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I hereby recommend that the thesis prepared under my supervision by Richard Peake Krebs

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be accepted as fulfilling this part of the requirements for the degree of Doctor of Philosophy

Approved by: Harold J. Kersten

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APPLICATIONS OF ELECTRONICS TO BIOPHYSICAL MEASUREMENTS

A dissertation submitted to the

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requirements for the degree of

DOCTOR OF PHILOSOPHY

1942

by

Richard Peake Krebs

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M. S. University of Cincinnati 1941

ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
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APPLICATIONS OF ELECTRONICS
TO BIOPHYSICAL MEASUREMENTS

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INTRODUCTION

Electronics affords the experimenter in biophysical research many of his most useful tools.

Its applications are legion. It opens up entire fields of research the only approach to which is through the vacuum tube and its associated apparatus.

Electronic devices because of their qualities of relative consistancy, sensitivity, and discrimination, offer the experimenter refinements in laboratory technique which reduce the inaccuracies constantly present in the human element.

Relative consistency: Electronic mechanisms are used to start or stop any number of operations at a predetermined time, in definite intervals, or in a precise sequence. In the field of control alone their application is practically unlimited. The regulation of temperature, pressure, light intensity, voltage and current, are but a few of their services.

Sensitivity: Electronic instruments have the ability to measure quantities so small that they have not yet been detected by any other means. Short time intervals can be investigated and the exact sequence of events in recurrent intervals so magnified as to permit a study of them. Small voltages and currents, small amounts of light, small quantities of radiant energy, and the energy of radioactive decay, which heretofore have not been measured by any other instrument, are accurately determined in common applications of vacuum tubes.

Discrimination: Through photo-tubes color differences may be distinguished and degrees of turbidity compared which are imperceptible to the human eye. Again, small changes in temperature and other physical properties can be detected by means of electronic apparatus with a precision beyond that of any other methods.

It is the purpose of this thesis to present a few of the principles employed to make full use of the vacuum tube's capabilities as a research tool. The author has made a comprehensive investigation of small current measurements. This paper will present a macroscopic picture of the small current measurement problem, and its solution. From the great mass of theoretical considerations encountered by him, the author has selected that material which he considers most essential, and has purposely written this paper for those who wish to make small current measurements without going into unnecessary and involved theoretical work. The author has tried to present in any understandable fashion the answers to some of the questions which baffled him at the beginning of his investigation.

The first part of this thesis describes the prominent electronic circuits for measuring currents less than one microampere. Since these measurements were to be made under conditions found in a practical biophysical laboratory, the author has restricted his presentation for the most part to apparatus operated from the alternating current line, since such apparatus requires a minimum of attention from the operator to keep it performing satisfactorily. Where a source of power other than the 110-volt alternating current line has been used the advantages obtained from such a departure have been pointed out.

Several different types of small current measuring instruments are described, to-gether with a discussion of the features and limitations of each model.

The second part of this thesis is given over to apparatus design, built, and tested in the laboratory for use in biophysical research problems.

PART I

CURRENT MEASUREMENTS

PART I

CURRENT MEASUREMENTS

The measurement of currents greater than one microampere falls within the range of portable, d' Arsonval, moving coil meters. These are of sturdy construction, may be operated in any position, and can be produced to give results of a reasonable degree of accuracy down to the limit indicated above.

In order to measure currents smaller than this it is necessary to use some other type of instrument. The experimenter has available the moving-coil galvanometer, the electrometer, and vacuum tubes.

With a high-sensitivity galvanometer currents of the order of 10^{-10} amperes can be measured directly. Electrometers will detect currents as small as 10^{-13} amperes. A vacuum tube circuit has been developed capable of measuring as little as 3×10^{-19} amperes, or 2 electrons per second.

In considering the applications of vacuum tubes to current measuring equipment, it is well to bear in mind that vacuum tubes are often used in current ranges other than those in which they alone may function. Vacuum tubes have been used to measure microamperes. The occassion may have arisen with a single instrument whose current measuring range was from 10^{-5} to 10^{-11} depending on certain adjustments on the instrument itself. Or, in the interest of economy and portability, a vacuum tube and a rugged and inexpensive milliammeter might have been used in place of the more delicate and more expensive galvanometer required for the same precision measurements. Such a unit could have been built with batteries for extreme portability, or constructed to operate from the 110-volt a.c. line.

For currents of magnitude between one microampere and 10^{-11} amperes flowing in high resistance circuits vacuum tubes are in a class by themselves. The apparatus used is a self-contained unit, operating from the alternating current power line. The meter itself is of the rugged, portable type, and the entire apparatus may be used in any position. Adjustments for operation require no special technique, and as soon as the vacuum tubes are heated a measurement can be made with the full assurance that the reading is correct. The instrument is self-calibrated. With care this same type circuit may be used for currents as low as 10^{-13} amperes.

With slightly more elaborate apparatus, but still using commercial receiving tubes and a portable meter, currents down to 10^{-15} amperes can be measured. Below 10^{-15} amperes current measurements require a special technique. In the first place, ordinary radio tubes are unsatisfactory for reasons to be discussed later. An especially built, so-called electrometer tube, must be employed. This tube was designed and developed solely for the purpose of measuring small currents. When such currents are to be measured the sturdy, portable meter must be replaced with a very sensitive galvanometer, and a special circuit used.

Before proceeding into the description of current measuring devices it would be well to point out that there are two types of measuring instruments. The factor which determines the classification of a given piece of equipment is the time required to make a reading. If the current be determined as soon as it is applied, the instrument is instantaneous reading, or an indicating instrument . However, a vacuum tube may be used as an electroscope, and the amount of charge collected over a measured period of time used to determine the current. Such an instrument is called an integrating instrument, and the means of determining the current is designated as the floating-grid, or rate-of-drift method.

The problem of current measurements may be stated briefly as follows: The current to be measured is made to flow through a resistance and produce a voltage drop. This voltage is applied to the grid, or control element, of a vacuum tube. The size of the voltage applied to the grid is determined by the change affected in the plate current. Dividing this voltage by the resistance in the grid circuit results in the magnitude of the current being measured.

Two avenues of approach are open toward increasing the sensitivity of a current measuring device. One is to increase the resistance through which the current flows. The upper limit of such a prodecure is discussed in Chapter I. The second avenue is to make the remainder of the circuit, including the power supply, so stable that a very delicate instrument may be used to detect the smallest change in anode current, and to have a change indicated only when the potential of the control element has been changed by the current under investigation.

Both of these approaches must be developed to their fullest extent in order to measure currents as small as a few electrons a second.

CHAPTER I

THE CONTROL GRID CIRCUIT

In most vacuum tube applications the control grid circuit is considered as that part of the tube circuit to which a voltage is applied while an amplified image of that voltage is taken off the plate circuit. The grid is considered a control element, and the current drawn by it is so small that it is neglected. Another way of expressing the same thing is to say that in common applications of vacuum tubes the input impedance of the tube is very large compared to the impedance of the external grid circuit.

This, however, is not true when a vacuum tube is used to measure small currents. For such applications the current to be measured is used to produce a voltage on the control grid of the tube, and the amount of this voltage is determined by the change affected in the plate circuit. The current under investigation is made to flow through a resistor R-g in the grid circuit, see Fig. I-a. If the current is I then the voltage developed by it across the resistor R-g is R-g x I. If we suppose the minimum grid voltage change detectable in the plate circuit to be E, then the smallest detectable current will be $I = E / R\text{-}g$. It is abvious that the larger R-g is made, the smaller will be the detectable current.

Consequently, when a small current is to be measured, every effort should be made to have the grid resistance as high as possible . However, it must be remembered that the grid circuit of a tube is actually the input resistance and capacity of the tube in parallel with the external resistor. The maximum input resistance is therefore equal to the dynamic input resistance of the tube itself when any external shunting resistance has been removed. The dynamic input resistance is defined as the reciprocal of the slope of the grid current-vs-grid voltage curve. Steps taken to reduce the magnitude of the grid current usually result in a reduction in the slope of the afore mentioned curve.

Except in the case of a floating grid circuit, to be discussed later, the input resistance of the tube cannot serve as the grid resistor, because in order to have control of the bias on the tube it is necessary to use an external resistor.

The input resistance of a tube may be determined experimentally by use of the circuit shown in Fig.I-b. Select the voltages under which the tube is to be operated. Connect the tube with these voltages on all the electrodes and a current meter in the plate circuit. Connect the control grid directly ($R_g \doteq 0$) to a seurce of adjustable bias. Change the bias throughout the operating range of the tube and make a plot of plate current as a function of grid bias, all other voltages being held fixed. Repeat this process with a large resistor of known value connected between the grid and adjustable bias. This may be done for several values of resistance.

Figs. I-c and I-d show several of these curves* plotted for a 12J7-GT pentode with $22\frac{1}{2}$ volts on the plate and screen, the suppressor tied to cathode, and 7.5 and 4.0 volts, respectively, on the filament. It will be noted that for a given plate current I-p the grid bias E-c applied through the grid resistor R-g differs from the bias E-g (with no grid resistor.) The difference between E-g and E-c is equal to the voltage drop in R-g, or the product of R-g and the grid current I-g at the grid voltage E-g. The same calculation may be carried out for other values of I-p and the corresponding E-g. The grid current I-g may now be plotted as a function of the grid voltage E-g, and from this curve the grid input resistance determined. In making these tests both the tube and grid resistor must be well shielded.

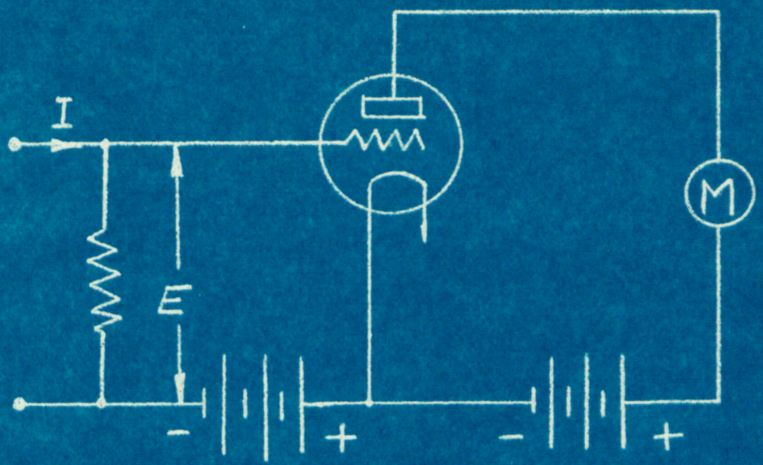
Metcalf[I] has made a thorough study of the grid current in a vacuum tube. Actually, the grid current may be considered as consisting of two components: negative electrons and positive ions. These two components are of nearly the same magnitude, and when they are equal there is no grid current. The potential of the grid when there is no grid current is called the floating grid potential. It is the potential the grid will take on if cut free from any external grid resistor.

---

*All graphs, except Fig. I-f, were plotted from data compiled by the author for individual tubes. Most such data is not given by tube manufacturers and when given represents average characteristics of many tubes.

Fig. I-a Fundamental circuit for current measurements with a vacuum tube.

Fig. I-b Circuit for determining grid current and grid resistance.


I
E
M
-
+
-
+

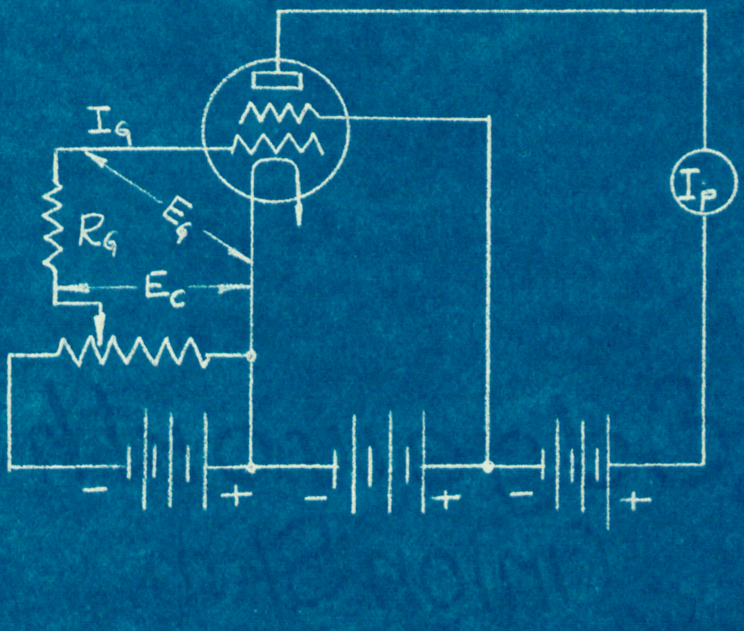
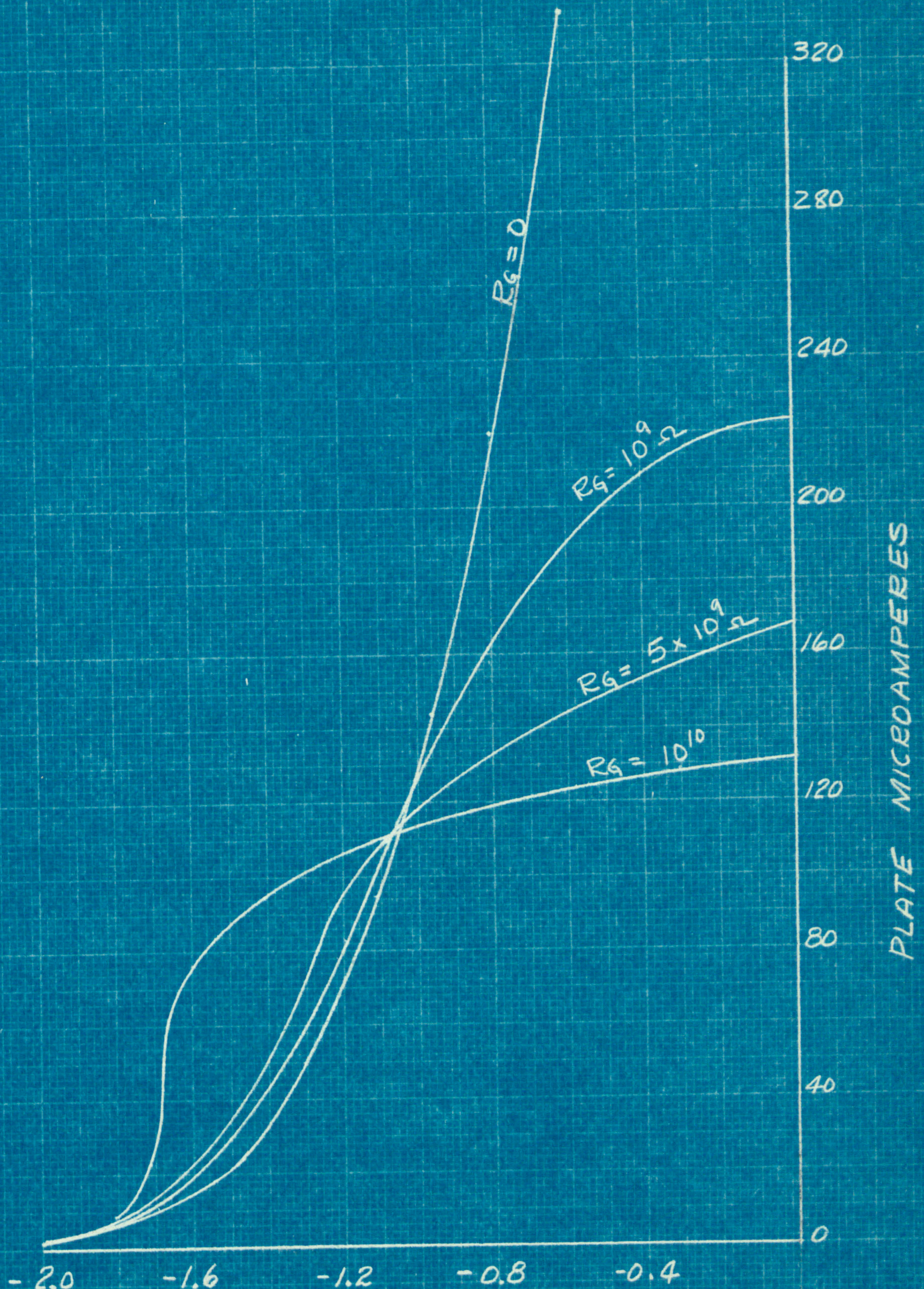
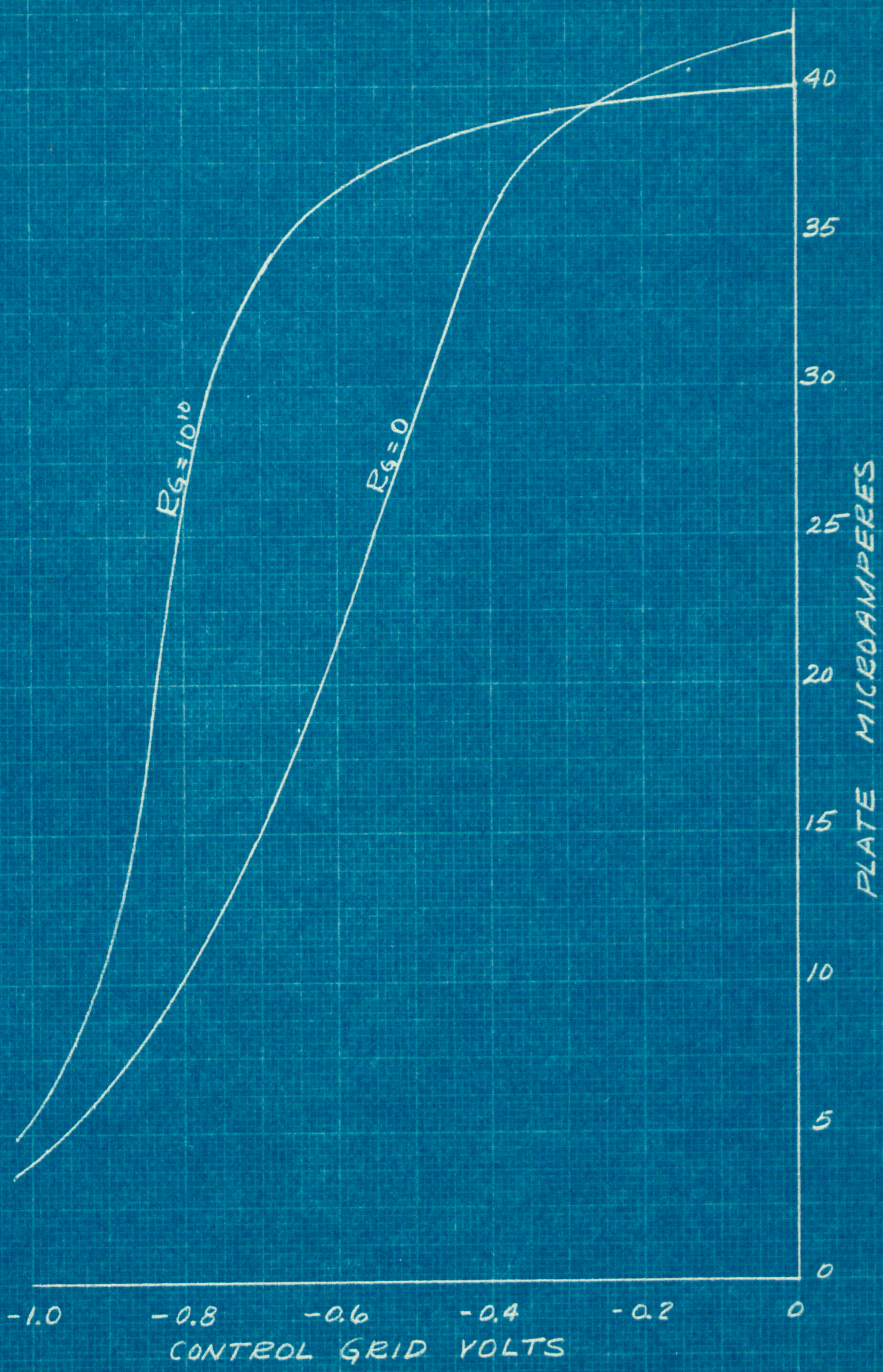

