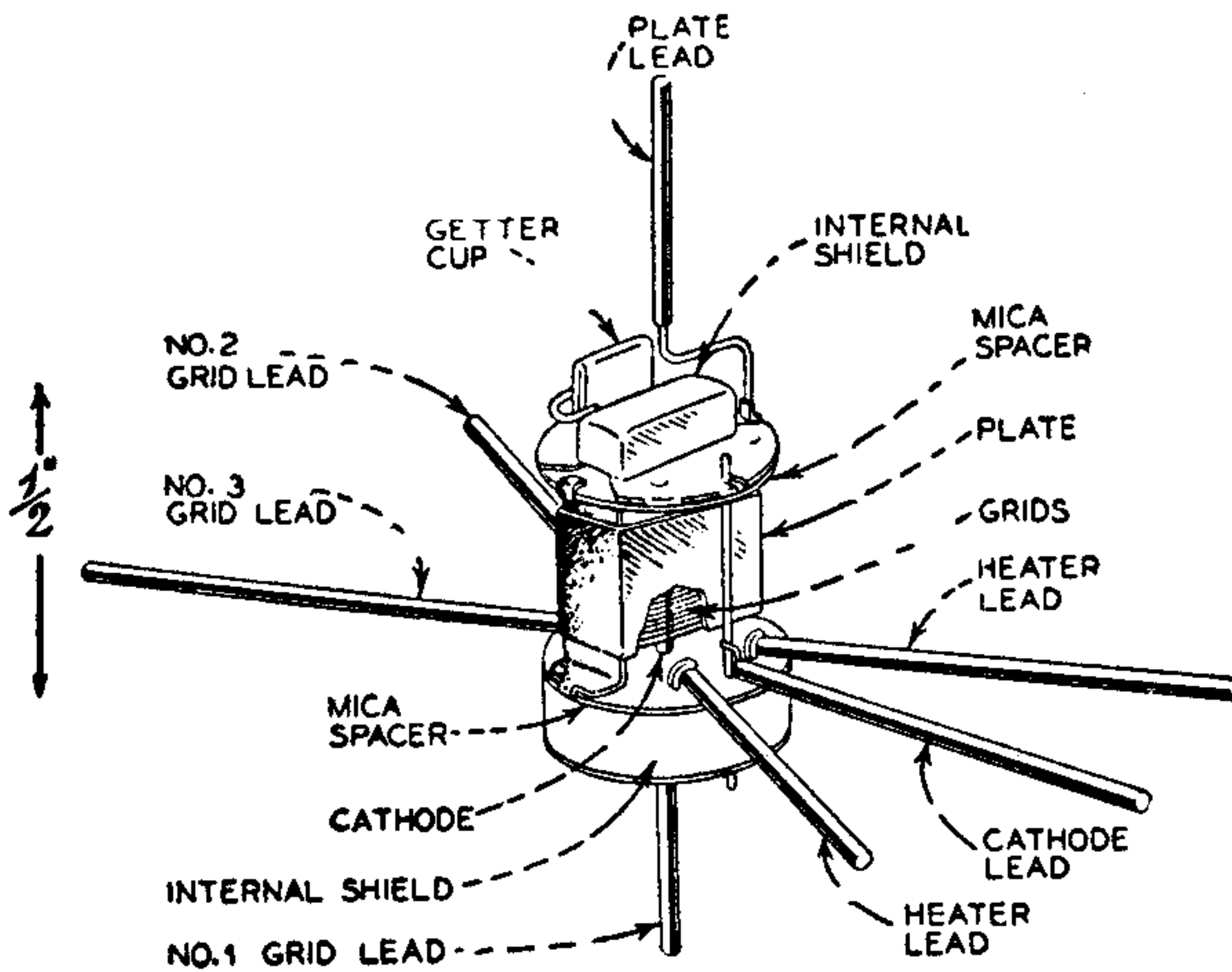Fig. 2—Internal Structure of the triode.

Fig. 3—Internal structure of the pentode.

COMMON PIN

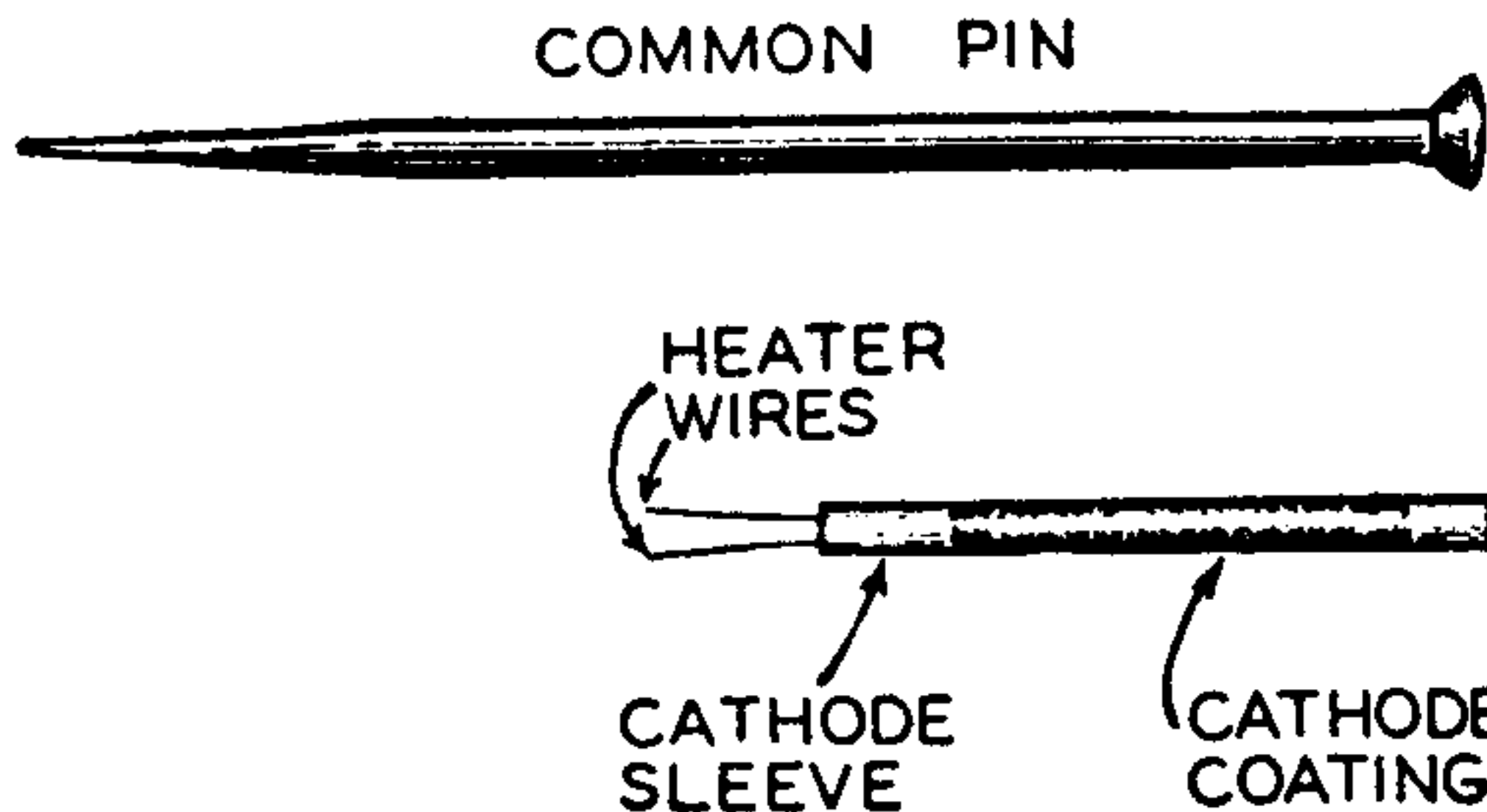HEATER WIRES

CATHODE SLEEVE   CATHODE COATING

Fig. 4—Comparison of heater cathode assembly and an ordinary pin.

