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Methods of Measuring Properties of Electron Tubes

Introduction

In papers dealing with the operation of electrical circuits which use electron tubes, as well as in the design of radio equipment using electron tubes, certain properties of the tube appear to be of much importance. This pamphlet describes apparatus used at the Bureau of Standards for measuring some of these properties.

Those included are.

I Combination alternating-current bridge for measurement of
(1) Internal input resistance
(2) Internal output resistance
(3) Amplification coefficient

II Arrangement for measurement of
(1) Direct-current characteristics
(2) Power output of generator tubes

III Measurement of detection factor

There are other important factors which are not covered by this letter circular. Some of the more important of these are, inter-electrode capacities, mutual conductance, and detection factors defined differently from the one included in Part III.

The methods of measurement used have been described by several writers* on the subject and this paper is intended to give convenient circuit arrangements that may be used for the rapid determination of the various properties with the values of the circuit constants that have been found most convenient.

* J.M.Miller, Proc. I.R.E., June 1918.
H.J.van der Bijl "The Thermionic Vacuum Tube" Chap. VII
J.H.Morecroft "Principles of Radio Communication" Chap. VI

I. Combination Alternating-Current Bridge for the Measurement of Internal Input Resistance, Internal Output Resistance, and Amplification Coefficient.

This bridge is an alternating-current bridge which by

simple switching arrangements may be used to measure internal input resistance, internal output resistance, and amplification coefficient under any condition of grid voltage, plate voltage and filament current. The principle involved in each of these measurements can be seen by reference to Fig.I In each case the contact on the slide wire is varied until there is no sound in the telephone receivers. When this condition is satisfied the value of the factor desired is given by the relation indicated.

The complete circuit arrangement is given in Fig. 2 in which

1 and 2 are SPDT switches,
3 is a SPST switch,
4, 5, 6, 7, 8 and 15 are terminals to which auxiliary apparatus is connected as indicated,
9 - filament ammeter,
10 - grid voltmeter,
11 - standard receiving tube socket,
12 - terminals for connecting non-standard tubes,
13 - slide wire,
14 - Two-stage audio-frequency amplifier,
G - ground terminal
R - Standard resistance box, variable from 0-100,000 ohms,

R_1 - filament rheostat
R_2 - grid voltage divider
R_3 - Rheostat 0-10000 ohms
R_4 - Rheostat 0-1000 ohms
R_5 - Voltage divider 0-1000 ohms
S - Reversing switch by means of which the grid may be made either positive or negative with respect to the negative side of the filament, as indicated by the + and - signs on the switch.

(1) Measurement of internal Input resistance (r_g)

Switches. 1. Closed at a
2. Closed at c
3. Open

When the switches are as indicated the circuit may be reduced to the simplified diagram Fig. 1a.

The tube to be measured is placed in the socket 11 or connected to the terminals G, F-, F+, P shown at 12 in Fig. 2.

A filament battery is connected to the terminals at 4 and the current indicated by the ammeter (9), adjusted by the rheostat R_1 to the desired value. Between the two of the three terminals at 8 marked "Plate Bat." is connected a battery which must have the exact plate voltage desired as no means is provided for varying this voltage except by the addition of series cells. A voltage divider cannot be used because of the extra resistance inserted in the plate circuit. A battery giving the voltage desired for the grid is connected to terminals 5. All the batteries must be placed near the apparatus and connected with as short leads as possible so as to minimize induction from any a.c. sources. The audio-frequency generator used may be either an alternating-current machine or an electron tube generating set. It is desirable that it be capable of being varied over the audible range although this is not necessary. Best settings may be obtained with frequencies of 1000 to 1500 cycles per second.

A high-resistance direct-current voltmeter having a resistance of 100,000 ohms or more, is connected to the terminals at 8 marked "Plate VM." The telephone receivers used for indicating a null point are connected to the second stage of the amplifier unless there is too much noise due to induction to make an accurate setting, in which case measurements may be made with less accuracy using only one stage of amplification. The grid voltage, indicated by the voltmeter (10), is adjusted by the voltage divider R_2 to the desired operating point, R is set at 100,000 ohms and the slide wire adjusted for a minimum sound in the phones. Further adjustments are made by changing the position of the slider of R_4 until the best minimum is obtained, then readjusting the slide wire, repeating this operation until almost a complete silence is obtained for the minimum. It will be noticed that R_4 is a resistance across the input leads, with a variable midpoint at which the ground is connected. It is possibel to compensate for capacity-to-ground effects almost entirely by changing the position of the ground in R_4. When there is complete silence in the phones T then

$$r_g = \frac{r_1}{r_2} R$$

If it is desired to measure the alternating current voltage applied to the tube during a measurement a low-voltage a.c. voltmeter (for example a high resistance thermo-element and micro-ammeter calibrated in volts) may be connected across the input terminals (7, Fig. 2). It is evident that the alternating current grid voltage is equal to the

voltage drop across r_1 (see Fig. 1a) when silence is obtained in the phones T. Then the impressed voltage

$$e_g = \frac{r_1 \quad E}{r_1+r_2+R_3}$$

where E is the voltage impressed on the bridge and measured by the voltmeter connected across the input terminals.