I_g
R_g
E_g
E_c
I_p
-
+
-
+
-
+

Fig. I-c   Plate current as a function of grid bias for several values of grid resistor, for a 12J7-GT tube. E-f = 7.5 volts, E-p = E-sc = 22.5 volts.



$R_G = 0$
$R_G = 10^9 \Omega$
$R_G = 5 \times 10^9 \Omega$
$R_G = 10^{10}$
320
280
240
200
160
120
80
40
0
PLATE MICROAMPERES
- 2.0
-1.6
-1.2
-0.8
-0.4
CONTROL GRID VOLTS

Fig. I-d Plate current as a function of grid bias for R-g = 0 and R-g = 10^{10} ohms for a 12J7-GT tube. E-f = 4.0 volts, E-p = E-sc = 22.5 volts



$R_G = 10^{10}$
$R_G = 0$
0
5
10
15
20
25
30
35
40
PLATE MICROAMPERES
-1.0
-0.8
-0.6
-0.4
-0.2
0
CONTROL GRID VOLTS

When a tube is operating with rated voltage on its elements the control grid current is moderately high. Commerical receiving tubes pass inspection if their grid current is less than 10^{-8} amperes. By lowering all the operating voltages of the tube the grid current can be greatly reduced. Fig. I-e shows the grid current--grid voltage curve for the 12J7-GT under the conditions listed above. Curve A is with 7.5 volts on the filament; Curve B with 4.0 volts on the filament.

Other tubes are available with still lower grid currents and correspondingly higher input resistances. Gabus and Pool[2] describe a special circuit using a 965 acorn tube in an unusual arrangement for the especial purpose of increasing the input resistance of the control element. The suppressor grid is used as the control grid, while the #1 grid is tied to the cathode. The heater is operated with only 4½ volts, the plate at 6 volts, and the screen or #2 grid, at 13½ volts. Under such conditions the dynamic input resistance was about 10^{14} ohms.

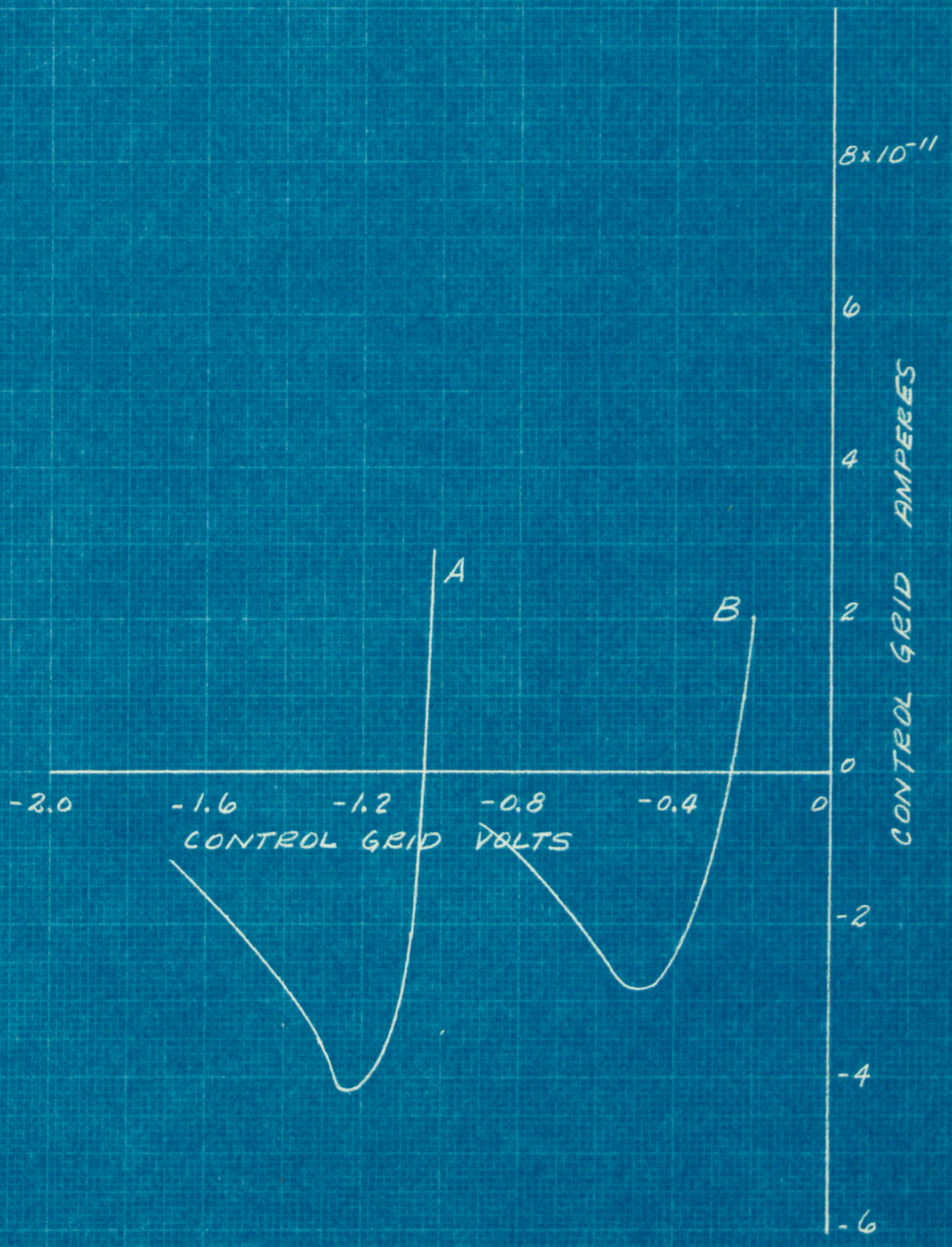
Two special electrometer tubes developed by General Electric[1] and Western Electric[3] for small current measurements have still lower grid currents. The operating voltages and currents for these two tubes are given below in table I-1.

Fig. I-f shows the grid current-vs-grid voltage curve for the Western Electric D-96475 tube.

The curves in Fig. I-e show that for the more negative values of grid voltage the grid resistance of the 12J7-GT

<u>Fig. I-e</u> Grid current as a function of grid voltage for a 12J7-GT tube with 22.5 volts on the plate and screen grid.

Curve A E-f ≠ 7.5 volts
Curve B E-f = 4.0 volts


8x10⁻¹¹
6
4
2
0
-2
-4
-6
CONTROL GRID AMPERES
-2.0
-1.6
-1.2
-0.8
-0.4
0
CONTROL GRID VOLTS
A
B

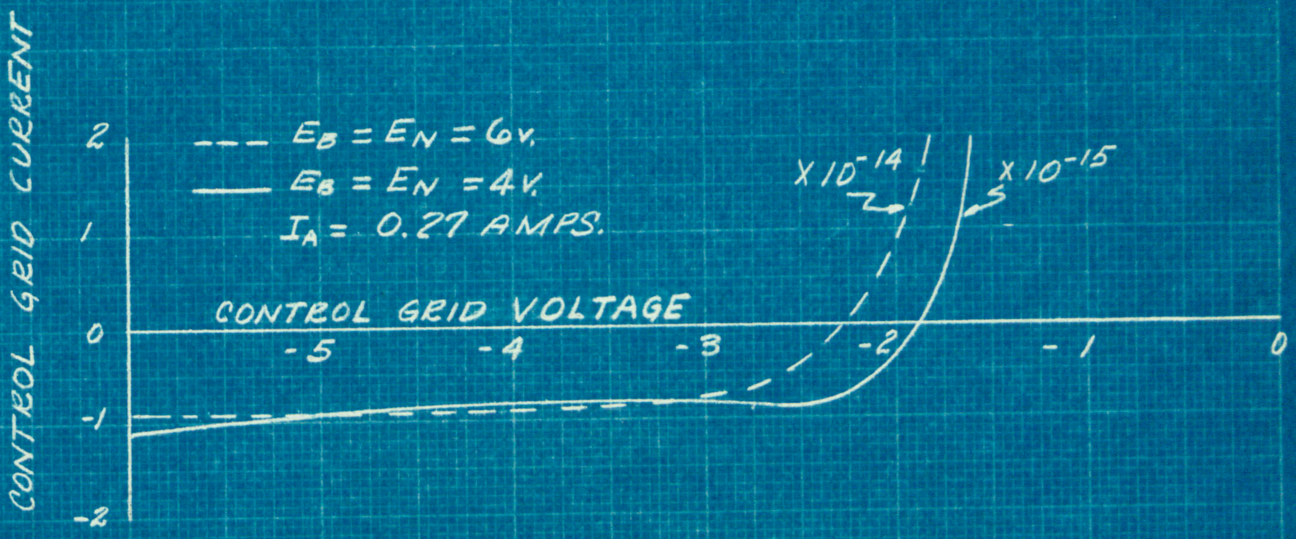
pentode xonnected is negative. MacDonald[4] has used this feature in the construction of a current amplifier. The tremendous gain which may be realized is shown in the curve for R-g $\cong 10^{10}$ ohms in Fig. I-c where in the neighborhood of -1.7 volts on the grid the plate current increases very rapidly with change in grid voltage. However, if R-g is made too large an unstable condition is reached. This is explained by referring to Fig. I-8. Suppose R-g to be very large, and the tube to be biased so that the grid voltage is -1.4 volts. If the current in R-g decreases in absolute value the grid voltage will also decrease, further reducing the grid current. Thus the process in regenerative, and if R-g is too large the grid is only able to sustain one of two

Table I-1

	FP-54	D-96475
Filament volts	2.5	1.0
Filament milliamperes	90	270
Normal Operating Volts		
Plate	6	4
Space Charge Grid	4	4
Control Grid	-4	-3
Normal Operating Currents		
Plate microamperes	60	85
Space Charge Microamperes	200	450
Control Grid amperes	10^{-15}	10^{-15}
Plate resistance	45,000	16,000
Grid-Plate conductance	20	42
Grid resistance	10^{16}	10^{16}

<u>Fig. I-f</u> Grid current vs. Grid voltage for a W. E. D-96475 tube.

(Taken from Bell Telephone Laboratories
Sketch No. ES-519365, IS.2)


CONTROL GRID CURRENT
2
1
0
-1
-2
--- E_B = E_N = 6v.
—— E_B = E_N = 4V.
I_A = 0.27 AMPS.
CONTROL GRID VOLTAGE
-5
-4
-3
-2
-1
0
X 10^-14
X 10^-15

potentials, either cut-off or that where the input resistance becomes positive.

Considerable attention has been given to the grid circuit of a vacuum tube in this chapter because its importance is easily overlooked and the matter here presented will be used extensively in Chapter III.

Bibliography for Chapter I

[1] Metcalf and Thompson:	Physical Review	36, 1489	(1930)
[2] Gabus and Pool:	R.S.I.	8, 196	(1937)
[3] Pennick:	Bell Lab. Record	XIV, 3, 74	(1935)
[4] MacDonald:	Physics	7, 265	(1936)

CHAPTER II

BRIDGE CIRCUITS

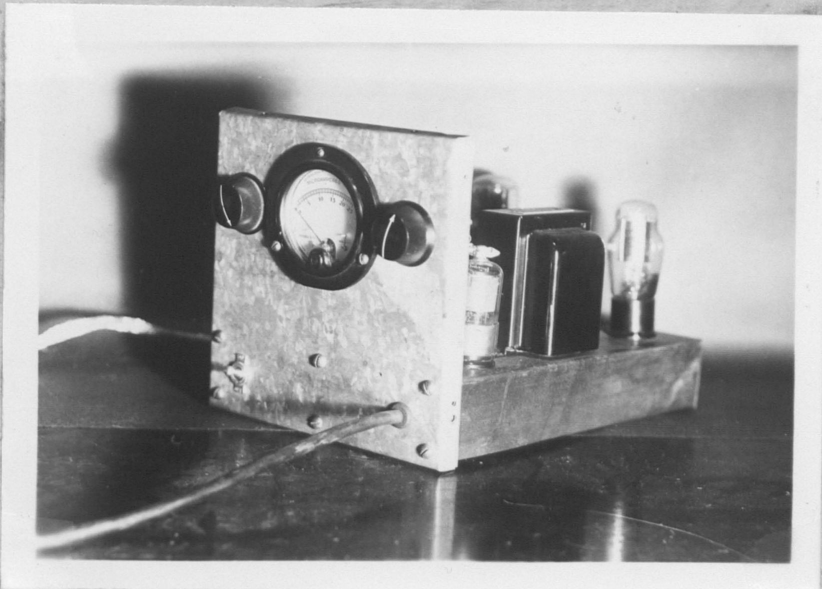
The chief reason for including the bridge circuit in a discussion of current measuring equipment is that this was the first circuit used for such a purpose. Wold[1] was granted a patent on the application of the bridge to current measurements in 1916.

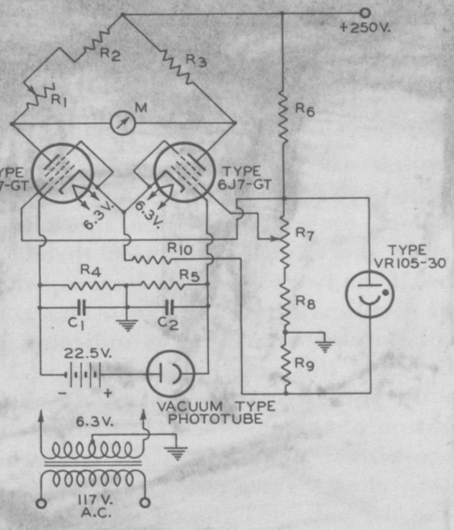
Two tubes as nearly alike as possible are connected in a Wheatstone bridge arrangement, the plate load resistors of the two tubes serving as the other two arms, to the same sources of grid, filament, and plate potentials. The current to be measured flows through one of the grid leaks. It was supposed that with two like tubes connected to the same power source that the plate potentials would remain equal for small changes in applied voltage, and be subject to a mutual change only when an external current flowed through one of the resistors in the grid circuit. The arrangement was found satisfactory in cases where no great current sensitivity is required.

Pictured in Fig. II-a with a schematic diagram[2] shown in Fig. II-b is a modern a.c. operated bridge circuit used as a phototube amplifier. The phototube may be removed and any other input device substituted. Where it is desirable to have one side of the input grounded connections for the input may be made between either grid and ground. Although the bridge

Fig. I-a A Bridge-type Amplifier

Fig. I-b Circuit diagram of bridge-type amplifier





R_1 = 1000 OHMS, 1 WATT
R_2, R_3 = 50,000 OHMS, 1 WATT
R_4, R_5 = 5 MEGOHMS
R_6 = 6,000 OHMS, 4 WATTS
R_7 = 10,000 OHMS, 1 WATT
R_8 = 2500 OHMS, 1 WATT
R_9 = 500 OHMS, 1 WATT
R_{10} = 900 OHMS, 1 WATT
C_1, C_2 = 0.01 µf
M = MULTI-RANGE MICROAMMETER, 0-10, 0-100, 0-1000 MICROAMPERES.

circuit is supposedly unaffected by changes in applied voltage, regulation of the screen supply voltage is provided by the VR 105-30 tube.