and in the case of the triode the only seal, is of the joined-flare type, made at the plane of the tube leads between the two glass sections. After the sealing-in operation, these leads are cut quite short, the com-

bination of the heavy glass of the joined-flare seal and the stub pins constituting a practical and extremely sturdy base. This arrangement obviates the need for soldering the tube to the circuit elements and also avoids the deleterious effects of the conventional base. The leads themselves are radial, the two heater leads being symmetrically placed 30 degrees on either side of the cathode lead, the grid and plate leads (in the triode), 60 degrees apart on the same diameter as the heater leads. In the pentode, the latter two leads are replaced by the numbers 3 and 2 grid leads, respectively, and the plate and control-grid leads are brought out at opposite ends of the bulb, a very convenient circuit arrangement. These lead arrangements provide the necessary separation between the active radio-frequency leads and the grounded radio-frequency leads. In the pentode, the control-grid lead is brought out through the exhaust pipe, an innovation in tube manufacture: incidentally, the resultant tube is thus a very special form of the "tipless" variety. The getter flash in this tube is of the directed beam type, necessary because of the small size of the structure in order to avoid leakage between elements. The inside surface of the pentode bulb is coated with carbon to reduce the emission of secondary electrons which results from the bombardment of this surface by primary electrons which escape through the interstices between the mica spacer and plate. This is particularly important at the lower frequencies, where it is desirable to keep the high load impedances from being shunted by the additional plate losses introduced by such effects.

Characteristics of the Tubes

I. Static and Low-Frequency Characteristics

The heaters of both tubes are rated at 6.3 volts, making them suitable for both battery and alternating-current operation. The tubes themselves were designed so that the electrode voltages could be set at "preferred" values.

A typical plate family for the triode is shown in Fig. 5. Because of the reduced allowable plate dissipation, such miniature tubes are not especially suited for use as audio power amplifiers. Within maximum ratings, however, this tube is entirely suitable for audio-frequency amplifier and high-frequency oscillator uses. Operated as a class A audio amplifier with a load of approximately 19,000 ohms, the triode delivers an undistorted power output of 130 milliwatts. Table I shows the comparative characteristics of the miniature triode and a standard triode, type 76. It will be observed that at the same electrode voltages, not only is the miniature triode not *inferior* to the conventional tube,

but it is actually *superior* to it. One point not specifically tabulated is the electron grid current which flows from the grid due to thermionic emission. This is negligible, even with abnormal heater voltages, due to a combination of methods which reduce the temperature of the grid and otherwise reduce the tendency of the grid to emit. The lower
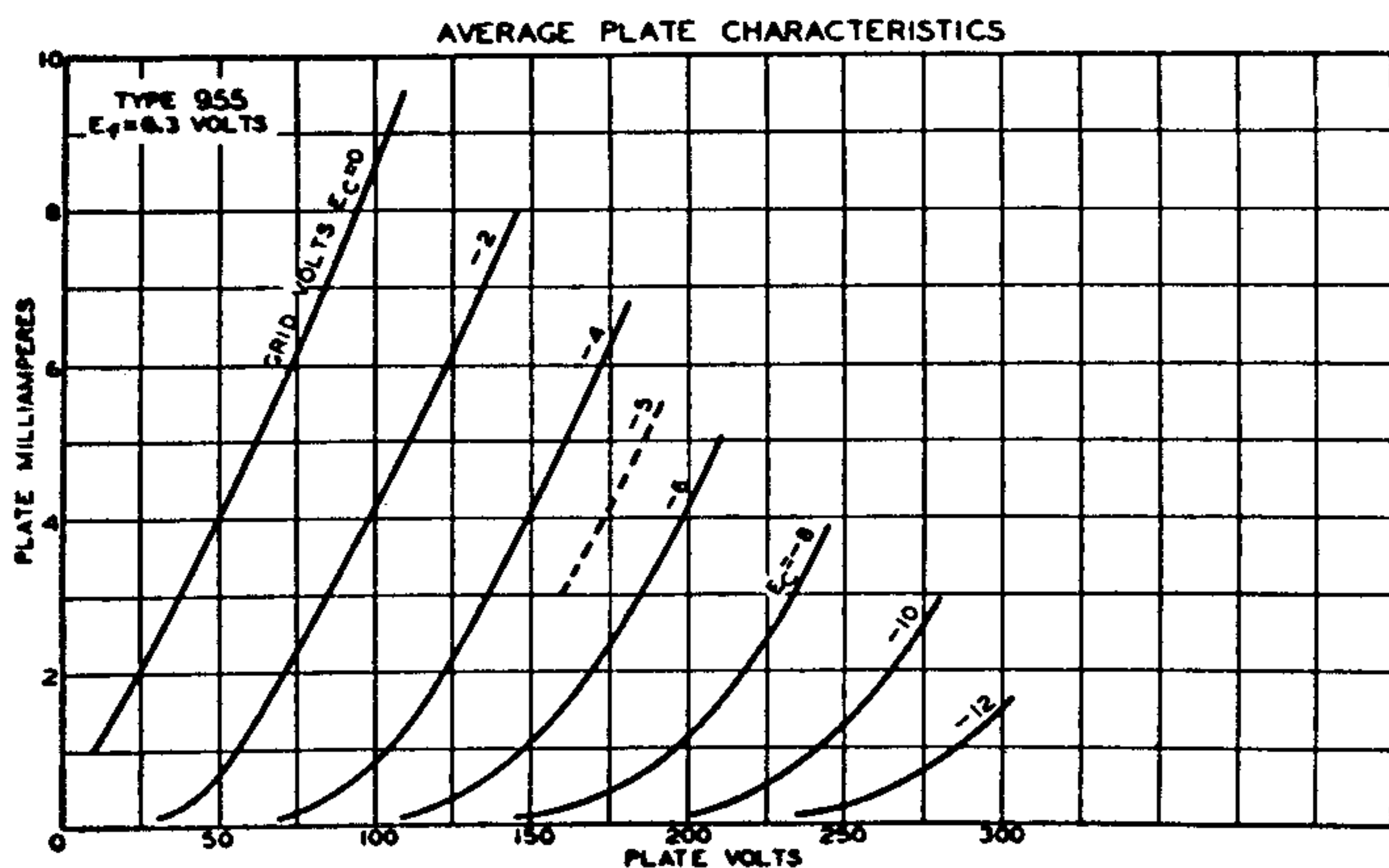

Fig. 5—A typical plate family for the triode.

capacitances of the miniature tube are very desirable at the lower frequencies, as well as the higher frequencies, because they allow higher gain over wider frequency spans. Laboratory tests of tubes of this type made up to the present writing have indicated over 1000 hours of continuous and useful life.