If the input resistance of the tube is high (over 10^6 ohms) difficulty will be experienced in making accurate settings and accuracy of the bridge decreases.

(2) Measurement of internal output resistance (r_p)

Switches 1. Closed at b
2. Closed at c
3. Open.

When the switches are as indicated the circuit arrangement reduces to that of Fig. 1 (b).

Resistance R is set at about 50000 ohms and the point C on the slide wire adjusted until a minimum is obtained. R_4 is adjusted along with the slide wire until complete silence is obtained in the telephone receivers. If the ratio $\frac{r_1}{r_2}$ is too large or too small for accuracy then R is changed to bring the setting near the middle of the slide wire. Readings are taken with two or more values of R and the results averaged.

With silence in the phones

$$r_p = \frac{r_1}{r_2} R$$

This measurement includes the resistance of the plate battery which for new cells can be neglected in comparison with the resistance of the tube.

(3) Measurement of the amplification constant (μ)

Switches 1. open
2. closed at d
3. closed

This arrangement of switches reduces the circuit

to that of Fig. 1 (c)

The slide wire and R_4 are adjusted for minimum sound as described above and when silence is obtained

$$\mu = \frac{r_2}{r_1}$$

General

In all the preceding measurements, and especially in the measurement of r_g, care should be taken to keep the alternating current input as low as possible consistent with accurate setting of the slide wire.

When adjusting for minimum sound in measuring μ, the importance of adjusting R_4 closely is not marked, as it does not affect the slide wire setting appreciably, but in all the other measurements, changes in R_4 affect both the amount of sound at the minimum, and the setting of the slide wire, so R_4 must be adjusted carefully to obtain a minimum as close to silence as possible. This is best done by moving the slider of R_4 back and forth over the minimum point and at the same time turning the slide wire (13) slowly in one direction until the nearest to complete silence is obtained when R_4 passes its minimum point R_4 is left at this point and the final adjustment made on the slide wire.

Tubes should be left burning for two to five minutes before making measurements to allow them to come to a condition of stability.

II. Determination of Direct-Current Characteristics and Power Output of Generator Tubes.

(1) Determination of Direct-Current Characteristics.

This determination is the usual step-by-step method of determining the characteristic curves as described in any book on radio measurements (such as Bureau of Standards Circular 74 p. 203) Fig. 3 shows the measuring instruments that are necessary and the factors that it may be desirable to vary. The arrangement that has been found convenient for use is shown in Fig. 4 in which

1. Switch for connecting either milliammeter or sensitive galvanometer in the grid circuit.
2. Grid ammeter short circuiting switch,
3. Reversing switch for grid ammeter,
4. Reversing switch for grid voltage,

5. Switch and terminals for connecting grid voltmeter
6. Switch for connecting R_3 in parallel with R_2.
7. Switch for connecting to plate of small tube or terminal at 18.
8. Grid return switch, connecting to + or – side of filament.
9. Filament voltmeter connecting switch.
10. Plate ammeter short circuiting switch and terminals.
11. Plate voltmeter switch and terminals,
12.
13. Plate voltage disconnecting switch,
14. Grid voltage terminals,
15. Grid voltmeter,
16. Filament voltage terminals,
17. Standard receiving tube socket,
18. Terminals for non-standard or high power tube,
19. Plate voltmeter,
20. Short circuiting switch and terminals for plate impedance
21. Short circuiting switch and terminals for grid impedance
22.
23. Terminals for plate voltage,
24. Galvanometer shunt,
25. Grid Milliameter,
26. Filament voltmeter
27. Filament ammeter.
28. Plate milliammeter,
29. Grid voltage disconnecting switch,
30. Filament voltage disconnecting switch,

C_1 Mica condenser 0.2 µf capacity,
C_2 Mica condensers 0.1 µf capacity,
R_1 Grid voltage divider, 3000 ohms,
R_2 Filament rheostat, fine adjustment
R_3 Filament rheostat, rough adjustment
R_4 Plate voltage divider, 2000 ohms.

The operations necessary to obtain the characteristic curves of electron tubes consist of making filament, grid, and plate current measurements with the filament, grid and plate voltages set at any desired value varying one of these by steps over a range sufficient to give the desired curve.

The tube under test is placed in the socket, 17, and switch 7 thrown to the left, if it is a standard receiving or low power transmitting tube, or connected to the terminals, 18, and switch 7 thrown to the right if the tube is non-standard or for high power. The plate circuit is disconnected from the socket 17 and connected to terminal P at 18 for high power tubes in order to prevent a break down of the insulation on the small socket when the high voltage used on large tubes is applied.

Switches 20 and 21 are closed.