The circuit is subject to drift until all of the elements reach thermal equilibrium. This, to a greater or lesser extent, is true of all direct-current amplifiers. Another observation pertinant to all circuits having high resistance in them is the necessity of adequate shielding.

There is an error and an omission in the circuit shown in Fig. II-b. The connections to the screen grids on the two 6J7-GT tubes must be interchanged. The coarse adjustment of R-7 provides a means of raising the plate potential of the tube to which it is connected while the addition of R-1 provides a means of lowering the plate potential of the tube to which it is connected. It is obvious that these two adjustments must operate on the same tube. The connection for the minus of the 250-volt supply has been omitted. It should connect to the cathode of the VR 105-30 tube.

The response of this instrument is linear from the lowest readable value on the meter to about 1 volt on each grid. The actual calibration depends on the individual tubes used. A test run on two tubes in the laboratory showed the sensitivity to be about 0.75 microamperes /millivolt with the input connected between one grid and ground. With a grid resistor of

5 megohms a reading on the meter of one microampere would indicate 2.67 X 10^{-10} amperes flowing in the input circuit. The sensitivity would be doubled with the grid- to - grid input connection.

Bibliography for Chapter II

[1] Wold U.S. Patent 1,232,879
[2] RCA Phototubes P. 14 (1940)

CHAPTER III

INTEGRATING METERS

When dealing with current measuring devices employing large resistors in the grid circuit, another tube characteristic plays an important part in the operation of the circuit. Shunted around the external grid leak is, in addition to the tube resistance, the capacity of the tube and the input circuit, as shown in Fig. III-a. This capacity is of the order of a few micro-microfarads. When the input resistance and grid leak are of the order of 10^{12} ohms the time constant of the input circuit becomes measurable in seconds, and for each exponent added to the input resistance the time constant*, which is the product of the resistance and capacity of the grid circuit and is equal to the time required for the voltage across the circuit to build up to 63% of its final value, increases by ten fold. Where the increased time constant is tolerable the increased sensitivity brought about by increasing the grid resistance is advantageous.

The smallest current measurements have been made with one of the special tubes referred to in Chapter I. For such measurements three features are essential in the apparatus: power supply stability, high voltage sensitivity, and a high impedance grid circuit.

---

*The equation for the voltage E developed by a current I flowing through a resistance R in parallel with a capacity C is:

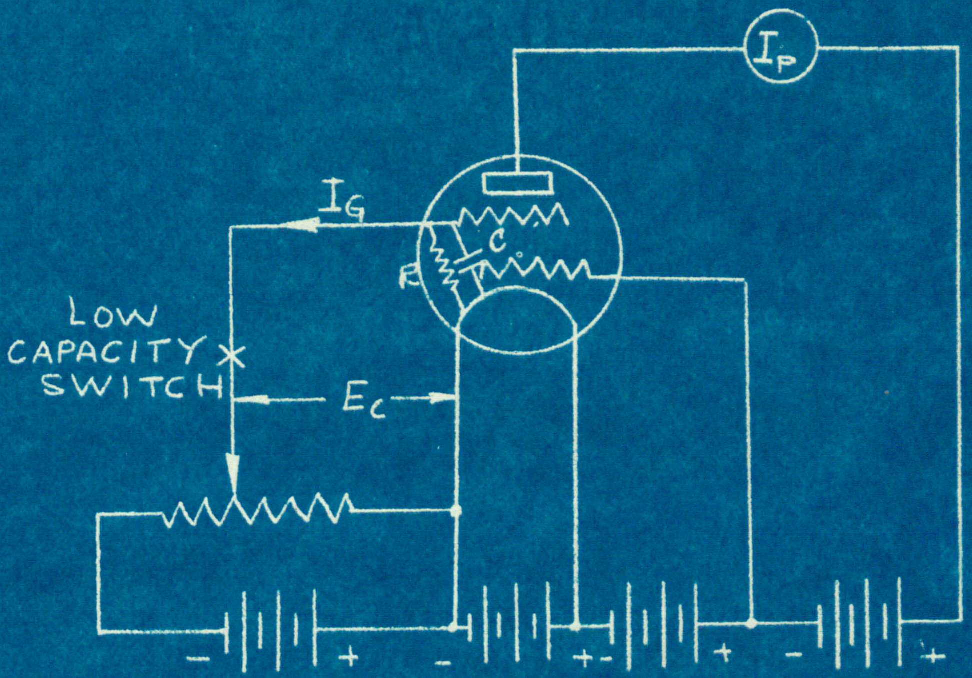
$$E = IR\,(1 - \epsilon^{-t/RC})$$

The "time constant" is defined as the time at which t is numerically equal to the product of R (in ohms) and C (in farads). At this time ϵ^{-1} has a value of 0.368, and $E = 0.632$ IR.

<u>Fig. III-a</u> Circuit showing the grid input circuit of a tube, and a means of determining the input capacity of the tube.

The input resistance of an electrometer tube may be used as the resistor through which the current to be measured flows. The grid and the input circuit with the external current cut off are connected to a source of fixed bias through a low-capacity switch, as shown in Fig. III-a. On opening this switch the grid will be free to take on or give off electrons. The grid potential will drift steadily in one direction until the grid reaches a potential which will render the grid current equal to zero. This potential is called the floating grid potential. At this time the number of electrons and the number of positive ions entering the grid are equal.

While the grid is assuming its floating potential grid current will flow through the internal tube resistance. As a result of this current flow and change in grid potential a meter in the plate circuit which can measure small changes in plate current will likewise drift. If the grid current has already been determined by methods outlined in Chapter I, the rate of drift for that particular value of current in the grid circuit is established. Upon repeating this process with an external current superimposed on the grid current, preferably in the opposite direction, a different rate of drift will be noted. As there is a linear relation between the current in the grid circuit and the rate of drift, provided the tube is operated in a range where its input resistance is constant, the sum of the external and grid current may be readily found.



Ip
IG
C
R
LOW CAPACITY SWITCH
Ec
−
+
−
+
−
+
−
+

The above method is only good for currents of about the same order of magnitude as the current in the tube. For much smaller currents the method fails because of the inconstancy of the grid current. The variations in the grid current are of sufficient size to conceal the presence of any additional current smaller than about 1/10 the average grid current.

Much smaller currents may be measured if the tube is operated without grid resistor at its floating grid potential. This arrangement eliminates the difficulties given above. The sole disadvantage lies in the fact that the grid input resistance is always less at the floating grid potential than at a bias somewhat more negative. As a result, the voltage sensitivity of the measuring equipment must be increased when measurements are made with the floating grid.

For example, in the case of the electrometer tube, Fig.I-f, the input resistance at -3.0 volts is about 10^{16} ohms, while at the potential where the grid current is zero, it is only 10^{14} ohms. In order to produce a deflection of 100 mm with 10^{-16} amperes a galvanometer which would give the amplifier a sensitivity of 100 mm/volt would be required if the grid were set free at a bias of -3.0 volts, whereas if the tube were operating at its floating grid potential the amplifier sensitivity would have to be 10,000 mm/volt in order to yield a 100 mm deflection for a current of 10^{-16} amperes.

In some instances it is useful to know the input capacity.

This is necessary when the time constant for the system must be used in making current calculations. As has been described in Chapter I, it is readily possible to determine the grid current for any value of grid voltage. The input capacity may be found from the rate-of-drift curve referred to above. By means of the mutual characteristics of the tube the plate current-time curve may be changed into a grid voltage - time curve. The equation for this curve is given by:

$$E = IR\,(1 - \varepsilon^{-t/RC}) \qquad \text{III-I}$$

where E is the voltage across the input circuit, I is the grid current, and R and C the resistance and capacity of the input circuit. C may be found by curve fitting methods, or since

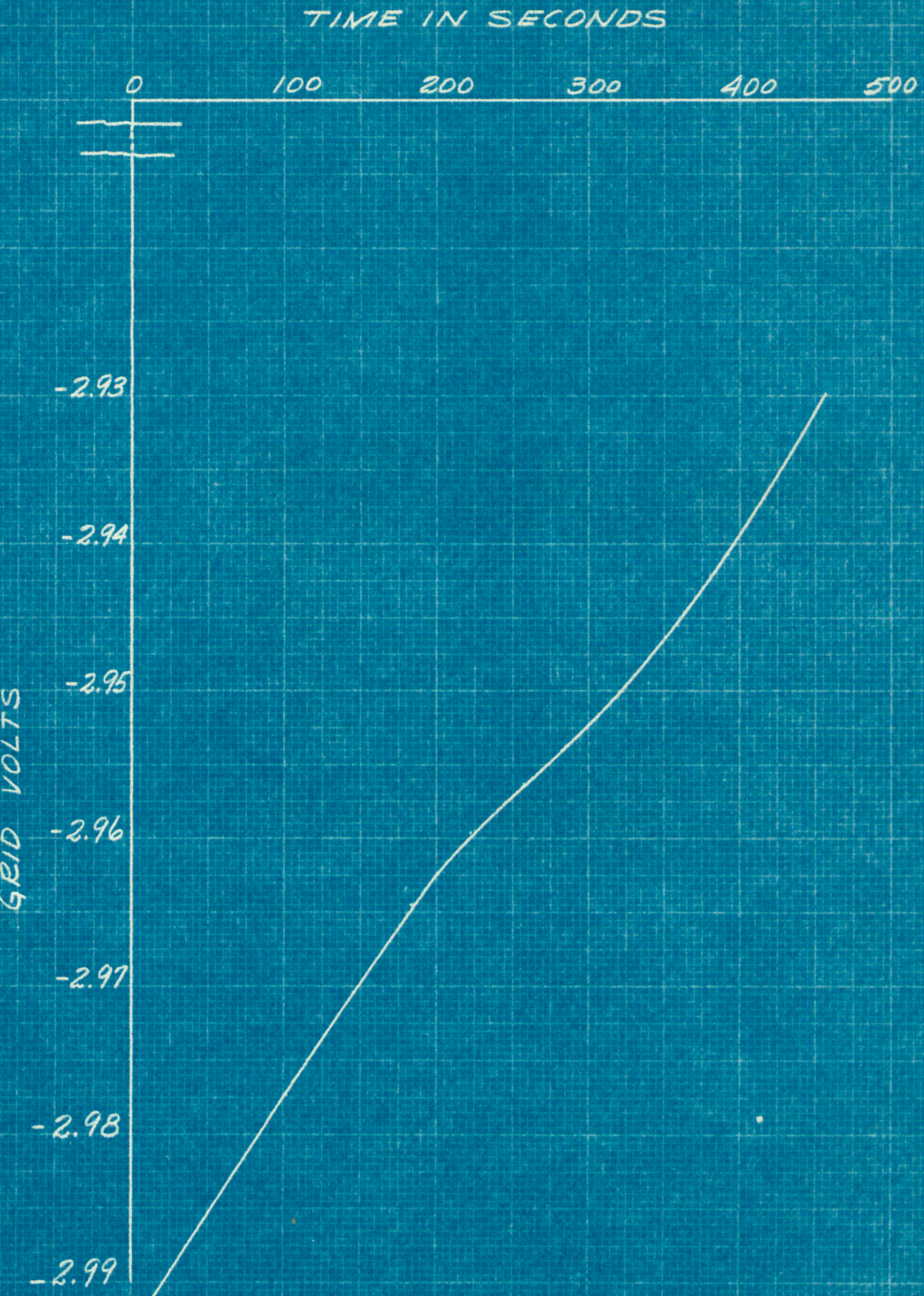
$$\frac{dE}{dt} \doteqdot \frac{IR}{RC}\,\varepsilon^{-t/RC}$$

and at $t = 0$, $$\frac{dE}{dt} = \frac{I}{C} \qquad \text{III-2}$$

C may be found by measuring the initial slope of the E-g vs. time curve. A typical curve for a Western Electric Tube is shown in Fig. III-b. In this instance the grid current at -3.0 volts was 2×10^{-15} amperes. The original slope of the curve is almost 2×10^{-4} volts/sec. Using the formula III-2 the input capacity for this circuit was found to be 10mmfds.

Although the apparatus used by Hafstad[1] was not a.c. operated a dissertation on small current measurements would not be complete without some reference to the peak of sen-

Fig. III-b Grid voltage as a function of time for a W. E. D-96475 tube with the control grid floating.


TIME IN SECONDS
0
100
200
300
400
500
GRID VOLTS
-2.93
-2.94
-2.95
-2.96
-2.97
-2.98
-2.99

sitivity which has been realized. Where extremely small currents are to be measured, an electrometer tube, either the General Electric FP-54 or the Western Electric D-96475, must be used. This type of tube has the most favorable grid input circuit. Most applications of this tube are in balanced circuits, to be discussed in Chapter IV, where it is impossible to compensate for instability caused by battery fluctuations. A balanced circuit is very suitable where an external grid resistor is used, but the author knows of no balanced circuitiin which the control grid is left floating.

For this reason, and to realize higher amplification, Hafstad did away with the balance features, and gained his stability through the use of several sets of batteries so arranged as to mutually compensate for their losses in voltage through use. By permitting the grid to float he also eliminated the instability introduced by fluctuations in the grid current.

Hafstad gave copious data on his instrument and showed several photographic traces of measurements made with it. He used a galvanometer having a sensitivity of 10^{10} mm/ ampere shunted so that the over-all sensitivity of the amplifier was 85,000 mm/volt. The input resistance of the FP-54 tube was approximately 10^{14} ohms, while the input capacity was about 3mmfd. Correlating this data indicated a current sensitivity of 1.2×10^{-19} amp/mm and a charge sensitivity of 200 electrons/mm with an instrument time constant of 300 seconds. The random deflections amounted to ± 3 mm.

When the amplifier was used as a galvanometer a reading of 6 cm. was noted after a period of 7 minutes. This deflection corresponded to a current of 7.2 x 10^{-18} amps. or 45 electrons/sec. Since this reading was only exact to ± 3 mm. the accuracy amounted to 5%. Employing the amplifier as an electrometer Hafstad showed an almost linear trace of galvanometer deflection vs. time in which the deflection was 41 mm. in 30 seconds. This corresponded to a current of 4.3 x 10^{-17} amps. accurate to 7%.

A second type of floating-grid current-measuring instrument, much less complicated and using a type 222 commercial radio receiving tube, is shown in Fig. III-c to-gether with the circuit diagram, Fig. III-d[2]. To operate the instrument the switch is first closed and the potentiometer whose resistance is not critical is adjusted until the meter reads 15 microamperes. If the air in the chamber is now ionized by X-rays or other radiation, the meter will read less in proportion to the ionization current. Although the instrument must be calibrated for each individual tube used, some average values of tube constants and sensitivities will be given. With the voltages shown in Fig. III-d the input resistance of a type 222 tube is 4 x 10^{12} ohms, and the transconductance at the floating grid potential is 20 microamperes/volt. Since on a 0-15 microampere meter it is possible to read 0.1 microamperes, each scale division corresponds to 1.2 x 10^{-15} amperes. These figures were taken from Bennett's original article.

The floating-grid tube has also been used in an a.c.

Fig. III-c A battery-operated integrating meter.

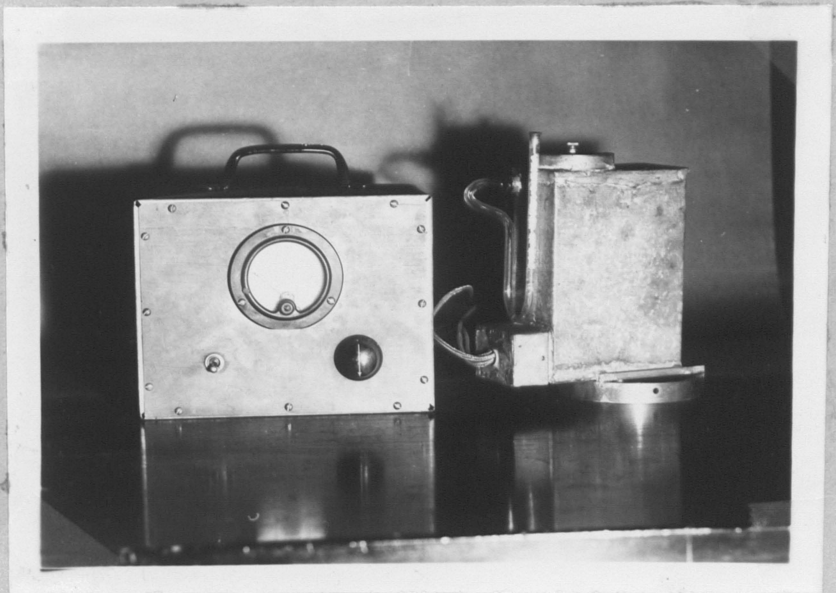
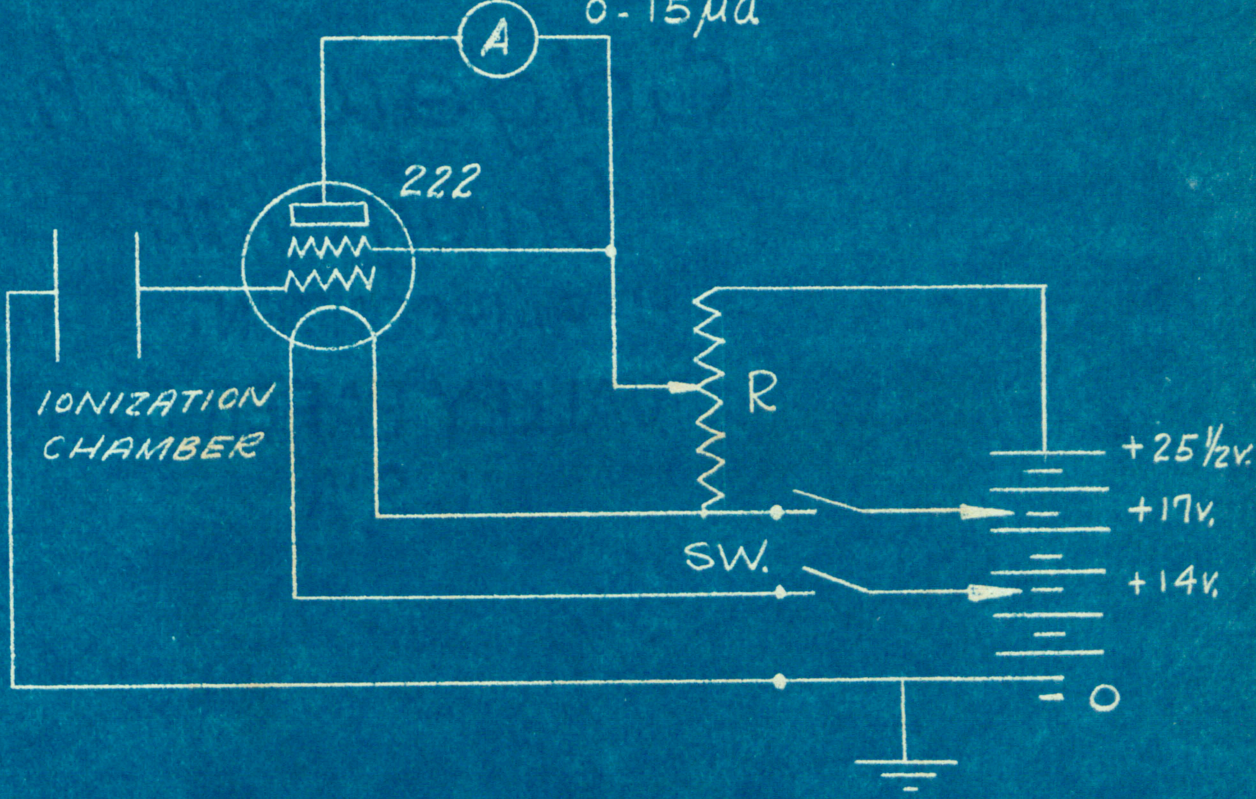


Fig. III-d Circuit diagram for a battery-operated integrating meter.