TABLE I
COMPARATIVE CHARACTERISTICS

	RCA-76 Conventional Triode	RCA-955 Acorn Triode	
Heater Voltage	6.3	6.3	volts
Heater Current	0.30	0.15	amp
Plate Voltage	180	180	volts
Grid Voltage	−9.8	−5.0	volts
Plate Current	3.2	4.5	ma
Amplification Factor	13.8	25	
Plate Resistance	11200	12500	ohms
Grid-Plate Transconductance	1200	2000	μmhos
Input Capacitance	3.5	1.0	$\mu\mu$f
Output Capacitance	2.5	0.6	$\mu\mu$f
Grid-Plate Capacitance	2.8	1.4	$\mu\mu$f

Figs. 6 and 7 illustrate typical plate and transfer families, respectively, for the miniature pentode. It will be observed that these static characteristics are similar to the usual characteristics obtained with conventional tubes of this type; i.e., high grid-plate transconductance,
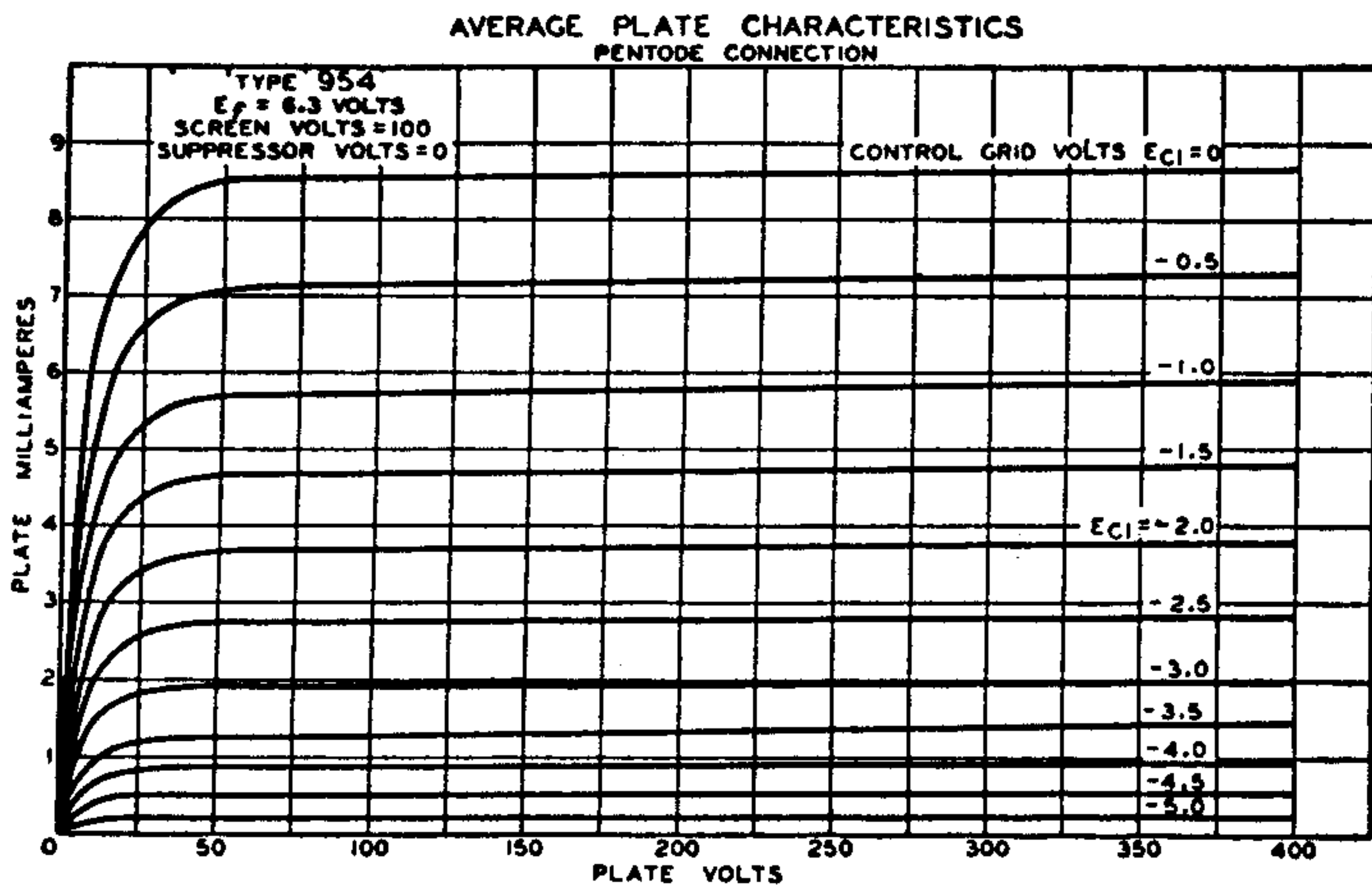
AVERAGE PLATE CHARACTERISTICS
PENTODE CONNECTION

Fig. 6—A typical plate family for the pentode.