The grid voltage, of a value slightly higher than the highest required for the measurement is applied to the terminals, 14, and connected by the switch, 29, which is fused with 0.5 ampere fuse wire, to the voltage divider R_1 and by moving the slider on R_1 the voltage applied to the tube may be varied continuously from zero to the value applied at 14. This voltage is measured by the voltmeter, 15, when switch 5 is closed, and may be reversed by means of switch 4; the grid being positive with 4 to the right and negative with 4 to the left. The grid voltage is ordinarily measured from the negative side of the filament, but by means of switch 8, the grid return may be connected to either side of the filament, to the negative with 8 left and positive with 8 right.

The grid current is read on the milliammeter 25, or on the sensitive galvanometer, either one of which is connected in the grid circuit by switch 1. The milliammeter is used to measure grid currents of about 0.02 to 200 milliamperes, but for smaller currents, the more sensitive galvanometer is used. Its sensitivity can be varied by the shunt 24, calibrations being necessary for each value of the shunt resistance. In order to measure current flowing in either direction, the reversing switch 3, is provided, the current flow being positive, i.e., from grid to filament in the tube, when 3 is to the right, and negative with 3 to the left. The grid voltage divider and measuring instruments are shunted by the condenser C_1, to bypass radio-frequency current when this circuit is used to make the power output measurements described below.

The filament voltage is applied to terminals 16, and connected by switch 30, through the filament ammeter 27, and rheostat R_2 and R_3 to the filament terminals of 17 and 18, the voltage across the filament terminals being indicated by voltmeter 26 when switch 9 is closed. This switch should always be open when adjusting the filament current as the current taken by the voltmeter flows through the ammeter 27 and may cause appreciable error, particularly with tubes using a small filament current.

The plate voltage is connected to terminals 22 and 23, The voltage on 23 should not exceed about 200 volts as it is connected through switch 13 to the voltage divider R_4, any higher voltage necessary being connected to terminals 22. Since 22 and 23 are in series, connection should be made to both of these in order to complete the plate circuit. Switches 12 and 13 are fused with 0.5 ampere fuse wire.

By changing the slider on R_4, the plate voltage is varied over a range afforded by the voltage connected to 23, and the total voltage applied to the plate, being the sum of that obtained from the voltage divider and that connected to 22, is measured by the voltmeter 19. By means of switch 11, the voltmeter can be connected directly to the plate (switch 11 to left) so as to measure the actual voltage acting between plate and filament, or (11 to right) to the positive side of the voltage supply to measure the voltage applied to the circuit, excluding the drop across any impedance inserted in the circuit at 20. For ordinary characteristics 11 is thrown to the left and switches 20 and 21 are closed.

The plate current is read on the milliammeter 28, which is in series in the plate circuit and can be short circuited by the switch 10, when not in use. The capacity C_2 is shunted across the voltage supply and measuring instruments to bypass high-frequency current when this circuit is used for power output measurements.

Measurements for the two most important characteristic curves having grid and plate current plotted against grid voltage, with constant filament current and plate voltage are made simultaneously. With the tube in place, and the proper voltages connected, the filament current is adjusted to its proper value, having switch 9 open while reading the current, the plate voltage adjusted and the grid voltage increased toward the negative (switch 4 to the left) until the plate current has been decreased to zero, reading the grid voltage and current. Now the grid voltage is decreased to zero by steps, at each setting the grid voltage and current and plate current being recorded, then switch 4 is thrown to the right and the voltage increased positively, readings being made as before. The plate voltage is read each time to insure that it remains constant. The filament current will vary according to the amount of electron current flowing in the tube. When a positive grid voltage is applied to the tube, great care should be taken to prevent the high plate current from overheating the tube; by leaving the grid voltage on no longer than necessary to obtain readings. This applies more to power tubes than receiving tubes, since high grid voltages are not necessary for receiving tube characteristics. When the grid voltage has been varied over a range sufficient for the characteristic, a few check points are taken to insure that the tube has remained constant during the run.

It may be found necessary to adjust the plate voltage each time readings are made as there may be an appreciable voltage drop in the plate voltage divider, R_4 caused by the plate current, which changes as the grid voltage is varied.

Tubes should be left with the filament burning and the normal plate voltage applied for 2 to 5 minutes before making measurements.

Other characteristics may be obtained in a like manner, adjusting the voltages or currents it is desired to hold constant first, then varying the remaining ones by steps.

(2) Power Output Measurements.

The arrangement shown in Fig. 4 may be used to control and measure the various currents and voltages of the electron tube when it is used to furnish power to a tuned circuit. The power output of a tube under any fixed condition can be measured by the use of this circuit. For the case of an inductively-coupled circuit Fig. 5 shows the arrangement used the notation being the same as in Fig. 4.

Measurements are made by connecting to the terminals 20, Fig. 4, a suitable radio frequency oscillatory circuit of known constants. After adjusting the tubes to the desired operating conditions, the radio frequency current is measured, and the power calculated from the circuit resistance and current. Several coils of varying sizes are provided for the grid and plate coupling coils. The plate and grid coils are respectively mounted on the terminal blocks 20 and 21. If an inductively-coupled circuit such as the "Meissner Circuit" is used (see Bureau of Standards Circular 74 p. 210, Principles Underlying Radio Communication, p. 493) the coil for the tuned circuit is so constructed that the grid and plate coils fit into it and the coils are so arranged that the mutual inductance between any two of them may be varied.