0-15 μa
A
222
IONIZATION CHAMBER
R
+25½v.
+17v.
SW.
+14v.
- 0

operated pH meter, to be described in the second part of this thesis.

Bibliography for Chapter III

[1] Hafstad: Phys. Rev. 44,201

[2] Bennett: Rev. Sci. Inst. 1, 466

CHAPTER IV

BALANCED CIRCUITS

With the exception of the floating grid circuit described in the preceding chapter, the special purpose electrometer tube used in a balanced circuit has the greatest current sensitivity of any of the pieces of apparatus available for this purpose. The balanced circuit was first described by Soller[1]. Since his original article, many slight modifications have been made, but they all incorporate the basic idea of the Soller circuit.

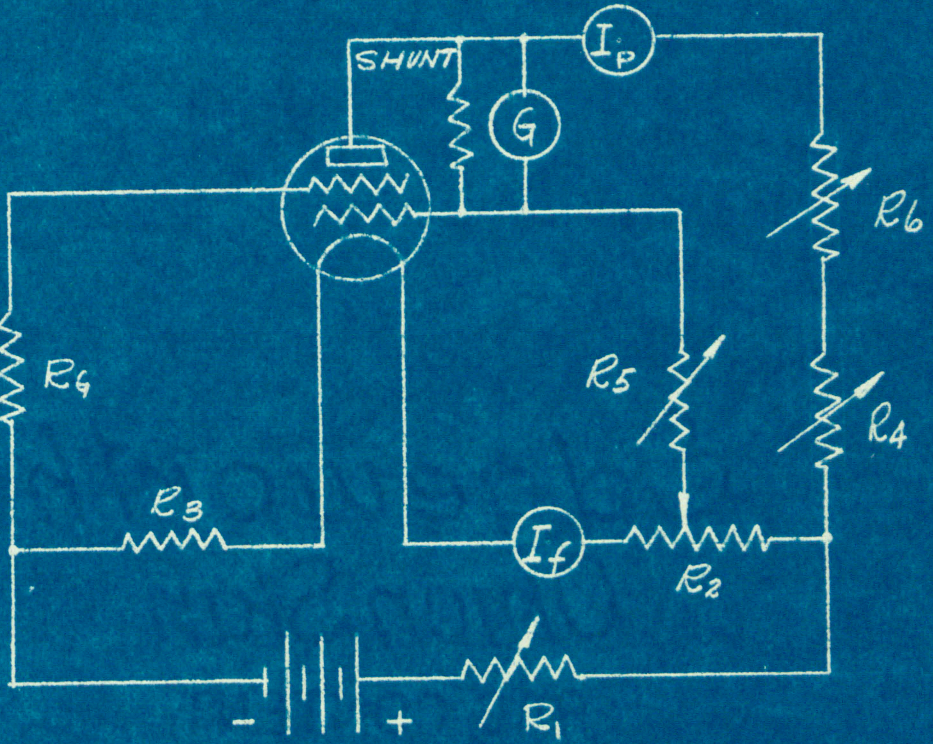
The balanced circuit consists of a vacuum tube amplifier in which two junctions of circuit elements stay at the same potential with respect to one another for small changes in the voltage supplied to the amplifier, while at least one of the junctions is subject to a change in potential when the potential of the control element changes.

While it is possible to construct a balanced circuit in which more than one power supply is used, most balanced circuits use a single supply for grid and anode voltages as well as filament supply. Since the power supply must furnish anode potential at filament current, if the unit is to be run from a single source, the circuit is very wasteful of power if either the anode voltage or the filament current is high. The electrometer tubes described in Chapter I serve admirably in a balanced circuit, since their anode and grid voltages are so low that two 6-volt storage batteries are sufficient for satisfactory operation.

Fig. IV-a shows a typical balanced circuit for a Western Electric D-96475 tube. The circuit is so arranged that the control grid, inner grid, and plate all operate at their rated potentials; i.e., -3 volts on the control grid, a filament current of 0.27 amperes, and a plate and inner grid potential of 4 volts with respect to the negative filament. The plate and inner grid are connected through the variable resistors R-4 and R-5 to sources of different potential on a bleeder consisting of the potentiometer R-2. The galvanometer is connected between the anode and the inner grid assuring these two elements being at the same potential when there is no current indicated in the galvanometer. A plate current meter and a filament current meter are inserted in the circuit as shown to assure proper operating potentials on the various elements.

In balancing the circuit the filament current is first adjusted to its rated value by means of R-1. R-5 and R-6 are then adjusted until the plate current is correct and the galvanometer reads zero simultaneously. A finer adjustment on the galvanometer zero setting may be had by means of R-4. A change in filament current similar to that which would occur with a change in supply voltage is affected by an adjustment of R-1. If a curve of galvanometer deflection is plotted against filament current one of the curves shown in Fig. IV-b will result. Similar curves may be obtained at different inner grid supply potentials which are changed

Fig. IV-a Modified Barth Circuit for a D-96475 tube.
R-1, 7 ohms (see text); R-2, 20 ohms; R-3, 11.1 ohms; R-4, 100,000 ohms; R-5, 10,000 ohms; R-6, 1,000 ohms; I-p, 0-100 microammeter; I-f, 0-300 milliammeter.

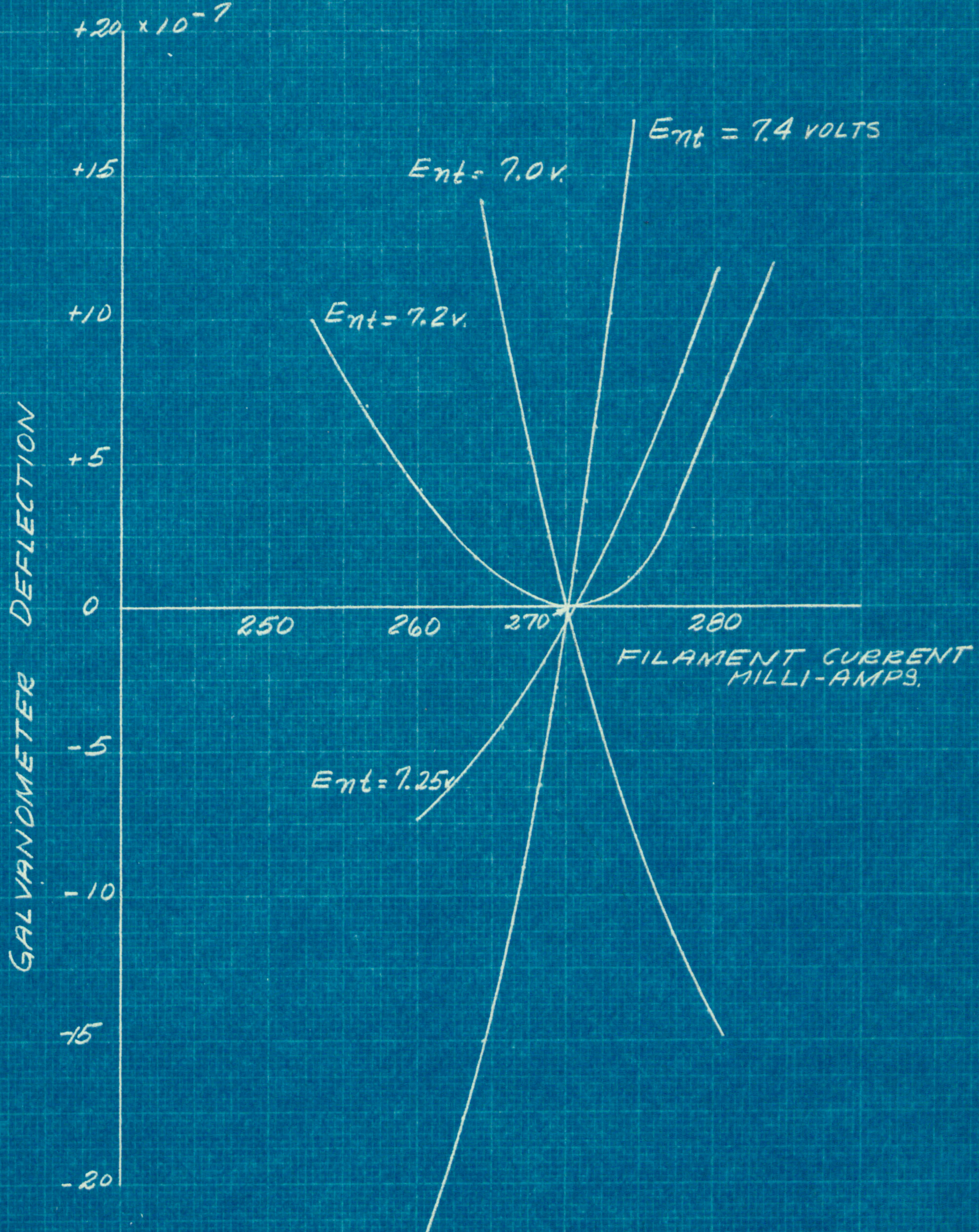


SHUNT
I_p
G
R_6
R_G
R_5
R_4
R_3
I_f
R_2
-
+
R_1

by means of R-2. After one of these changes has been made the galvanometer is returned to zero by an adjustment of R-5. For different values of inner grid supply potentials the curves will have different slopes for zero galvanometer deflection at rated filament current (270 ma.), some negative and some positive, and one will have zero slope; i.e., a flat bottom. This curve is marked 7.2 volts in Fig. IV-b. On these curves the plate supply potential was 9.1 volts. The condition of the circuit when a curve with zero slope is obtained is the "balanced" condition, and for small changes in supply voltage either up or down there will be only a very small change in the galvanometer reading.

As was stated previously there have been various modifications of the original balanced circuit. Pennick[2] has studied these circuits, tested them, and concluded that the Barth circuit, or modified Barth described above and shown in Fig. IV-a, is the most desirable among them. The Barth circuit differs from Fig. IV-a only in the supply potentials for the anode and inner grid. In the Barth circuit the anode supply potential is less than the inner grid supply potential, while in the modified Barth the inner grid is supplied from a lower potential than the plate supply. Whether the Barth or modified Barth circuit is used depends entirely upon the tube to be incorporated in the circuit. The electrometer tubes differ sufficiently in their characteristics so that only by setting up one or the other circuits and running curves as shown in Fig. IV-b

Fig. IV-b Galvanometer Deflection as a function of Filament Current for various settings of R-2 in the Modified Barth Circuit.


+20 ×10⁻⁷
+15
+10
+5
0
-5
-10
-15
-20
GALVANOMETER DEFLECTION
250
260
270
280
FILAMENT CURRENT MILLI-AMPS.
Ent = 7.4 VOLTS
Ent = 7.0 v.
Ent = 7.2 v.
Ent = 7.25 v

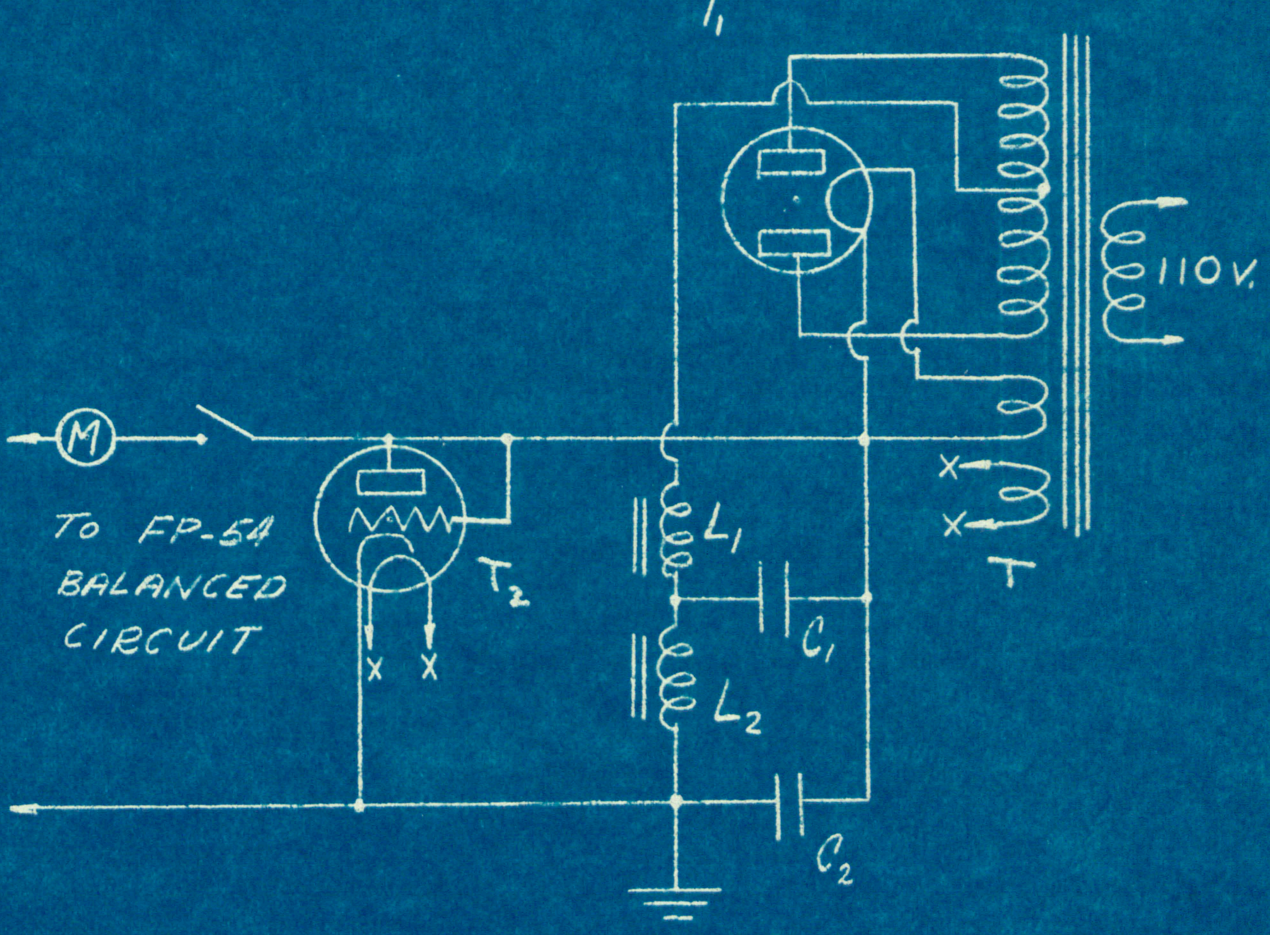
is it possible to determine which circuit is required for the particular tube on hand. If, for example, the modified Barth circuit has been set up and the curves for different values of inner grid supply potential run, and if no setting gives a curve with zero slope, although the slope of the curve becomes numerically less as the inner grid supply is increased up to the plate supply potential, then it will be necessary to change over to the Barth circuit.

With lead storage batteries and a balanced circuit sufficient stability can be had to use a galvanometer having a sensitivity of 10^{-10} amperes per millimeter. With such a galvanometer the balanced circuit has a voltage sensitivity of 250,000 millimeters per volt. If an input resistor of 10^{12} ohms is used then 10^{-17} amperes is detectable. The instrument will have a time constant of about 3 seconds.

Two types of a.c. operated balanced circuits will be shown and discussed. In a balanced circuit operating from the 110-volt alternating current line the balanced circuit itself is left unchanged, and the alternating current rectified, filtered, and stabilized so as to give a voltage of constancy comparable with that of a set of batteries.