AVERAGE CHARACTERISTICS
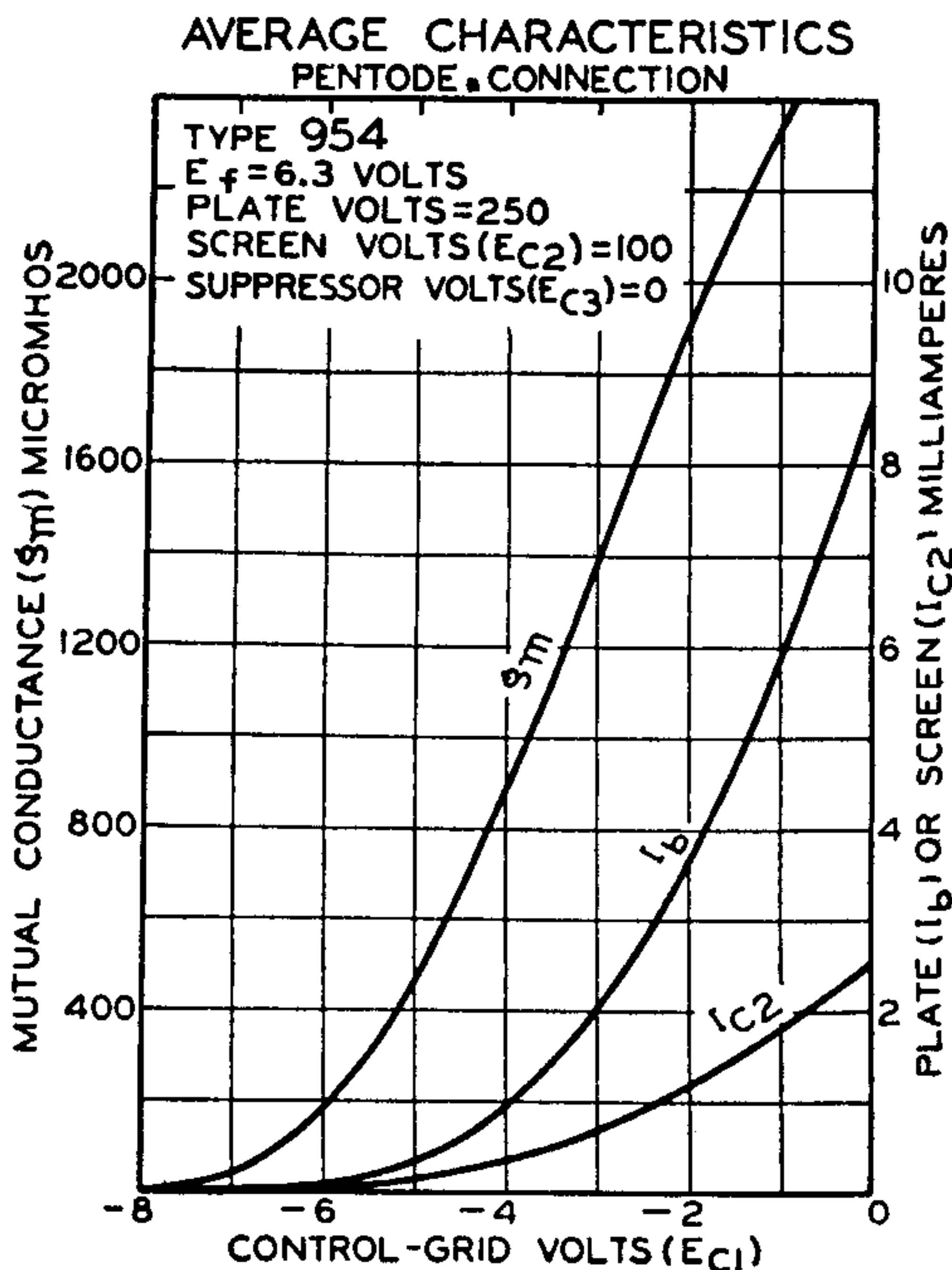PENTODE CONNECTION

Fig. 7—A typical control-grid plate transfer family for the pentode.

high plate resistance, and sharp cutoff. Table II shows the compara-
tive characteristics of the miniature pentode and a standard pentode,
type 6C6. It will be observed, once more, that at the same electrode

voltages, the miniature pentode is actually superior to the conventional pentode, even on a strictly static comparison basis.

TABLE II

COMPARATIVE CHARACTERISTICS

	RCA-6C6 Conventional Pentode	954 Acorn Pentode	
Heater Voltage	6.3	6.3	volts
Heater Current	0.30	0.15	amp
Plate Voltage	250	250	volts
Screen Voltage	100	100	volts
Suppressor Voltage	0	0	volts
Control-Grid Voltage	−3.0	−3.0	volts
Plate Current	2.1	2.0	ma
Plate Resistance	1.5	1.5	megohms
Control-Grid—Plate Transconductance	1225	1400	μmhos
Input Capacitance	5.0	3.0	$\mu\mu$f
Output Capacitance	6.5	3.0	$\mu\mu$f
Control-Grid—Plate Capacitance	0.010	0.005	$\mu\mu$f

II. High-Frequency Characteristics

The reduction in size of these tubes has allowed operation of the triode as a radio-frequency feed-back oscillator in conventional circuit arrangements down to a wavelength somewhat below 40 centimeters, and the operation of the pentode as a radio-frequency amplifier, also in conventional circuit arrangements, down to wavelengths of the order of 70 centimeters.
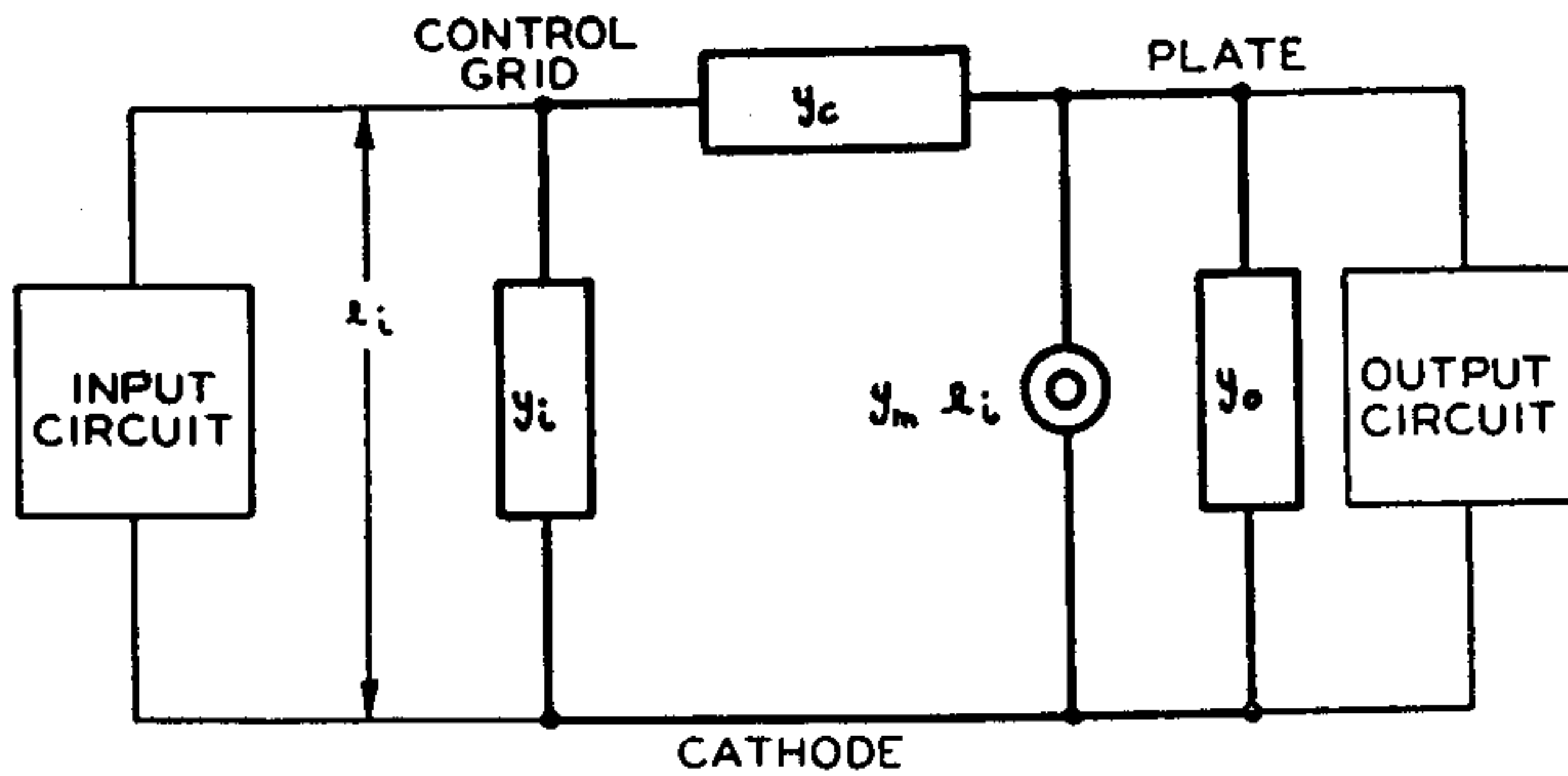
$\mathbf{y_i}$ = TUBE INPUT ADMITTANCE = $g_i + j\,b_i$