The tuned circuit containing a hot-wire ammeter is connected to the coils, the tube voltages adjusted to the desired value and the alternating current I recorded. The radio-frequency resistance R, is measured by means of the resistance-variation method* at the frequency at which the circuit is used.

*Bureau of Standards Circular 74 page 180.

The power output is, in watts.

$$P_0 = I^2 R$$

From the d.c. plate input voltage E_b, measured by voltmeter 19, and current I_p measured by milliammeter 28, the power input is in watts

$$P_i = E_B I_B \text{ watts}$$

and the efficiency, disregarding the grid and filament power is

$$\frac{P_o}{P_i} = \frac{I^2 \quad R}{E_B \quad I_P}$$

Unless changes are made in the setup connections, a series plate voltage supply must be used. The capacity C_2 is connected across the plate power supply circuits and serves as a bypass for radio-frequency currents when the power measurement is made. The coupling coils and output coils provided are so constructed as to allow their use in direct coupled, semi-direct coupled or inductively coupled, output circuit.

III. Detection Factor.

Various detection factors have been proposed* to express the merits of the electron tube as a detector. A factor to be useful should be readily determinable and simple of application in desired calculation. The audio-frequency output voltage (or current) produced by the rectification of a completely modulated radio-frequency input varies for most detector tubes over a limited voltage range approximately as the square of the input voltage. So for a load of given impedance in the plate circuit, the ratio of the voltage across this load to the square of the input voltage will be nearly a constant over this limited range of voltages. This ratio forms a convenient detection factor which may be readily determined with the tube under actual operating conditions. (This factor is used in calculations by L.M.Hull in the report mentioned above).

The method of measurement can be understood by reference to Fig. 6. It consists of applying a completely modulated radio-frequency voltage to the input of the tube and measuring the audio-frequency output by comparison with a known audio-frequency voltage of the same frequency.

The complete circuit arrangement is shown in Fig. 7 in which the following legends are used.

1. Leads to radio frequency supply
2. Leads to audio frequency supply
3. Terminals connected to input of tube under test

* Stuart Ballantine Proc I.R.E., April 1919
L.M.Hull Radio Laboratory Report, Bureau of Standards CR134d
John R. Carson, Proc I.R.E. April 1919
Hulbert & Breit, Phys. Rev. 16. 1920 p. 274 and p. 408
H.J. van der Bijl, "Thermionic Vacuum tubes" page 339

4. Terminals connected to input of tube under test
5. DPDT switch
6. Galvanometer shunt
7. Vacuum Thermoelement of low resistance.
8. 3-stage audio-frequency amplifier (resistance coupled)
9. Audio frequency transformer
10. Grid leak, 2 megohms and 2.5 volt battery in input circuit of amplifier.
11. Mica Condenser, 0.02 microfarads capacity
12. Crystal detector (carborundum) (These may be replaced (by thermoelement and
13. Milliammeter, (galvanometer
14. Filament battery terminals.
15 DPST switch

C. Variable condenser, maximum capacity 0.005 microfarad.
G. Sensitive galvanometer (low resistance)
L_1 and L_2 radio-frequency coupling coils
R. Radio-frequency link resistance
R_1 Decade resistance box 0-1000 ohms

R_2 Resistance box, 0-10000 ohms
V. Hot wire voltmeter, 0-30, 0-150 volts

The tube and measuring apparatus are completely enclosed in a grounded screen wire cage which shields the apparatus from the radio generator and from stray radio signals or disturbances, and is supplied with modulated radio frequency and audio frequency current from apparatus outisde of the cage.

The modulated radio frequency is supplied by an electron-tube radio-frequency generating set enclosed in a metal lined box and placed about 5 meters from the cage. The wave length of the generated radio frequency is variable over the range desired. The plate voltage is about 120 volts alternating current supplied by a small 500-cycle motor generator, which also furnishes through a step-down transformer 30 volts to the leads 2.

The radio frequency, adjusted to the wave length at which measurements are to be made, is introduced into the cage by means of coils L_1 and L_2, the coupling of which can be varied. The coil L_2 outside the cage, has an inductance of about 140 microhenries and since it is in an untuned circuit is used over the entire range of wave lengths. Two coils are used at L_1 in the tuned circuit, L_1-C-15-7-R, inside the cage, to cover the range of wave lengths required, one the same size as L_2 used from 600-1500 meters, and a larger coil having an inductance of about 860 microhenries used from 1500-4000 meters. This input circuit is tuned to the radio-frequency current in L_2 by varying the condenser C.

The input to the tube is the iR drop across the resistance R due to the radio-frequency current flowing through R, and is varied by using different values of R and varying the current through R by changing C. This current is measured by the thermoelement 7 and galvanometer G which are calibrated with the shunt 6. The resistances used at R are standard high-frequency link resistances* varying from 0 to 30 ohms. They

* See Bureau of Standards Circular 74 page 176.

must be measured occasionally on a direct current bridge to check their resistance as they do not remain constant.