A rectifier circuit used by Harnwell[3] relies on the constancy of the voltage drop in an 885 tube to stabilize the direct current output. The circuit diagram for the rectifier is shown in Fig. IV-c. This circuit may be connected to any balanced circuit[2] using an FP-54 tube. It is a conventional rectifier-filter circuit in which the load consists of the balanced circuit and 885 tube in parallel. The voltage drop across this gas-filled tube

Fig. IV-c Regulated Power Supply for a FP-54 balanced circuit.
T, transformer with 2.5 v. or 6.3 v., 5.0 v., and 270-0-270 v. windings; T-1, 80; T-2, 885 or 884; C-1, C-2, 16 mfds, 250 v.; L-1, L-2, 30 h. 500 ohm, 0.2 amp. chokes; M, 0-100 milliammeter


T₁
110V.
M
X
X
T
L₁
C₁
L₂
C₂
T₂
X
X
To FP-54
BALANCED
CIRCUIT

is relatively constant over a wide range of currents, and the tube draws a sufficient current in addition to that drawn by the balanced circuit through the filter chokes to keep the voltage output constant at about 14 volts.

The disadvantage of this circuit is that when the switch to the balanced circuit is open, as it should be until the 885 is functioning properly, all the load current has to pass through the 885. This over-loads the tube and the power supply should not be left on for long periods with the balanced circuit disconnected.

A second type of power supply with probably greater stability is shown in Fig. VI-a in the chapter dealing with voltage regulators. Using this circuit and paralleling a second rectifier tube and a third 2A3 the power supply has sufficient current capacity for the Western Electric D-96475 tube. This regulated power supply has been used in place of the battery shown in Fig. IV-a, the resistor R-1 being replaced with a 600-ohm fixed resistor. A small variable resistor of sufficient size to change the output voltage by a few volts was inserted in series with R-2, Fig. VI-a. This was used to check for balance in place of a variable resistor R-1 as shown in Fig. IV-a. This is a considerable advantage as it provides a much smoother means of adjusting the voltage, and the change in voltage is accomplished without a sliding contact carrying a heavy current.

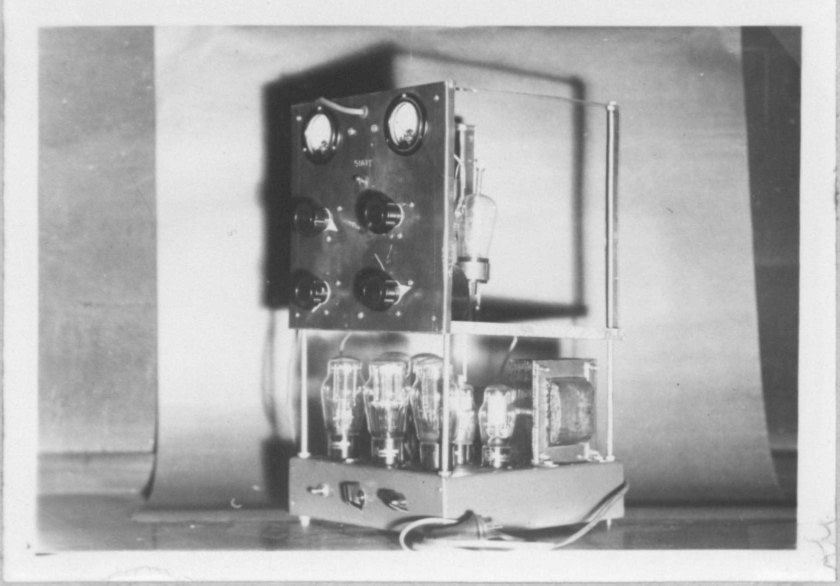
The combination of the units diagrammed in Figs. IV-a and

VI-a and photographed in Fig. IV-d have been tested and found very satisfactory for measuring small currents in a strong electrical field, such as is encountered in the neighborhood of a gas x-ray tube. Previous work[4] had shown that for sensitive measurements under such adverse conditions it was necessary to have all the equipment, including power supply, tube and meter in a single shielded unit. The apparatus shown in Fig. IV-d has several advantages over the equipment formerly used, which consisted of a balanced circuit, galvanometer, and two lead batteries in a single box. It is much smaller in volume, lighter, and completely a.c. operated.

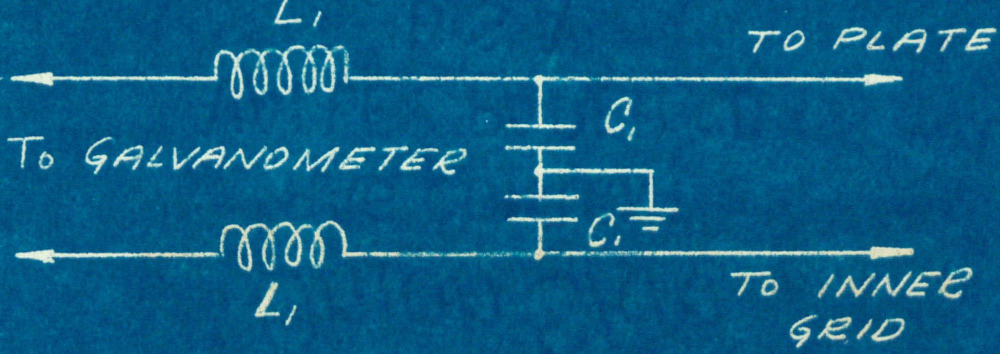
By means of the filter circuit shown in Fig. IV-e it has been possible to locate the galvanometer some distance from the rest of the apparatus. The whole problem of shielding and the reasons why it was not formerly possible to remove the galvanometer from the single enclosure surrounding the balanced circuit and power supply have been discussed in a previous paper[4]. The leads connecting an external galvanometer to the balanced circuit, being in a strong electric field, picked up a sizable radio-frequency voltage. Through the balanced circuit this voltage appeared on the control grid of the electrometer tube and was of sufficient magnitude to block the grid*, and render the amplifier inoperative. The filter, consisting of 85 mh.chokes

*A blocked grid is effected on any tube having a high resistance d.c. path in the grid circuit and subjected to an alter-

Fig. IV-d An A.C. Operated Balanced Circuit


START

<u>Fig. IV-e</u> Radio frequency filter for galvanometer
L-1, 85 millihenry shielded choke; C-1, 0.1 mfd.


L_1
TO PLATE
C_1
To GALVANOMETER
C_1
L_1
To INNER GRID

and 0.01 mfd. condensers prohibited most of the radio-frequency voltage from entering the balanced circuit, but at the same time afforded a d.c. path for the galvanometer current.

Tests made with the unit (R-g = 10^{12} ohms) located near the x-ray tube showed no deflection on a 100 microampere galvanometer when the x-ray tube was running.

The author has found one major disadvantage to the electrometer tube. This same disadvantage has manifested itself in several different types of circuits envolving the D-96475 tube. The tube is subject to a steady drift, regardless of the type circuit used. This drift continues, at a decreasing rate, for several days. For this reason, in using the electrometer tube it is necessary to have it run continuously so that the drift may be a minimum. The exact cause of this drift has not been ascertained by the author.

nating current voltage much greater than the bias. When the grid is swung positive by the a.c. voltage, positive grid current flows and builds up a negative charge on the grid and its associated capacitance which does not leak away on the negative half cycle of the a.c. voltage swing, since the negative grid current is so much less than the positive current. The net result of a large grid swing and a high-resistance d.c. path is to make the grid exceedingly negative and reduce the plate current to almost zero.

Bibliography for Chapter IV

[1] Soller: Rev. Sci. Inst. 3, 416 (1932)
[2] Penick: Rev. Sci. Inst. 6, 115 (1935)
[3] Harnwell: Am. Phys. Teach. 3, 82 (1935)
[4] Krebs: M.Sc. Thesis, U.C. (1941)

CHAPTER V

FEEDBACK AMPLIFIERS

The author has investigated rather completely most of the current measuring equipment described in the literature, and is able to make the unqualified statement that for current measurements between one microampere and 10^{-12} amperes in high resistance circuits, the feed-back amplifier is without peer. Original credit for feed-back amplifiers must go to Black[1]. As applied to the current measuring equipment under discussion, the feed-back principle was first described by Roberts[2]. Others[3] have made slight modifications in it. The author has combined all these with some of his own to produce an extremely simple, compact, and easily constructed and operated current measuring instrument for the range listed above.

Referring to the circuit shown in Fig. V-a the output of the amplifier appearing across R-2 is given by

$$E_o = R_2 (I_2 - I_1)$$

and the input voltage from ground to the first grid is

$$E_i = R_2 (I_1 - I_2) + R_1 I_1$$

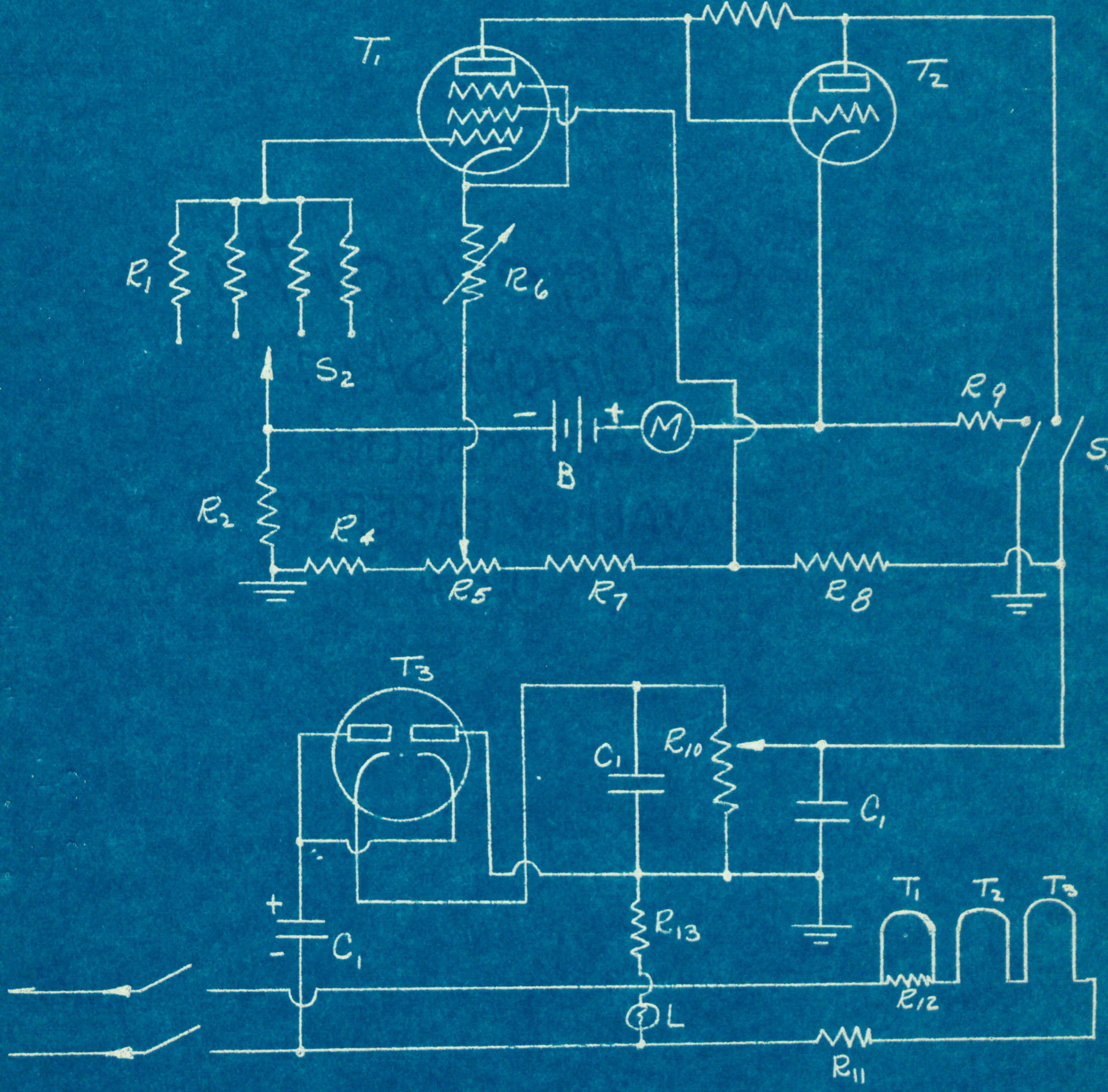
Then $E_o = u E_1$ where u is the voltage amplification of the two stages without feedback. Therefore,

$$R_2 (I_2 - I_1) = u \left\{ R_2 (I_1 - I_2) + R_1 I_1 \right\}$$

$$R_1 I_1 = R_2 I_2 \left(\frac{1}{u} - \frac{I_1}{uI_2} - \frac{I_1}{I_2} + 1 \right)$$

$$R_1 I_1 = R_2 I_2 \left\{ \frac{1}{u} + I \right) \left(1 - \frac{I_1}{I_2} \right\} \qquad \text{V-3}$$

Fig. V-a Circuit diagram for feed-back amplifier R-1, see text; R-2, 2,500 ohms; R-3, 3 megohms; R-4, 500 ohms; R-5, 500-ohm potentiometer; R-6, 1,000-ohm rheostat; R-7, 25,000 ohms; R-8, 120,000 ohms; R-9, 50,000 ohms; R-10, 25,000-ohm dividohm; R-11, 320-ohm cordohm; R-12, 150 ohms; R-13, 200 ohms; C-1, 16 mfds; T-1, 12J7-GT; T-2, 12SF5-GT; T-3, 50Y6-GT; S-1, DPST switch; S-2, six-position selector switch; S-3, DPST switch; M, 0-30 microammeter; B, 22½-volt battery; L, 0.5-ampere lamp.


R_3
T_1
T_2
R_1
R_6
S_2
R_9
S_3
−
+
M
B
R_2
R_4
R_5
R_7
R_8
T_3
C_1
R_{10}
C_1
+
−
C_1
R_{13}
T_1
T_2
T_3
R_{12}
L
R_{11}

And, if u is large compared with 1, and if I-1 is small compared with I-2, then the relation holds very closely that

$$I_1 R_1 = I_2 R_2 \qquad \text{V-4}$$

The outstanding features of this amplifier are as follows: First, it uses tubes and parts easily obtainable. Second, a single adjustment is required to prepare the meter for a measurement (the resistor R-6 is only a convenience.) Third, the instrument requires no calibration, and is always assured of giving results to the accuracy independent of fluctuations in line voltage up to ± 10 volts.

To operate the feed-back amplifier, the selector switch S-2 is set to connect the proper R-1 for the current to be measured. The power switch S is next turned on. If the amplifier is connected to an external ground, it is necessary to have the power cord correctly inserted in the 110-volt outlet. Should the plug be incorrectly inserted the pilot lamp L will burn when the switch S is closed. If this be the case, the plug must be reversed immediately.

After the plug has been correctly inserted, the instrument should be allowed to warm up several minutes. At the end of this period the switch S-3 may be closed. The potentiometer R-5 is then adjusted to bring the meter to zero. The rheostat R-6 will give a finer adjustment. The instrument is now ready for a current measurement.

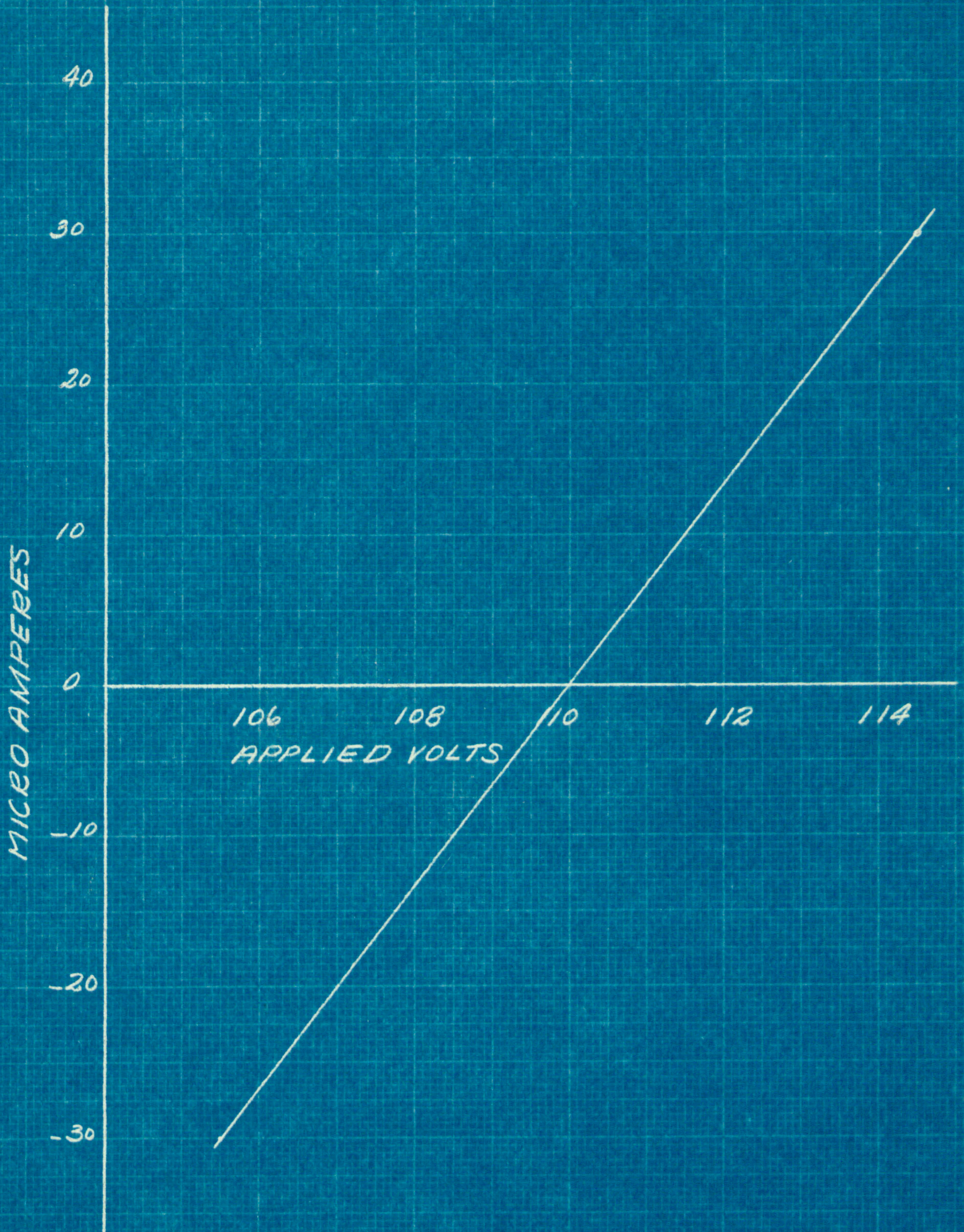
The circuit in which the current is to be determined should be opened, and the two ends of the circuit thus produced connected between the first grid and ground. By noting the change in the microammeter, and substituting in the formula V-4, given above, where all is known except I-1, I-1 may be solved for.