$\mathbf{y_c}$ = TUBE COUPLING ADMITTANCE = $g_c + j\,b_c$

$\mathbf{y_o}$ = TUBE OUTPUT ADMITTANCE = $g_o + j\,b_o$

$\mathbf{y_m}$ = TUBE TRANSFER ADMITTANCE = $g_m + j\,b_m$

Fig. 8—The schematic first order equivalent amplifier circuit representation of an amplifier tube.

Fig. 8 shows the schematic first order equivalent amplifier circuit representation of an amplifier tube. In order to specify completely the

behavior of such a tube at any frequency, it is necessary to specify the input, output, coupling, and transfer admittances at this frequency. At low frequencies, the input and coupling admittances are essentially pure susceptances, capacitive in nature. The output admittance consists of the plate conductance, usually in a radio-frequency amplifier pentode quite small in magnitude, and a susceptance due to the output capacitance. The transfer admittance consists of only a real part, the familiar g_m.

At high frequencies, the input admittance, and (unless the tube is well screened electrically) also the coupling admittance, acquire a real part and an altered imaginary part. In addition, the output admittance acquires an increased conductance and an altered susceptance. The transfer admittance also acquires an imaginary part. The increase in the conductance components of the input, output, and coupling admittances tends to reduce the gain which can be built up by the amplifier, and ultimately to limit its effectiveness. The change in the susceptance components of these admittances alters the tuning of the associated circuits, and in the case of an oscillator provides a potential form of frequency variation. The phase shift in the transfer admittance makes conditions for stability more favorable, but also affects the gain.[8] These admittances are functions of the time of passage of the electrons between the various electrodes. B. J. Thompson and W. R. Ferris of the RCA Radiotron Laboratory have already discussed the loading effects due to the increase of the input conductance of tubes at high frequencies,[9] and W. R. Ferris and D. O. North, also of the same laboratory, have made experimental and theoretical studies of this effect.[10]

Typical results of measurements of the equivalent shunt input resistance of the "acorn" pentode and the RCA-6C6 are shown in Fig. 9. This is the component of resistance which is due to the actual electronic flow past the control grid. The heavy section of the curve indicates the range over which measurements were made. The light line continuations are extrapolations. There is some justification for this extrapolation procedure because theory indicates that for small values of transit angle the conductance varies as the square of the frequency. The curves indicate that even at thirty meters, where it is perfectly feasible to build up a resonant circuit impedance of 150,000 ohms, the shunting effect of the conventional tubes is serious. At three meters, it

---

[8] Bernard Salzberg, "Notes on the theory of the single stage amplifier," to be published.

[9] B. J. Thompson and W. R. Ferris, "Grid circuit losses in vacuum tubes at very high frequencies," presented before joint U.R.S.I.–I.R.E. meeting, Washington, D. C. April 27, 1934; Abstract published Proc. I.R.E., vol. 22, p. 683; June, (1934).

[10] To be published.

amounts for conventional tubes to approximately 1600 ohms; this explains why the gain is so low at this wavelength when standard tubes are used.

In addition to the shunting which is due to the finite time of passage of the electrons between the various electrodes, there is an additional loss incurred as a result of the dielectric losses in the tube-lead support —glass, socket, etc.—and as a result of the capacitive currents which flow by way of the lead wires through the tube capacitances. The latter
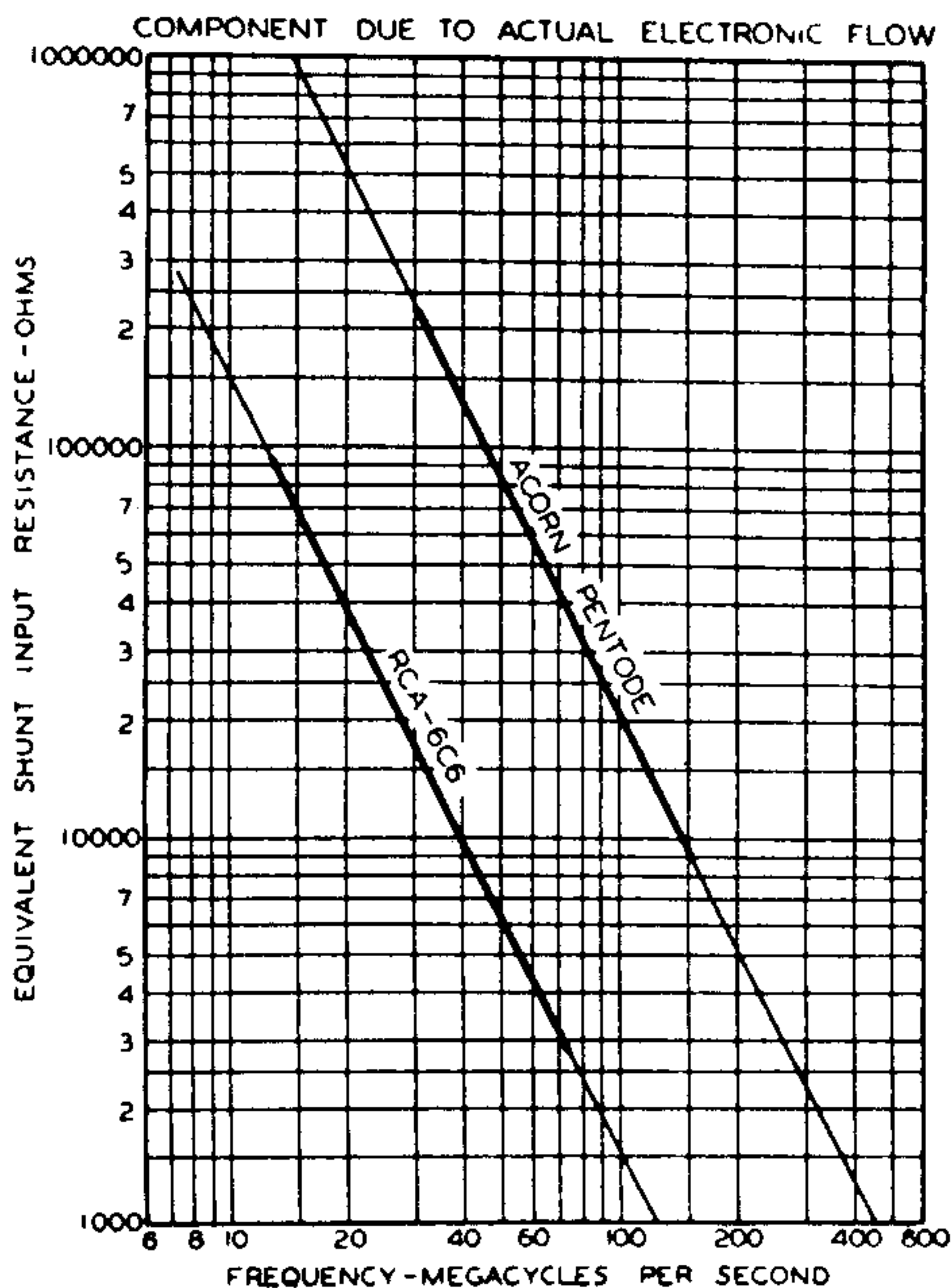