The grounded input terminal at 3 may be connected to either the negative or positive side of the filament. Short leads should be used in all connections to the tube.

The audio-frequency comparison voltage is supplied to the switch 5 through shielded leads by the voltage divider at R_1 R_2, consisting of a resistance R_1 variable by one ohm steps from 0-1000 ohms to which are connected the leads into the cage, in series with resistance R_2 variable from 0-10000 ohms in 10 ohm steps. The voltmeter V and supply voltage from the 500 cycle generator are connected across R_1 R_2 as indicated.

When either the audio-frequency output voltage of the tube under test or the comparison voltage obtained from the voltage divider is connected to the input of the voltage-indicating circuit by switch 5, it is amplifier by the three-stage audio-frequency amplifier 8 and transformer 9 causing an alternating current to flow in the circuit 9, 12, 13. This current is rectified by the crystal detector 12, and deflects the milliammeter 13.

With the frequency of the radio frequency generating set adjusted to the desired value and switch 5 up resistance links are inserted at R, always opening 15 before removing a link at R, increasing R until a suitable deflection is obtained on the milliameter 13.

The comparison voltage is now connected to the voltage-indicating circuit by throwing switch 5 down, and R_1 and R_2 are adjusted until approximately the same deflection on the milliammeter is obtained as previously. Switch 5 is thrown to the up position again and the tube input varied by varying C, it being equipped with a small variable condenser for fine adjustment, until exactly the same deflection is obtained with switch 5 either up or down. The audio output voltage e_t is now equal to the comparison voltage across R_1, and since the voltage E across R_1 and R_2 measured by voltmeter V, is known, the tube output voltage -

$$e_t = E \frac{R_1}{R_1 + R_2}$$

The galvanometer being calibrated, the current, i, flowing through R is obtained from the galvanometer deflection, and the radio input voltage

$$e_i = i\ R$$

From the definition given above the detection factor

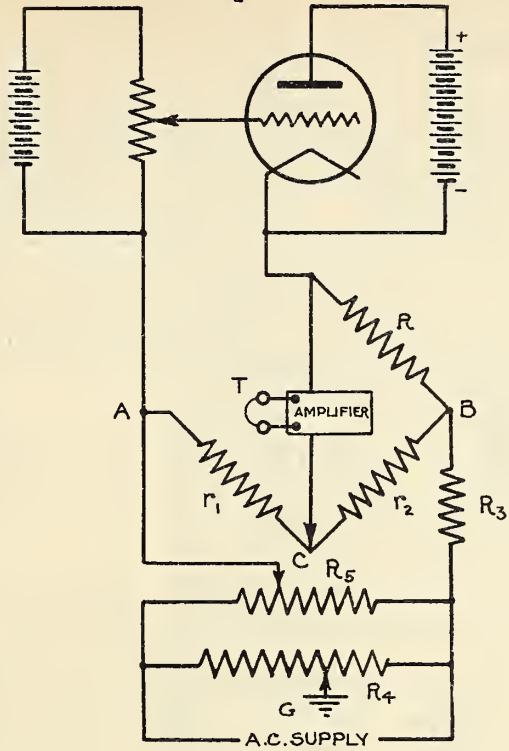
$$k = \frac{e_t}{e_i^2}$$

These measurements are repeated at different frequencies if desired.

This detection factor has the disadvantage that it must be specified with a given load in the plate circuit. However, for a comparison of several tubes this load may be kept constant and a good factor for judging the tubes is given.