In using the instrument, two factors limit its ultimate sensitivity. One is the stability of the power being supplied to the instrument, the other is the grid current in the first tube.

Variations in the line voltage produce changes in the zero reading of the instrument. Fig. V-b shows the meter reading as a function of line voltage. In cases where the current to be measured can be applied and removed quickly, this factor presents no difficulty, as the reading with the current flowing may be noted, the current removed, and a second reading taken. The difference in the two readings will give the indication of the amount of current under measurement. This difference will be constant for the same current and independent of the magnitude of the second reading, or so-called "zero-setting".

Much greater sensitivity may be obtained by using a wall-type galvanometer in place of the microammeter, and an electronically regulated power supply to be described in Chapter VI. The author has found that line-voltage fluctuations encountered in the laboratory can be reduced to the point where the variations shown on the galvanometer in the feed-back amplifier are only $\pm 5\times10^{-8}$ amperes with a 20 megohm grid resistor for R-1.

Fig. V-b Meter reading as a function of line voltage for a feed-back amplifier.


40
30
20
10
0
-10
-20
-30
-40
MICRO AMPERES
106
108
110
112
114
APPLIED VOLTS

So far as actual practice is concerned power supply voltage fluctuations do not limit the ultimate sensitivity of the instrument so much as the fluctuations in the control-grid current of the first tube. The magnitude of this current is of no great importance. Any drop accrued in R-1 may be compensated for by an adjustment of R-5. The necessary consideration is that this current be constant. Unfortunately, the grid current in commercial receiving tubes varies considerably. For example, in the case of a 12J7-GT running at 7 volts on the filament, and 20 to 25 volts on the screen and plate, the control-grid current varied $\pm$ 5x10^{-13} amperes. If the resistor R-2 were 2500 ohms and R-1 were 10^{10} ohms, then this variation in current would produce an unstable reading of $\pm$ 2 microamperes on the meter. Such inconstancy is greater than that encountered with line voltage fluctuations at lower values of R-1, and sets the upper limit for sensitivity through the increasing of R-1.

Where it is not necessary to have a convenient ratio between the currents I-1 and I-2, further sensitivity may be obtained by dispensing with R-2 altogether and substituting the galvanometer or microammeter in place of R-2. In changing the size of the resistance across which the output appears, care must be taken not to reduce the voltage amplification of the two tubes below a value consistent with the assumptions made in the foregoing derivations. It is probable that the first stage, even though operating at reduced voltages, still has a gain of about 100. The gain of the second stage is given by

$$\text{Voltage Amplification} = \frac{R_2}{1/g_m + (R_2 + R_g)\ (1 + 1/u)} \qquad \text{V-5}$$

where g_m is the mutual conductance of the second tube, u the amplification factor of that tube, and R-g the resistance of the meter or galvanometer. If the product of the voltage amplifications of the two tubes is still sufficient to keep the assumptions made above valid, then the amplifier should perform satisfactorily.

Another useful application of this instrument is in the measurement of high resistances. This is done by connecting the unknown resistance in series with a source of known potential to the grid of the first tube. The other terminal of the potential should be connected to ground. Ohm's law and the fundamental relation for the feed-back amplifier determine the value of the unknown resistance. Let I-2 be the current difference read on the meter when the potential E is applied through the unknown resistance R-x between the grid of the first tube and ground. Then (I-2)(R-2) is the voltage drop across R-2, and is equal to the voltage drop across R-1. But this drop is equal to (R-1) ÷ (R-1 + R-x) times E, or:

$$I_2 R_2 = \frac{E \times R_1}{R_1 + R_x}$$

and solving for R-x:

$$R_x = \frac{E \times R_1}{I_2 R_2} - R_1$$

An attempt was made to use an electrometer tube as the first tube in a feed-back amplifier. If this could be done, the input resistance R-1 could be made 10^{12} ohms instead of 10^{10} ohms, the limiting value for a tube such as the 12J7-GT or 6W7-G. This increase in the resistance would raise the current sensitivity of the amplifier 100 times.

The circuit used is shown in Fig. V-c. In a negative feed-back amplifier, such as this is, it is required that the output voltage be 180° out of phase with the input voltage. To fulfill this condition it is necessary to use the inner grid rather than the anode as the output element. An increase in the control-grid voltage also produces an increase in the inner-grid potential. With no phase shift in the first tube, one phase shift in the second tube, and no phase shift in the third tube, there is but one phase shift in the amplifier and the output voltage is opposite to that of the input, satisfying the conditions for inverse feed-back.

The gain obtainable from the inner grid of an electrometer tube is very small, even smaller than that realizable from the plate. Fig. V-d shows curves drawn to measure the voltage gain on this grid for two different W.E. D-86475 tubes. Curves 2 and 4 were taken with sufficiently high load resistors to make practically full use of the available gain. With

<u>Fig. V-c</u> Circuit diagram of feed-back amplifier using electrometer tube.
T-1, D-96475; T-2, 6W7-G; T-3, 12SF5-GT; R-1, 10^{12} ohms; R-2, 2,500 ohms; R-3, 11.1 ohms; R-4, 18 ohms; R-5, 50-ohm potentiometer; R-6, 100 ohms; R-7, 12,000 ohms; R-8, 100-ohm rheostat; R-9, 1,000-ohm rheostat; R-10, 500-ohm dividohm; R-11, 100,000 ohms; R-12, 1 megohm; B, 45-volt battery; M, 10^{-8} galvanometer.

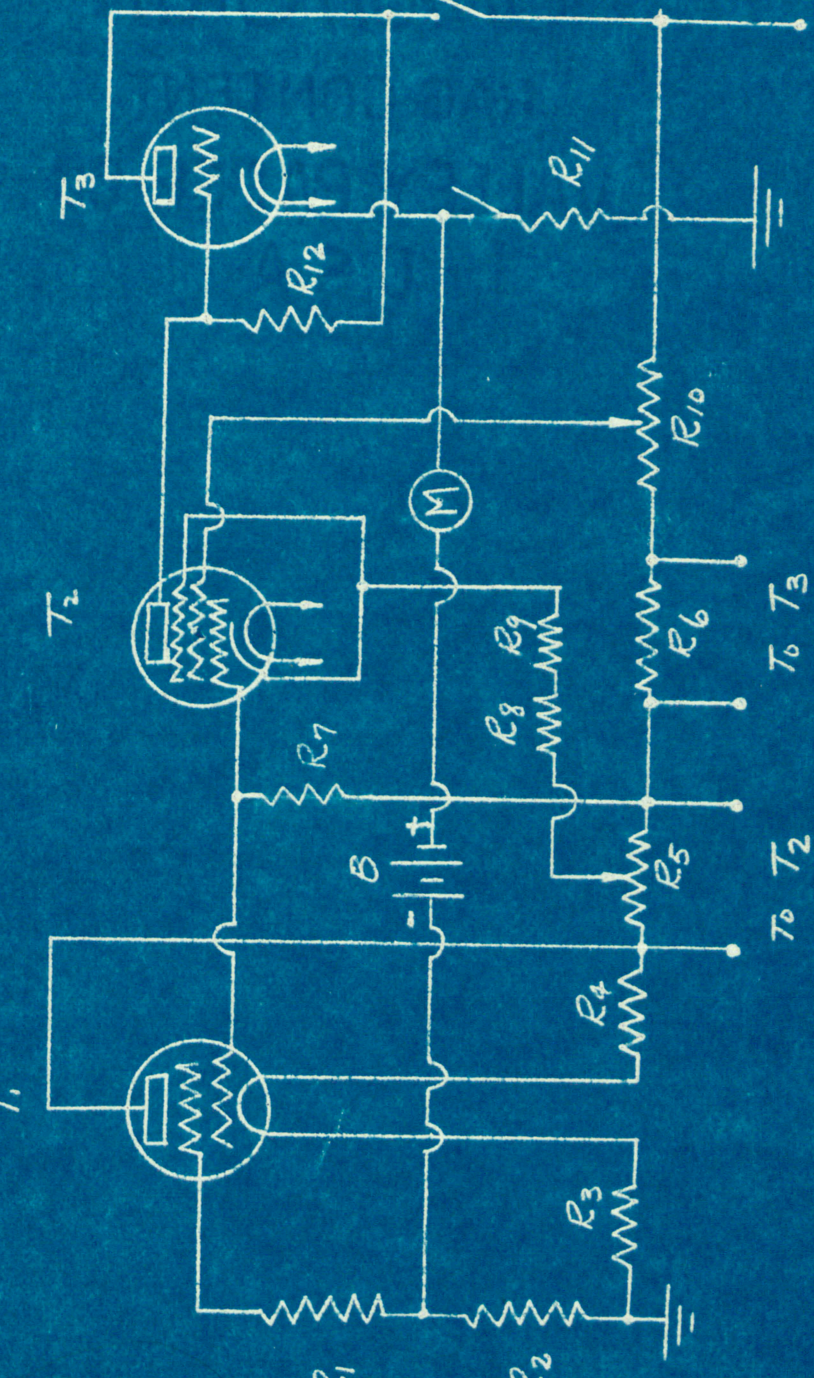

T1
T2
T3
R1
R2
R3
R4
R5
R6
R7
R8
R9
R10
R11
R12
B
-
+
M
To T2
To T3

Fig. V-d Mutual characteristics between control grid and inner grid for two D-96475 tubes.

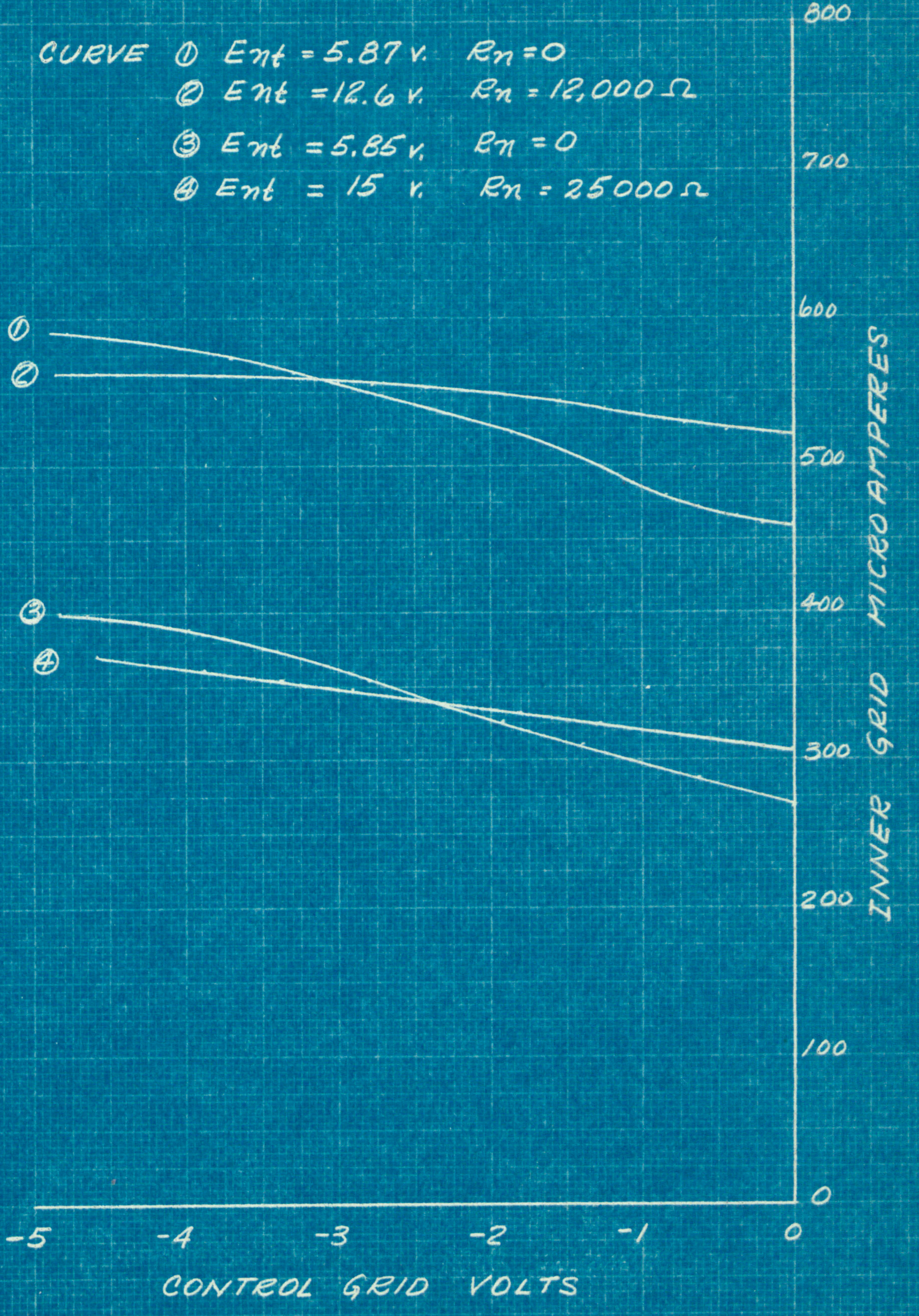
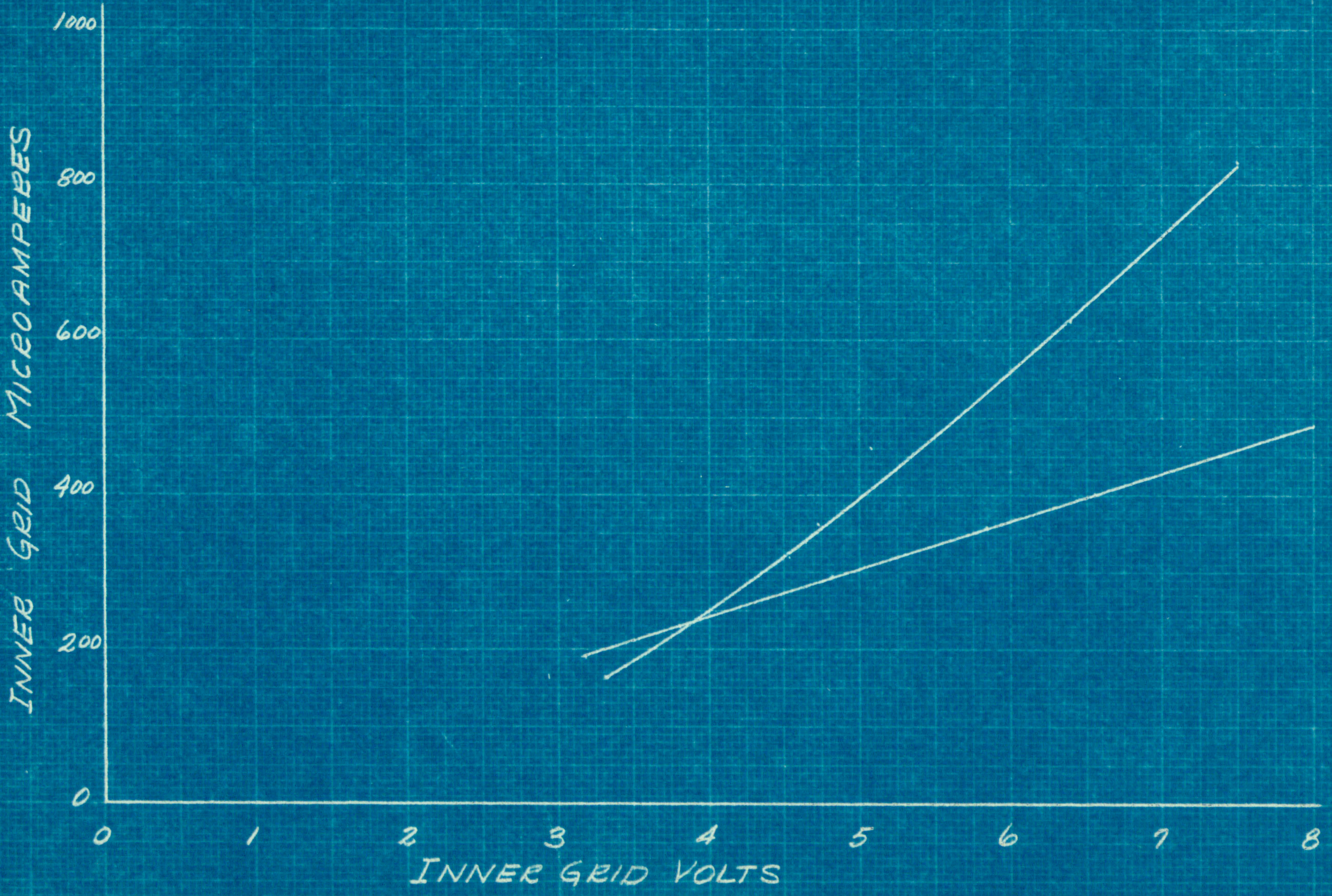

CURVE ① Ent = 5.87 v. Rn = 0
② Ent = 12.6 v. Rn = 12,000 Ω
③ Ent = 5.85 v. Rn = 0
④ Ent = 15 v. Rn = 25000 Ω
①
②
③
④
800
700
600
500
400
300
200
100
0
INNER GRID MICROAMPERES
-5
-4
-3
-2
-1
0
CONTROL GRID VOLTS

Fig. V-e Curves for computing inner grid resistance of two D-96475 tubes.