Fig. 9—The equivalent shunt input resistances of the "acorn" pentode and the RCA-6C6 as a function of the frequency. This is the component of resistance which is due to the actual electronic flow past the control grid.

cause assumes importance at the high frequencies, as shown by the curves of Fig. 10. Here is shown the shunting which takes place in the output circuit of a standard tube and of an early developmental "acorn" pentode which was used to study this effect. The losses are due partly to the dielectric loss, but mainly to the capacitive currents which passed through the leads. The same leads and by-pass condensers were used for both tubes. These curves are shown for the purpose of illustrating how significant this effect may become, and therefore how important it is to keep the radio-frequency losses in the connecting wires and the by-pass capacitors as low as possible. As seen from the

curves, this loss at the higher frequencies completely overshadows the shunting effect of the static or low-frequency plate resistance.

The measurements of the input and output admittances of tubes were made by a substitution method. A resonant circuit was coupled to a high-frequency oscillator and the voltage developed across this circuit at resonance was measured by means of an "acorn" pentode voltmeter, of the type shown in Fig. 13. The tube was operated at small space currents to reduce the electronic loading effects to a minimum.
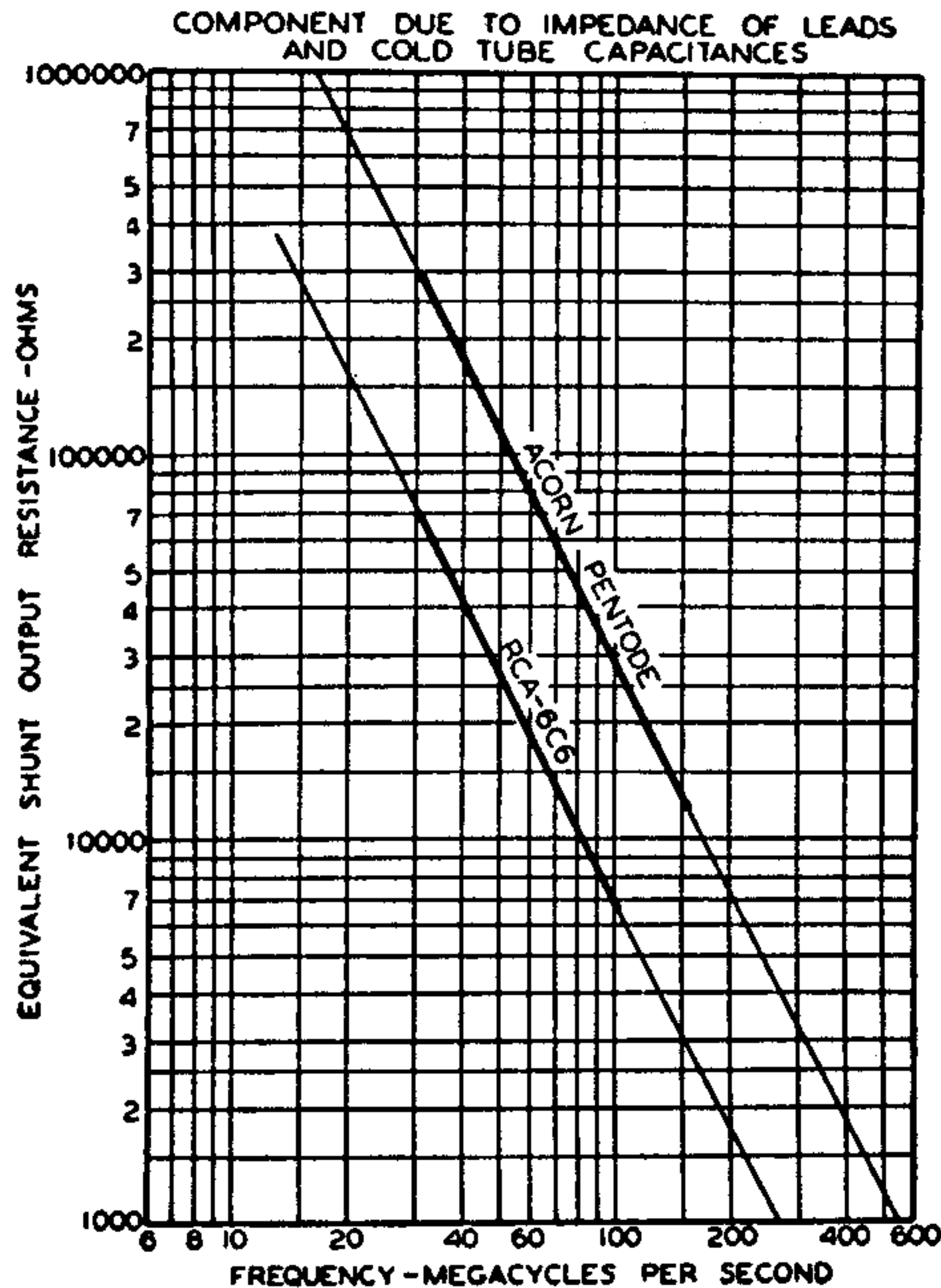
Fig. 10—The equivalent shunt output resistance of an early developmental "acorn" pentode and the RCA-6C6. This is the component of resistance which is due to the cold resistance of the tubes and the associated connecting wires.

This measurement circuit was calibrated by placing resistors, whose value at the operating frequency had been checked previously by a reactance substitution method, across the resonating capacitor, retuning to resonance and plotting the resulting resonant voltage against resistance. The conductance component of the admittance of a tube under test was then indicated by the value of the resonant voltage. The susceptance component was given by the frequency and the change (of the tuning capacitor) required to establish resonance.