FIG.1.(a) INTERNAL INPUT RESISTANCE (r_g) WHEN THERE IS SILENCE IN THE PHONES T

$$r_g = \frac{r_1}{r_2} R$$



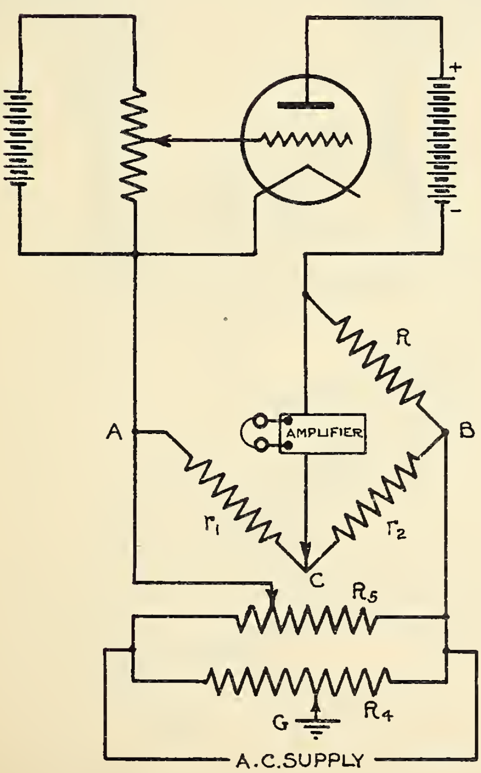


FIG.1.(b) INTERNAL OUTPUT RESISTANCE (r_g) WHEN THERE IS SILENCE IN THE PHONES T

$$r_p = \frac{r_1}{r_2} R$$

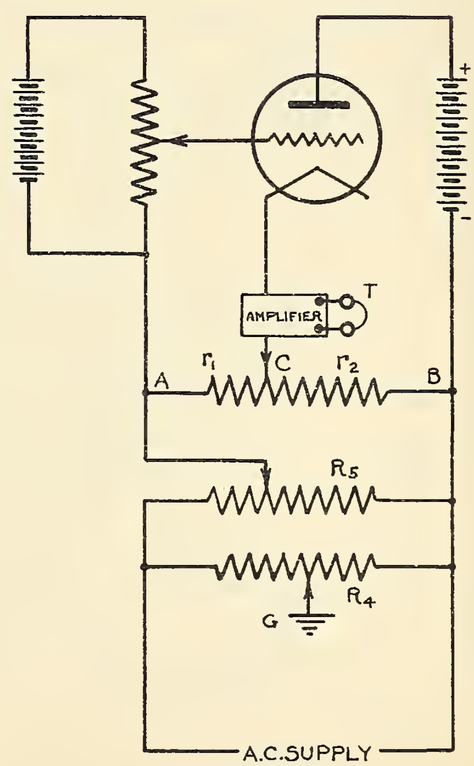


FIG.1.(c) AMPLIFICATION COEFFICIENT (μ) WHEN THERE IS SILENCE IN THE PHONES. T

$$\mu = \frac{r_2}{r_1}$$

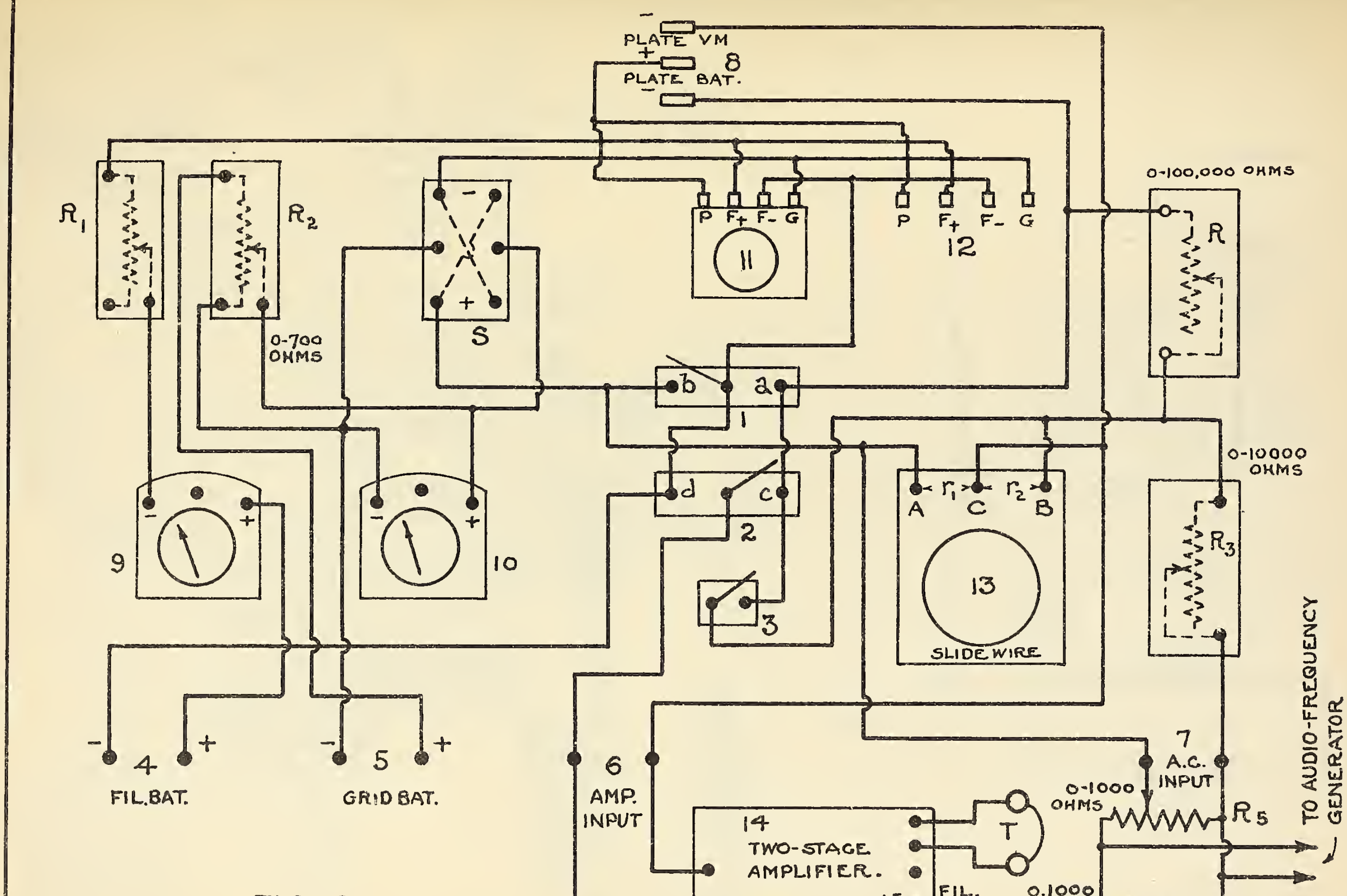


FIG. 2.