1000
800
600
400
200
0
INNER GRID MICROAMPERES
0
1
2
3
4
5
6
7
8
INNER GRID VOLTS

5.85 volts on the plate and -3.0 volts on the grid the measured gains were 0.086 and .35. (It will be noted that the two sets of curves differ widely for the two tubes, and also are much different from those values published by the Bell Laboratories). Curves 1 and 3 show the mutual characteristics for the inner grid of the electrometer tube while Fig, V-e shows the grid voltage-grid current characteristics.

In the circuit shown in Fig. V-c the gain of the first tube is about 0.08, the gain[4] of the second tube approximately 180, and the gain of the last tube, calculated from the formula V-5, 0.8. The over-all gain of the amplifier is, therefore, only about 12. This, as can be seen from formula V-3, puts formula V-4 in error by about 8.5%. This is not a serious disadvantage, as it is a correction which could be made on all readings. However, this low value of u greatly reduces the stability of the amplifier, so that even when the power supply is of the voltage regulator type, described in the next chapter, the change in the galvanometer with change in line voltage is as great as is the case of the amplifier shown in Fig. V-a.

Because the use of an electrometer tube as the first stage of a feedback circuit does increase the current sensitivity so much, the use of electrometer tubes in such circuits warrants further investigation. Perhaps another tube could be used in cascade with the three shown in Fig.V-c, a resistor inserted in the plate lead of the W.E. D-96475, and the plate used as the output element of this tube, without instability and positive feed-back arising, as is common in so many amplifiers using more than two high-gain stages. It goes without saying that the General Electric FP-54 tube could be substituted for the W.E. D-96475 with a considerable saving in power consumption.

<u>Bibliography for Chapter V</u>

[1] Black: Electrical Engineering 53, 114 (1934)
[2] Roberts: Rev. Sci. Inst. 10, 181 (1939)
[3] Langer & Kurie: Rev. Sci. Inst. 11, 181 (1940)
[4] RCA Receiving Tube Manual, Technical Series RC-14, 199, (1940)

CHAPTER VI

Voltage Regulators

When it is necessary to have extreme sensitivity in a piece of electronic apparatus, the most frequent limiting factor is inconstancy in some voltage in the apparatus. Very often there are means of increasing the sensitivity of the equipment provided it is sufficiently stable to use the increased sensitivity. Increasing the sensitivity by using a more sensitive meter or by increasing the amplification is of no use if the indicating instrument is unstable and shows random deflections. In such a case the maximum sensitivity is determined by the instability of the apparatus.

Should this instability be caused by changes in the applied voltage an electronic voltage stabilizer[1] may be employed. In laboratories served by public utilities voltage fluctuations throughout the day, and from day to day, of 5% are not uncommon. Incorporated in this chapter is a description of a voltage regulator rectifier which delivers a direct current output constant within 0.05% or better for these same changes in line voltage. This stabilizer is satisfactory for sudden changes in line voltage caused by starting a motor from the line, as well as for the more or less permanent changes in line voltage as the normal load changes.

A typical rectifier regulator is shown in Fig. VI-a. The operation of the unit is simple. The triodes T-1 and T-2 serve as variable resistors between the rectifier output and the load. Their resistance is controlled by the voltage applied to their grids. The voltage regulator tube T-3 serves as a constant voltage source with respect to ground. The cathode of the high gain pentode T-4 is always at a relatively fixed potential with respect to ground.

Now, assume that the voltage across the load, or the voltage across the two resistors R-1 and R-2, begins to decrease. The voltage of the grid of the pentode T-4 will become more negative with respect to the cathode which has remained at a fixed potential. The decrease in grid voltage decreases the plate current through R-3 and raises the plate potential. At the same time the grids of the regulating triodes T-1 and T-2 are raised. The triodes will now pass more current and almost completely restore the voltage on the load to its original value.

The constancy of the output with changes in input have been given above. The regulator will also hold the voltage output as near constant when the load is changed from zero to the full capacity of the regulator. The characteristics of the regulator whose circuit diagram is Fig. VI-a are given in the graphs of Fig. VI-b and VI-c. In these curves the various curves were obtained with different settings of R-2 in Fig. VI-a.

<u>Fig. VI-a</u> Circuit diagram for a voltage regulated power supply.

T, Thordarson T-13R09, or equivalent; L-1, 12 henry 0.2 ampere choke; T-1, T-2, 2A3; T-3, VR tube; T-4, 6SJ7-GT; T-5, 5Z3; R-1, 100,000 ohms; R-2, 250,000-ohm potentiometer; R-3, 100,000 ohms; R-4, 7,500 ohms; R-5, 5,000 ohms; R-6, 5,000 ohms; C-3, 16 mfds.; C-4, 16 mfds. (see text).

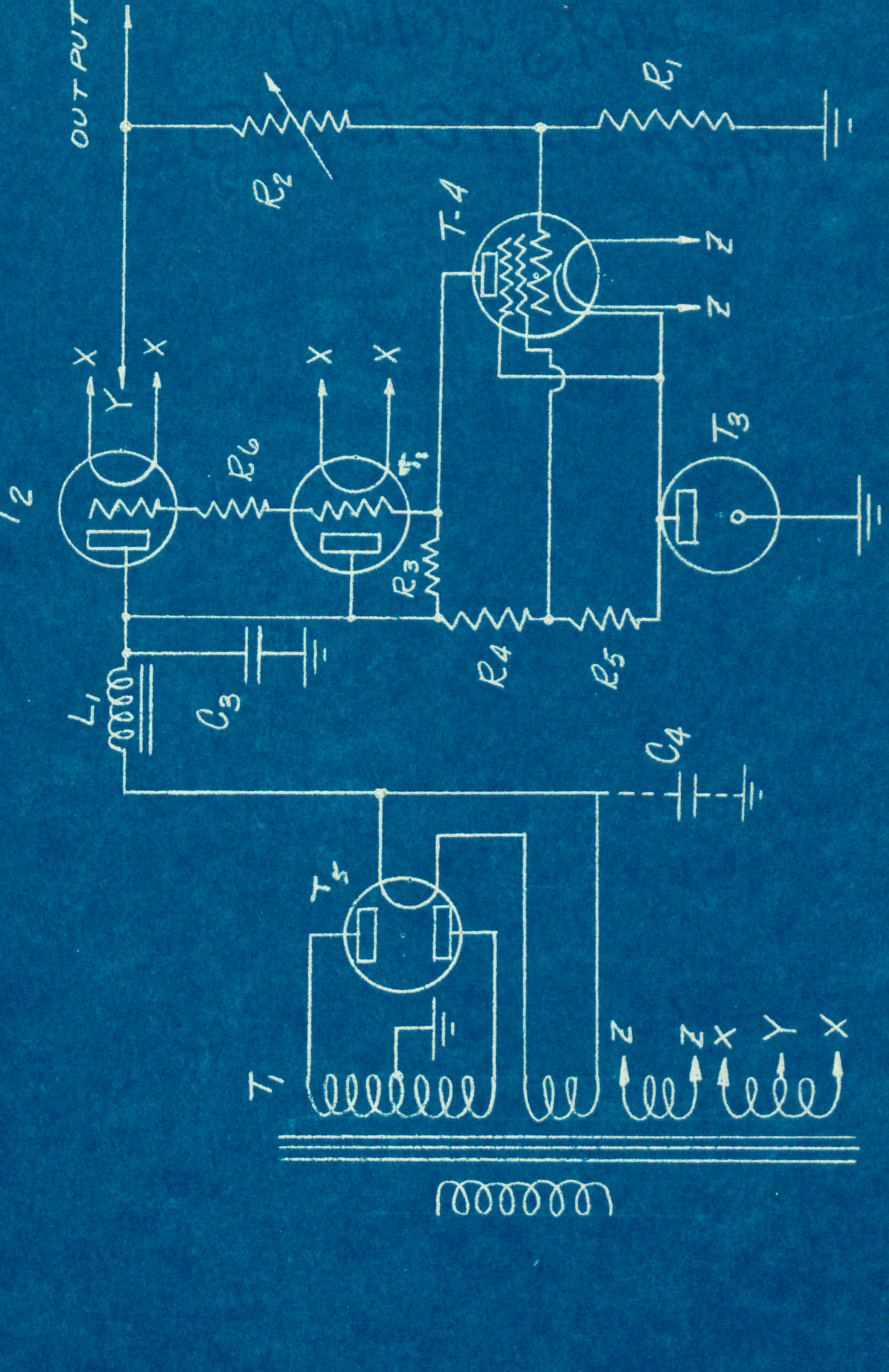

OUTPUT
R_2
R_1
T-4
Z
Z
X
Y
X
X
X
T_2
R_6
T_1
T_3
R_3
R_4
R_5
L_1
C_3
C_4
T_5
T_1
Z
Z
X
Y
X

Fig. VI-b   Output voltage as a function of line voltage for three settings of R-2.

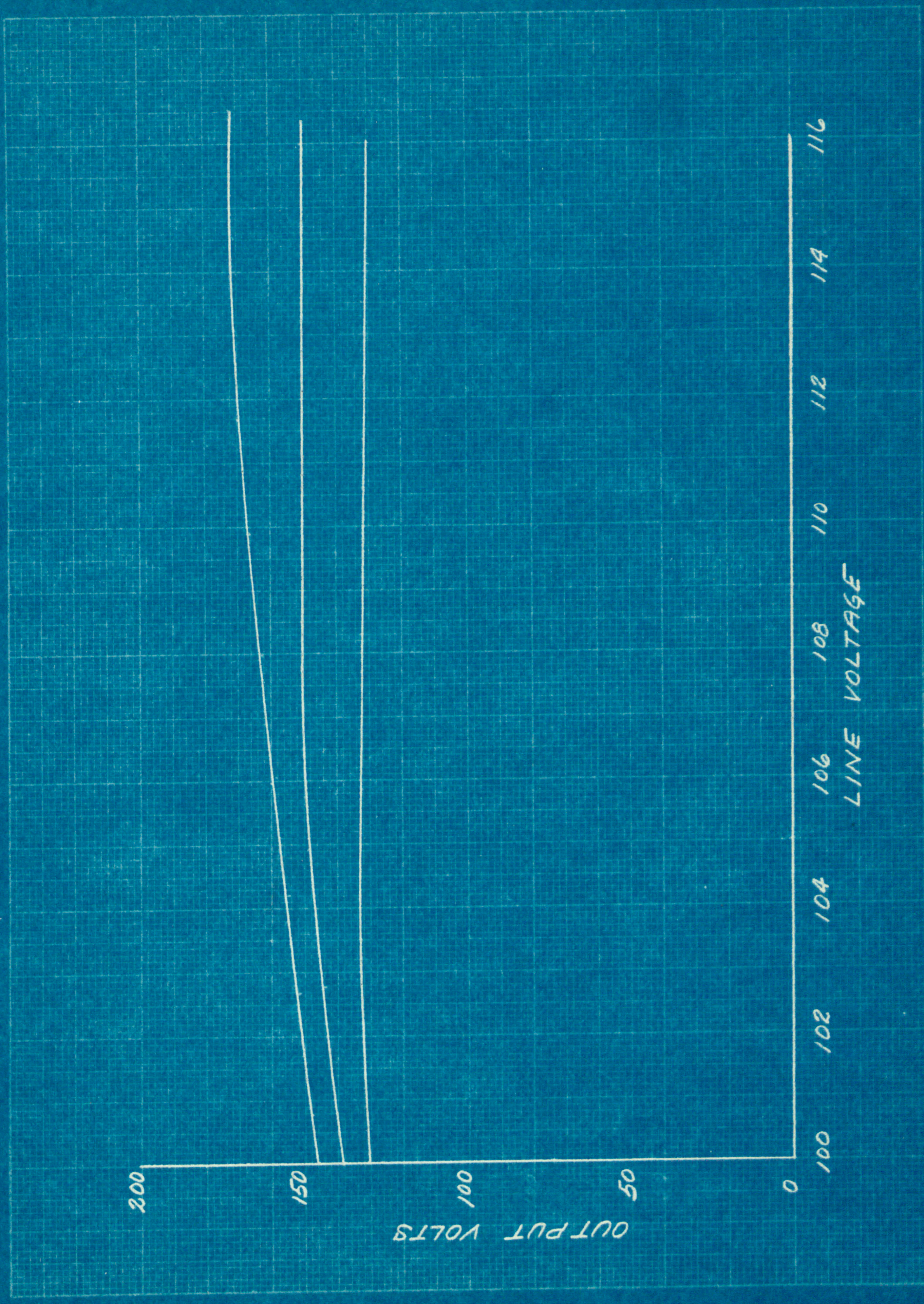
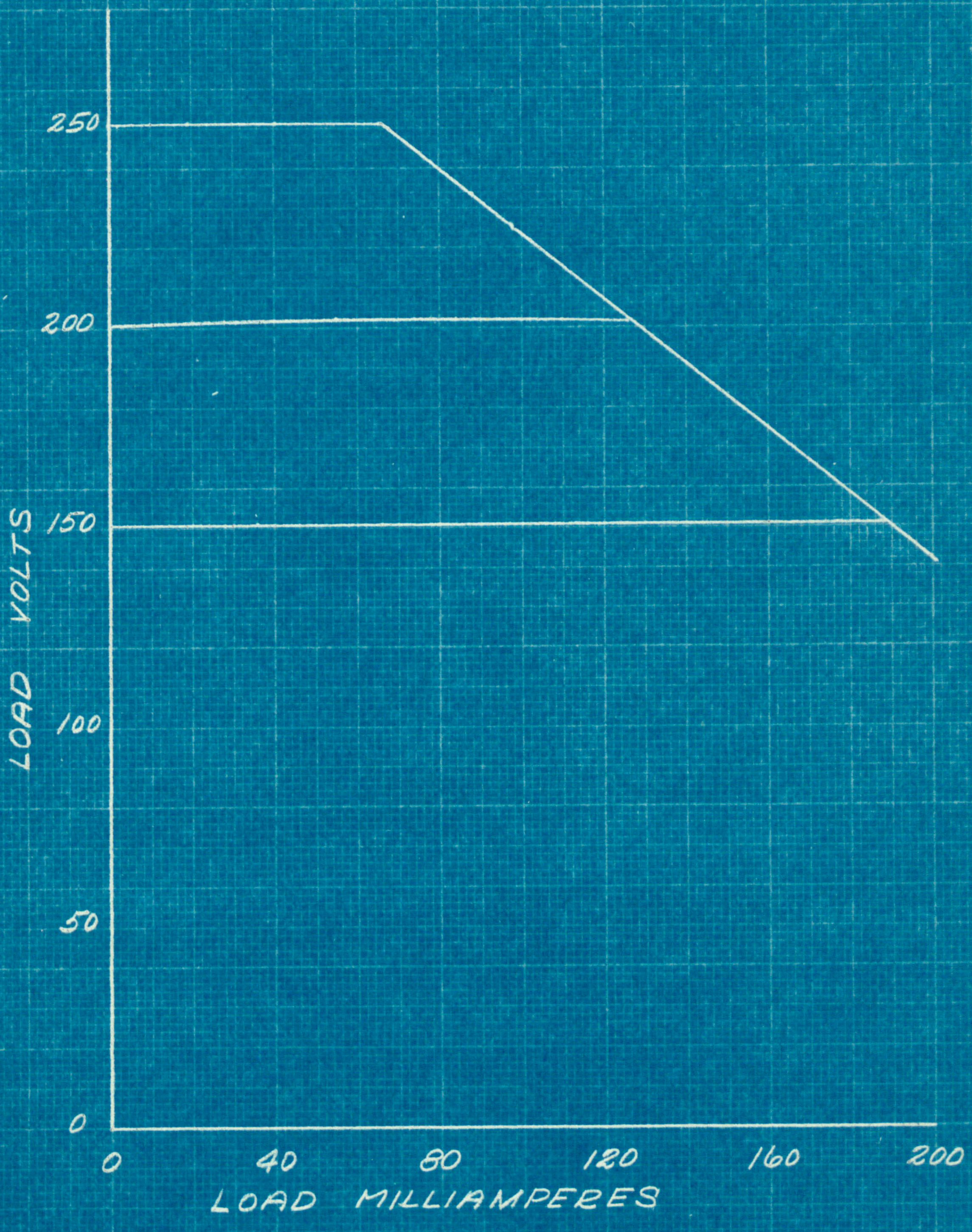

OUTPUT VOLTS
0
50
100
150
200
LINE VOLTAGE
100
102
104
106
108
110
112
114
116

Fig. VI-c Output volts as a function of load current taken for three settings of R-2.