The effects of the tube conductances on the associated input and output circuits may be minimized by matching the tube impedances

to these circuits. This may be done in a variety of ways, perhaps the simplest of which consists merely in connecting the tube at an intermediate point on the coil. It should be emphasized that since the shunt-
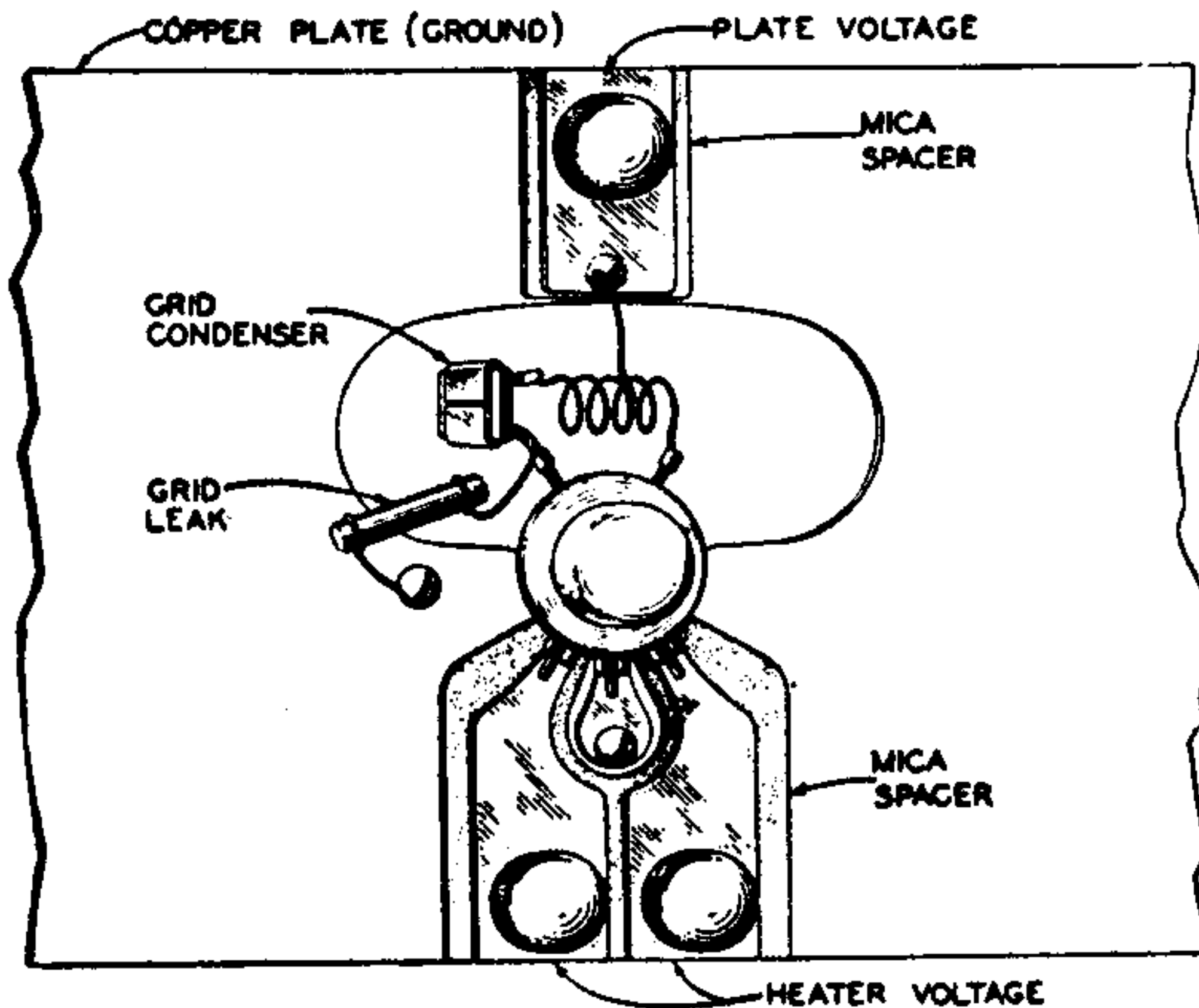

Fig. 11—A typical triode oscillator set-up.

ing effects are considerably less for the miniature tubes, there is less need for circuit arrangements of this type for these tubes. However, even for them, it becomes desirable ultimately to make use of such schemes.
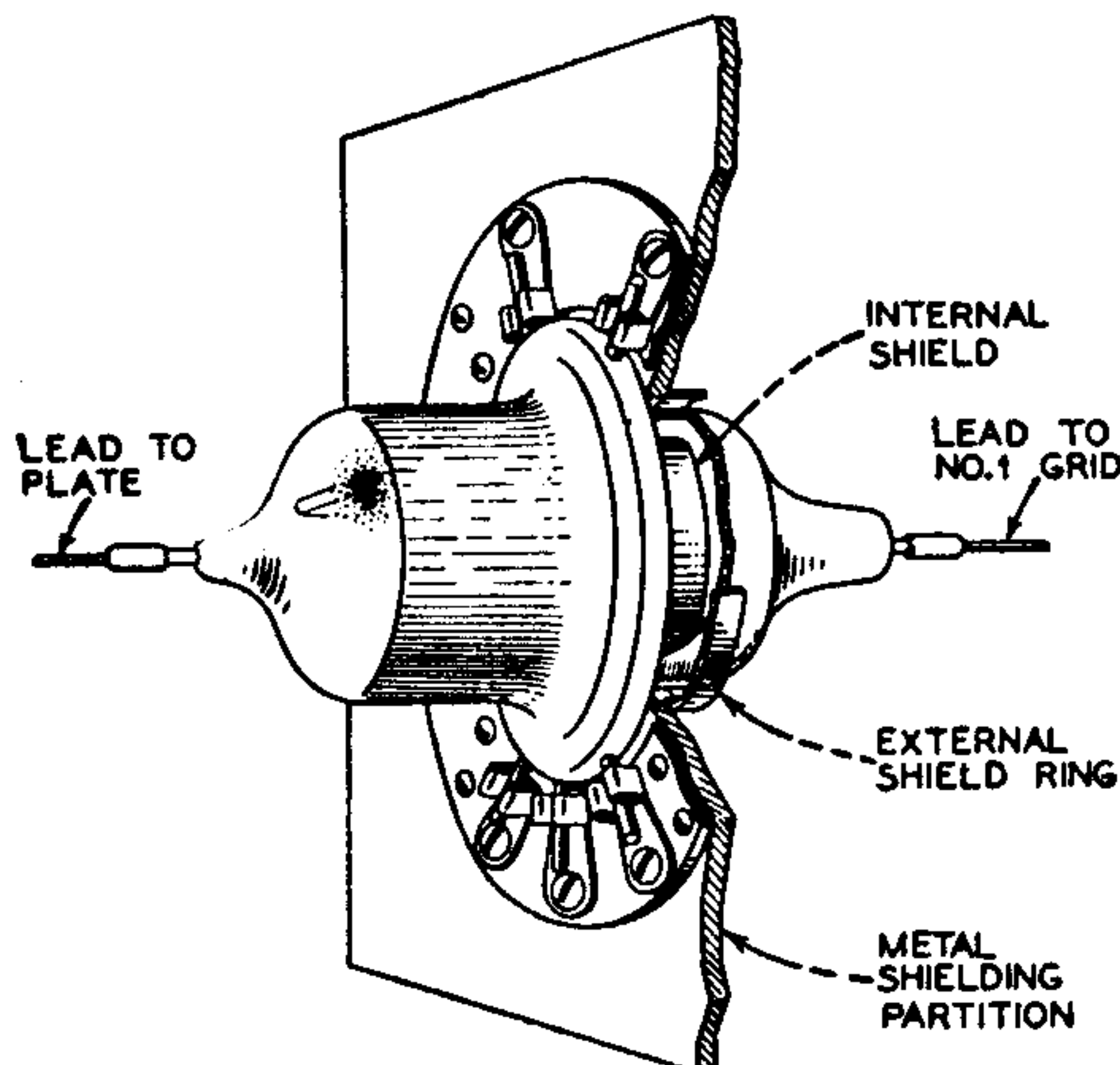

Fig. 12—A typical shielding arrangement for the miniature pentode.