COMBINATION BRIDGE FOR MEASUREMENT OF INPUT RESISTANCE, OUTPUT RESISTANCE AND AMPLIFICATION COEFFICIENT.

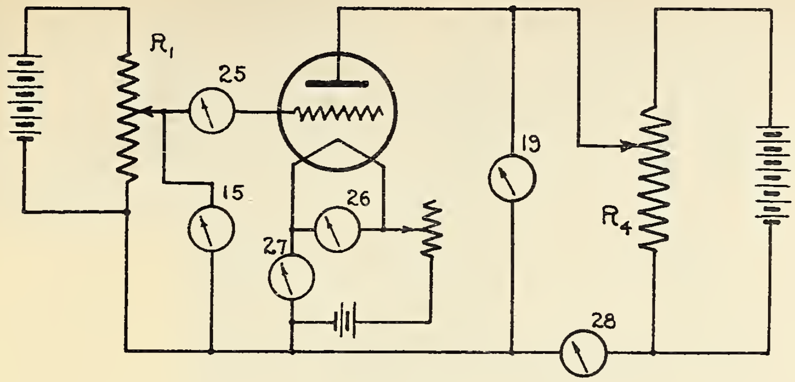
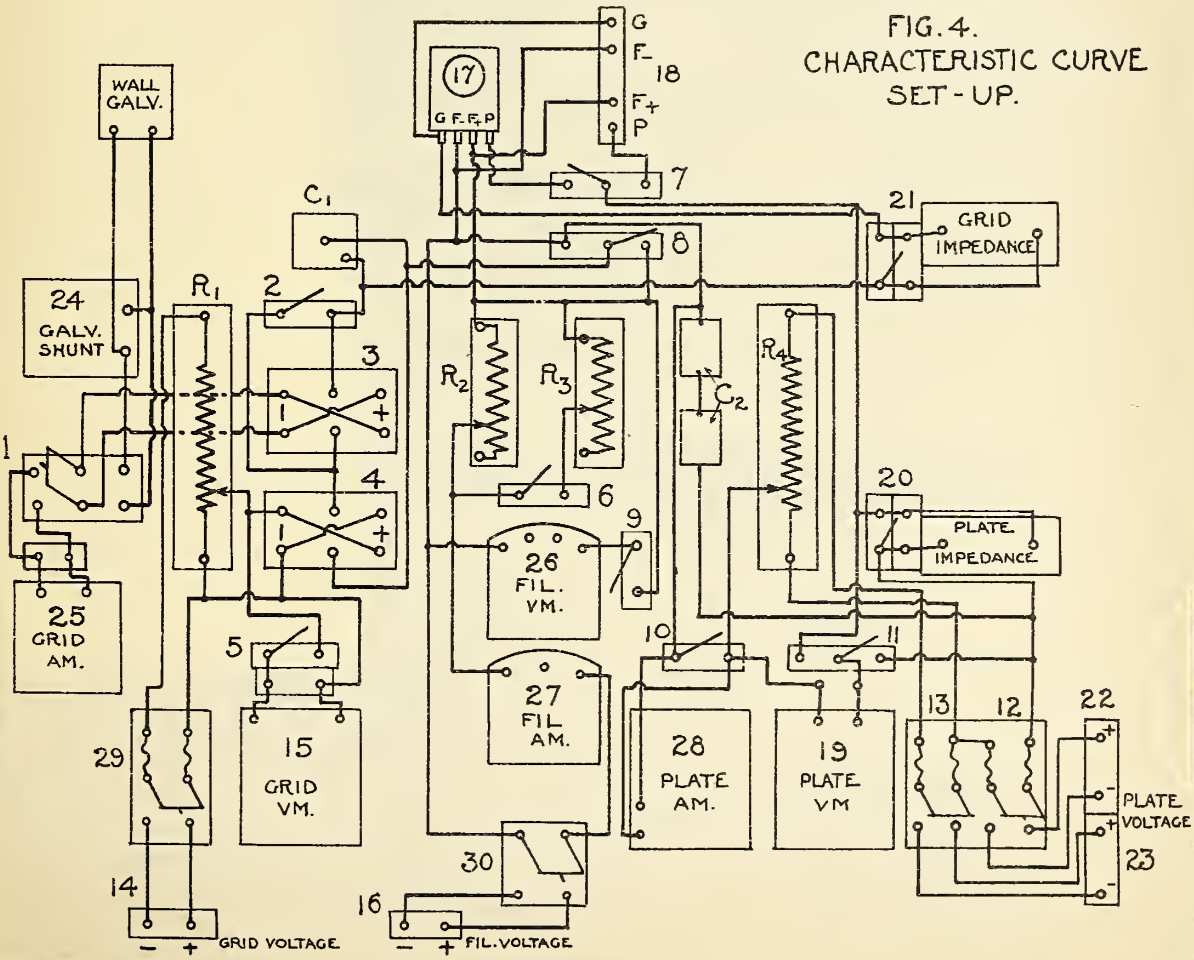


FIG. 3.
SIMPLIFIED DIAGRAM OF CHARACTERISTIC CURVE SET-UP

FIG. 4.
CHARACTERISTIC CURVE SET-UP.