LOAD VOLTS
250
200
150
100
50
0
0
40
80
120
160
200
LOAD MILLIAMPERES

It is well to point out the limitations of the regulator. There is a minimum voltage which can be delivered at the output. This minimum voltage is equal to the sum of the voltage across the regulator tube T-3, the minimum plate voltage for the pentode T-4, and the bias required on the triodes T-1 and T-2 for them to absorb the difference between the filter output and the delivered voltage. Since this bias is dependent upon the current the triodes are required to furnish to the load, the load current is also a factor in determining the minimum regulated voltage.

At the other extreme the maximum voltage which can be delivered is equal to the filter output voltage minus the voltage drop across the triodes at the bias where the triodes begin to draw positive grid current. Here again the load current is an important factor in determining the maximum regulated output voltage.

Needless to say, most satisfactory results will be obtained when the regulator is operated well within the limits outlined above. Within this range the voltage output is given very closely by the expression

$$\frac{R_1 + R_2}{R_1} \text{ times the voltage drop across T-3.}$$

Lower regulated voltages may be obtained by using a lower voltage transformer, or by using a regulator tube which operates at a lower voltage. In order to increase the maximum regulated voltage, the filter design may be changed from choke input to condenser input by the insertion of C-4, Fig. VI-a. This raises the filter output voltage and provides a greater available drop for the regulating triodes.

By slight changes in the bleeder supplying voltage for the screen grid of the pentode T-4, a battery may be substituted for the voltage regulator tube. Batteries afford the following advantages: A wider range of reference potentials are available. Voltage regulator tubes come only in the 75-, 90-, 105-, and 150-volt operating potentials. The internal resistance of a good battery is less than that of a regulator tube, which means that its voltage drop will change less with changes in current through it. Thirdly, a battery is not as susceptible to changes in potential with changes in temperature as is a voltage regulator tube.

The disadvantages of a battery are that the unit is no longer completely a.c. operated. A battery switch must be provided. In addition, the potential of a battery may change suddenly with the escape of gas from the battery cells. Any such change is magnified in the output.

Where a very small ripple, less than would be encountered in an inductance-capacity filter, is tolerable, the choke may be eliminated from the circuit. A large condenser, depending on the load current and voltage, from the triode plates to the minus of the supply is sufficient to keep the voltage at the input to the regulator up so that the regulator will operate satisfactorily.

The most satisfactory triode to serve as a regulating tube is the 2A3. These tubes may be calculated to have a minimum drop of about 100 volts at a current of 100 milliamperes and zero grid bias. When two or more of these tubes are connected in parallel to provide load currents greater than 0.1 ampere a resistor of 5,000 ohms should be inserted in the grid of each additional 2A3 tube (R-6 in Fig. VI-a) to prevent parasitic oscillations among the 2A3's. Parasitic oscillations manifest themselves when the regulator fails to work satisfactorily. Should the regulator have more satisfactory characteristics with a single 2A3 than with a pair even though the load exceed 100 milliamperes, it is a reasonably certain indication that parasitic oscillations are present. A cathode-ray oscillograph may be used for confirmation.

Because the screen grid potential is obtained from the unregulated side of the power supply, it is possible to construct the unit so that it will over-regulate from the supply side. In other words because of the screen-grid amplification an increase in supply voltage may actually result in a decrease in the voltage output of the regulator. By changing the size of the plate load resistor R-3 the unit may be made over- or under-regulating, and a certain value of R-3 will give almost perfectly constant output for changes in supply voltage.

Where even closer regulation is required, the filament of the pentode T-4 should be run from the regulated supply. This is necessary since the output voltage is a function of the filament voltage on this tube. If the filament is operated from the transformer as shown in Fig. VI-a the output voltage will be different for a given change in line voltage depending on whether the change was a sharp pulse or a permanent change of sufficient duration to permit the cathode to take on a new temperature.

The voltage regulated power supply has been used to advantage in connection with a balanced circuit, feed-back amplifier, and in a Turbidity Comparator to be described in Part II of this paper.

Bibliography for Chapter VI

[1] Grammers: QST XXI, 8, 14 (1937)

CONCLUSIONS

From the preceding chapters the following conclusions on small direct current measuring devices may be presented in tabular form. One or more models of each, with the exception of the most sensitive, were constructed and tested as part of this thesis.

Type of Circuit	Highest Sensitivity (per division of the meter)	Remarks
Bridge	10^{-10} amperes	Completely a.c. operated Uses portable meter. Has a voltage amplification, as well as a current amplification.
Feed-back	10^{-12}	A.c. operated with a portable meter.
	10^{-14}	Requires a voltage regulated power supply and a galvanometer with a sensitivity of 10^{-8} amperes/millimeter.
Integrating meter	10^{-15}	Completely self-contained, portable, battery operated. About the lower limit for commercial radio tubes.
Feed-back	10^{-16}	Uses an electrometer tube, regulated power supply, and galvanometer. Poor zero stability.
Balanced	10^{-17}	Requires an electrometer tube and 10^{-10} ampere/millimeter galvanometer.
Integrating meter	10^{-19}	Highest current sensitivity yet obtained. Has not been made a.c. operated.

One significant fact might be pointed out. With the exception of the bridge circuit, which has the lowest current sensitivity of the meters listed above, none of the current measuring equipment is suitable for voltage amplification. For example, in the feed-back circuit the voltage output is just equal to the voltage input, while the change in grid voltage exceeds the change in plate voltage when a current is measured with a balanced circuit. Furthermore, all of these amplifiers require the current to be measured in a high resistance circuit.

Hafstad has made a careful, analytical investigation of the limit of the current sensitivity he realized. It is his conclusion that the random deflections which persisted in his apparatus and which were always of the same magnitude were caused by a combination of thermal agitation in the high resistance input circuit and the shot affect arising from an irregular number of electrons striking the grid.

The random voltage produced by thermal agitation is a function of the magnitude of the resistance itself, To reduce the voltage it is necessary to reduce the size of the resistance in the grid circuit. This can only be done, retaining the same current sensitivity, if the amplification of the tube or the sensitivity of the galvanometer is increased. If a tube can be developed with 1) a higher amplification

2) the same stability of currents in the various elements, 3) as low or lower control-grid current than is now found in the electrometer tube, and 4) with a more evenly emitting cathode, it may be possible that even greater sensitivity in current measurements may be obtained.

Finally, no further increases in sensitivity may be expected until improvements in tubes are made or new basic principles discovered.

PART II

APPLICATIONS

APPLICATIONS

Turbidimeter: A photo-electric Turbidity Comparator has been developed for assaying the rate of certain biological growth in linquids. The comparator features an electronically stabilized voltage supply for both light source and amplifier. A paper describing this apparatus has been accepted for publication in the May 1942 issue of the Review of Scientific Instruments. A reprint of this article will be bound as part of this thesis.

Standard Ionization Chamber: This paper contains a description of apparatus suitable for calibrating the energy output of a soft x-ray tube. The calibration is accomplished through the application of the measurements used in defining the roentgen, or r-unit. The paper also contains a calibration of a soft x-ray tube which has been used in many biological and biochemical experiments. This paper is now in the hands of the editor. If accepted for publication a reprint will be bound with this thesis. If not accepted, a typewritten copy of the manuscript will be included.

Portable Dosimeter: This instrument has been found satisfactory for measuring x-ray dosages in both the soft (15 kv.) and hard (400 kv.) x-ray regions. After calibration it affords a convenient indicating instrument for dosages as small as one r-unit per minute.

This paper is in the hands of the editor. If accepted for publication, a reprint will be bound with this thesis. If not published, a typewritten copy of the manuscript will be included.

Time Delay Relay: As an example taken from the field of electronic control the time delay relay is entered into this thesis. The relay has been used in the laboratory in connection with other apparatus for exposing seeds to x-radiation for a predetermined period of time.

A description of the relay has been published (R. S. I. 13, 2, 83 (1941)) and a reprint is included in the thesis.

A.C. Operated pH Meter: This instrument used in connection with a potentiometer will read pH's as accurately as the potentiometer can be set, and draws no current through the cell under test. It is described in Chapter XI.

CHAPTER VII

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Time Delay Relay

Richard P. Krebs and H. Kersten
Department of Physics, University of Cincinnati, Cincinnati, Ohio
(Received December 29, 1941)

THIS note describes a relay with an adjustable time delay feature which was built for a special purpose in this laboratory but which can be adapted to other applications requiring a time delay between two operations. Its characteristics are that it: is completely a.c.-operated; closes ten seconds after the energizing contact is made; may be adjusted to open automatically at any predetermined time from five to 90 seconds after it has closed and manually at any time in its cycle of operation by opening the energizing circuit. For a consistent time delay operation the energizing circuit must be opened for at least ten minutes between successive cycles and it cannot be closed for several minutes after a cycle has been completed. If a period of ten minutes or more elapses between cycles, the time delay period is reproducible to about five percent.

The circuit, shown in the upper part of Fig. 1, uses two 117Z6GT tubes (T_1 and T_2), a 1000-ohm sensitive relay (R), a 25-watt rheostat having a resistance of 500 ohms plus 500-ohm auxiliary resistances which may be cut in with a selector switch (R_1); two 4000-ohm, 2-watt resistors (R_2) and a 25-μf 25-volt condenser (C). The two rectifiers are used each conducting in an opposite direction through the relay. When each rectifier conducts the same amount of current, there is in effect no current through the relay, and it opens. The time required for T_2 to draw the same current as T_1 is determined by R_1. A graph of the characteristics of the relay is shown in the lower part of Fig. 1.

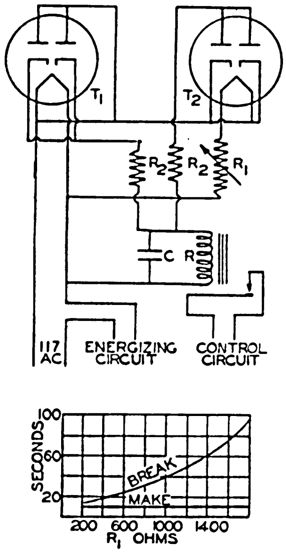


Fig. 1

CHAPTER VIIII

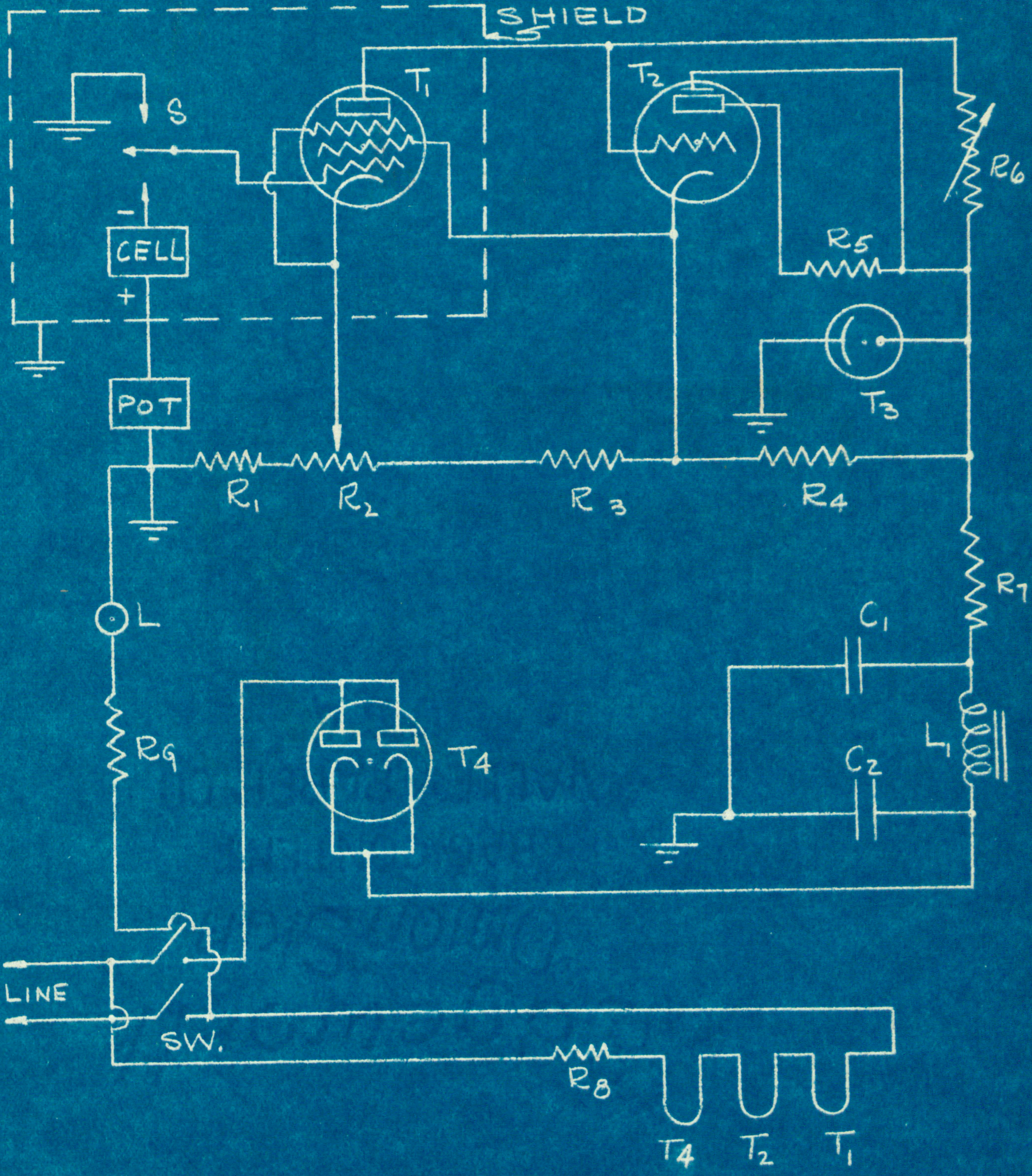
A. C. OPERATED pH METER

So important are pH measurements in a biophysical laboratory that an instrument for making these measurements deserves its place in a thesis of this type. The pH meter described is completely a.c. operated, and has been found to have sufficient sensitivity for readings ±0.5 millivolt, which is the smallest readable division on a Leeds & Northrup potentiometer.

In a pH meter the amount of current drawn through the cell is of equal importance to the voltage sensitivity of the instrument. In this particular model a vacuum tube with its grid at its floating potential is used to measure the voltage difference between the cell under test and a potentiometer. When the potentiometer voltage exactly equals that of the cell, there is no current drawn through the cell. In the process of adjusting the potentiometer only momentary contact need be made between the cell and the grid of the vacuum tube, so that polarization from current flow is reduced to a minimum.

The circuit for the pH meter is shown in Fig. XI-a. It is an a.c. operated adaptation of a circuit by Hill[1]. T-1 serves as an amplifier for the voltage difference between the cell and the potentiometer. It is mounted in its socket in such a manner that it may be rotated in a vertical plane. Its rotation is limited on either side by the two contacts of the switch S. T-2, an electric eye, serves as an indicator

<u>Fig. XI-a</u> Circuit Diagram for pH Meter
R-1, 100 ohms; R-2, 100-ohm pot.; R-3, 2,000 ohms; R-4, 8,000 ohms; R-5, ½ megohm; R-6, 100,000-ohm rheostat; R-7, 500 ohms; R-8, 220-ohm cordohm; R-9, 200 ohms; C-1, C-2, 16mfds; L-1, 10 henry, 30 ma. choke; T-1, 6C6; T-2, 6E5; T-3, VR 105-30; T-4, 25Z6-G/GT; S, see text; Sw, DPST switch; L, 0.5 ampere pilot light.


SHIELD
S
T1
T2
R6
−
CELL
+
R5
T3
POT
R1
R2
R3
R4
R7
C1
L
L1
C2
R9
T4
LINE
SW.
R8
T4
T2
T1

<u>Fig. XI-b</u> The pH meter

for this difference, while T-3 serves to regulate the voltage supplied to the amplifier. T-4 serves as a half-wave rectifier.

The cell whose pH is to be measured is first installed inside the metal shield covering both the cell, the tube, and the switch S, with the polarity as indicated. After the switch Sw has been closed, the meter should be allowed to warm up for at least a minute. Next, with tube T-1 in a vertical position, so that its grid cap touches neither contact of the switch S, R-6 should be adjusted until the electric eye, T-2, is just closed. The tube T-1 should then be tilted so that its grid cap touches the grounded contact of the switch S. R-2 should then be adjusted to just close the eye. After returning T-1 to its neutral position, R-6 is again adjusted to just close the eye. Adjustment of R-2 with the grid grounded, and adjustment of R-6 with the grid floating are continued until the eye remains just closed with T-1 in either position.

When R-2 and R-6 have been properly adjusted T-1 will be biased to the floating-grid potential when its control grid is grounded, and no current will flow in the control-grid circuit. If, now, the cell and the potentiometer are connected into the grid circuit of T-1, with no difference of potential between the minus of the cell and the ground, the electric eye will remain just closed, and no current will flow in the cell.

If the potentiometer and cell are not of equal potential, the electric eye will either open or overlap when T-1 is connected to the cell. While adjusting the potentiometer the tube should be allowed only momentary contact with the cell to minimize polarization effects. If balancing the potentiometer requires considerable time it is well to make sure that the eye retains its same degree of closure, whether the tube T-1 be in its neutral position or with its grid grounded.

Since this instrument is a.c. operated without a transformer, a power cord polarity indicating lamp L is included in the circuit. The function of this lamp is explained in detail in Chapters VIII and IX, and the reader is referred to these sections.

Bibliography for Chapter XI

[1] Dole: The Glass Electrode p. 58

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