Field measurements of noise developed in tubes at high frequencies indicate that the miniature tubes are definitely superior to the conventional tubes. Although elementary theory indicates that the shot noise in the plate circuit of a tube decreases with increasing interelectrodic

transit angle, the initiation of a noise component in the grid circuit which is a function of the cathode-grid and of the grid-screen transit angle results in an increase in the over-all noise.[11]

Figs. 11 and 12 illustrate how conveniently these tubes fit in with high-frequency circuit requirements. In the triode, the leads are arranged so that the active radio-frequency leads are on the opposite side of the flare seal from the radio-frequency grounded leads. In the pentode, the grounded radio-frequency leads are all brought out in the
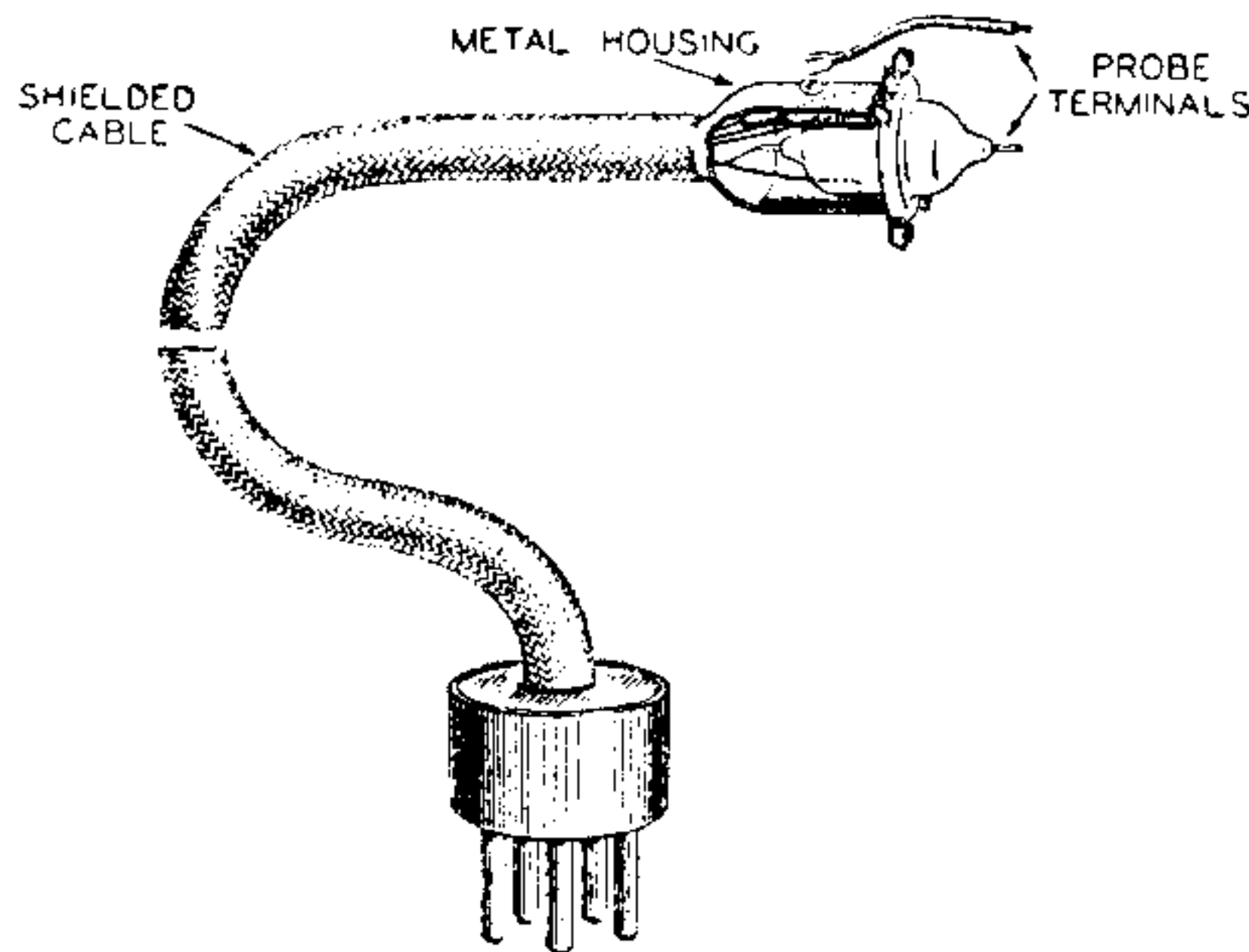

Fig. 13—A probe voltmeter using a miniature pentode.

plane of the flare seal, so that this may be used as a ground reference plane. The two active radio-frequency leads are brought out at the ends of the tube, which permits a very natural arrangement for connecting the tube to the input and to the output circuit. At high frequencies, it is usually desirable to bring all ground-return connections to one point, to avoid radio-frequency circulating currents in common impedances formed by shields.

Fig. 13 shows one of the many very useful miscellaneous applications of these tubes. A pentode is mounted at the head end of a shielded flexible cable and used as a probe voltmeter, thus permitting the measurement of voltages at their source.

Conclusions

Because of their decreased lead impedances, interelectrode capacitances and transit times, these miniature tubes allow considerable improvement to be made in high-frequency receiving equipment. It is possible to operate the triode as an oscillator in a conventional circuit down to a wavelength of approximately 40 centimeters. The pentode can be operated as a radio-frequency amplifier down to a wavelength of approximately 70 centimeters. It is practicable to obtain stable gains of

[11] Stuart Ballantine, "Schrot-effect in high-frequency circuits," *Jour. Franklin Inst.*, vol. 206, no. 2, p. 159, (1928).

ten to fifteen at three meters, a wavelength at which the standard tubes are almost entirely ineffectual. Both tubes can be used, down to much lower wavelengths, in exactly the same manner and for the same applications that the corresponding conventional tubes are used; i.e., as oscillators, amplifiers, detectors, converters, and as negative-resistance devices.

The small size of the tubes and their novel structural arrangements allow compact and convenient receiving equipment to be built. Even at the higher wavelengths, they are applicable to a large number of uses for which their size, low weight, and excellent characteristics make them particularly useful.

ACKNOWLEDGMENT