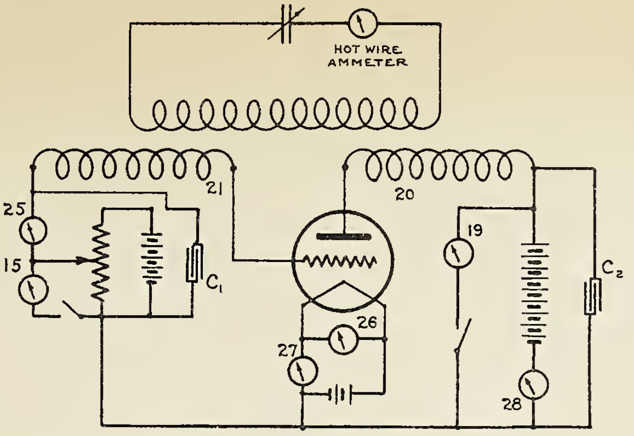


FIG. 5.

SIMPLIFIED DIAGRAM OF CIRCUIT FOR MEASUREMENT OF POWER OUTPUT OF ELECTRON TUBES.

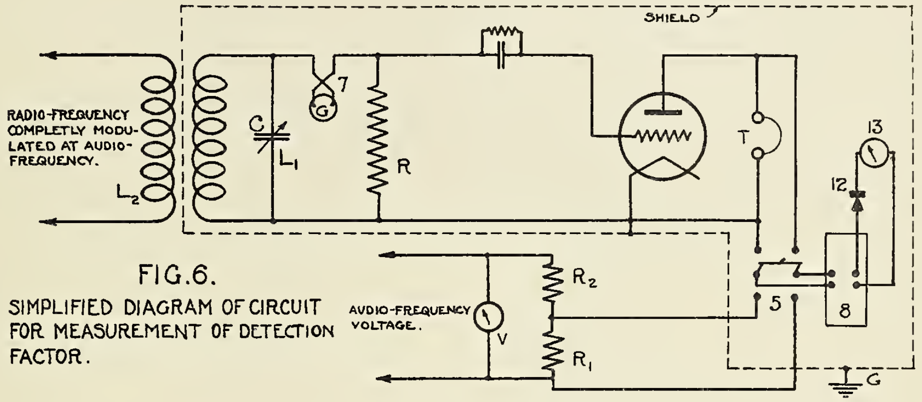


FIG. 6.

SIMPLIFIED DIAGRAM OF CIRCUIT FOR MEASUREMENT OF DETECTION FACTOR.

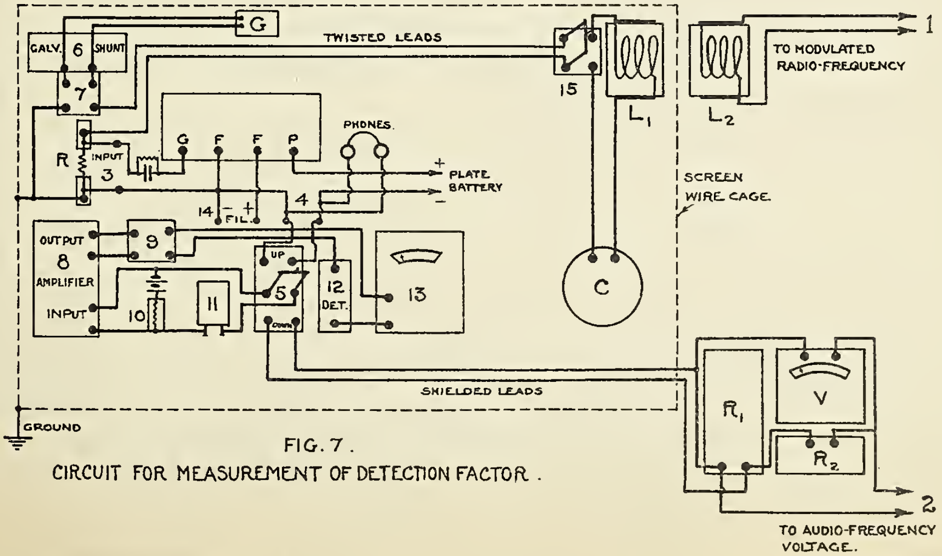


FIG. 7.

CIRCUIT FOR MEASUREMENT OF DETECTION FACTOR.