C. J. Overbeck
Professor of Physics
Northwestern University

R. R. Palmer
Professor of Physics
Beloit College

R. J. Stephenson
Professor of Physics
The College of Wooster

Marsh W. White
Professor of Physics
The Pennsylvania State University

EXP. No. ....

PRINCIPLES OF VACUUM TUBES

OBJECT: To investigate the principles and applications of the two-electrode and the three-electrode thermionic tube.

METHOD: A standard three-electrode tube is mounted on a test panel provided with a potential divider for altering the grid potential and with a rheostat for regulating the filament current. Connections are provided for the insertion of batteries and of meters to indicate grid voltage, plate voltage, filament current and plate current.

The variation of thermionic current with filament temperature is observed by altering the filament current while holding the plate voltage constant. The effect of plate voltage upon the thermionic current is studied by altering the plate voltage while keeping the filament at a constant temperature. The function of the grid is investigated by observing the variation of plate current caused by a given change in grid voltage, the filament temperature remaining constant. The results are shown by graphing the data on Cartesian coordinate paper.

THEORY: When a metallic body is heated in a partially evacuated enclosure, electrons are ejected from the surface of the metal. The number of electrons given off per unit area per unit time depends upon the kind of metal and upon the temperature of the emitter. This effect was first observed by Thomas Edison during the course of his researches on the incandescent lamp, and is often referred to as the *Edison effect*. Electrons liberated from a metal by virtue of its temperature are sometimes called *thermions*, and their emission is sometimes called the *thermionic effect*.*

Edison found that when the enclosure contains a second metallic body maintained at a positive potential by a battery, the negatively charged electrons, or thermions, are attracted to the positive body. The experimental arrangement is shown schematically in Fig. 1. The evacuated region is contained in a glass envelope V constructed much like an ordinary lamp bulb. The *emitter*, or source of electrons, is a wire filament F (usually tungsten) which is heated by the current from a battery A. The collector of electrons is a metal plate P placed near the filament and connected to the positive terminal of a second battery B.

In the early forms of the vacuum tube, the emitter was a simple tungsten filament similar to that used in an incandescent lamp. Various improvements have been made, involving two basic modifications. One of these modifications consists of altering the surface character of the emitter by coating it with an oxide of calcium, barium or strontium, or by impregnating the metal surface with thorium. Oxide coated filaments and thoriated filaments yield a greater electron emission than does untreated tungsten, thereby making it possible to operate the filament at a lower temperature.

The second basic modification of the emitter involves the use of an emitting surface that is heated by radiation from a nearby filament, instead of taking the electron emission directly from the filament itself. This type is more suitable for use with alternating current and the temperature of the so-called *radiant emitter* (and hence the thermionic emission) is more nearly uniform than that of the filament itself. Another advantage of this type is that all parts of the emitter are at the same potential, whereas there is, of course, a potential drop across a conduction heated filament.

The most common type of present day tube employs both of these modifications; the emitter is an oxide coated metal cylinder heated by a centrally located tungsten filament. The plate is usually a cylindrical sheath of molybdenum surrounding the emitter, or *cathode*, as it is frequently called.

The battery for heating the filament is a low voltage battery, from 1.5 volts to 8 volts, depending upon the type of tube. The battery for supplying the plate potential is a relatively high voltage one which may vary with different tubes from twenty or thirty volts to several hundred volts. In radio practice it is customary to refer to these as the "A battery" and the "B battery," respectively. In many present day applications, the A and B batteries are replaced by transformers and rectifiers so that the equipment can be operated directly from an alternating current power line.

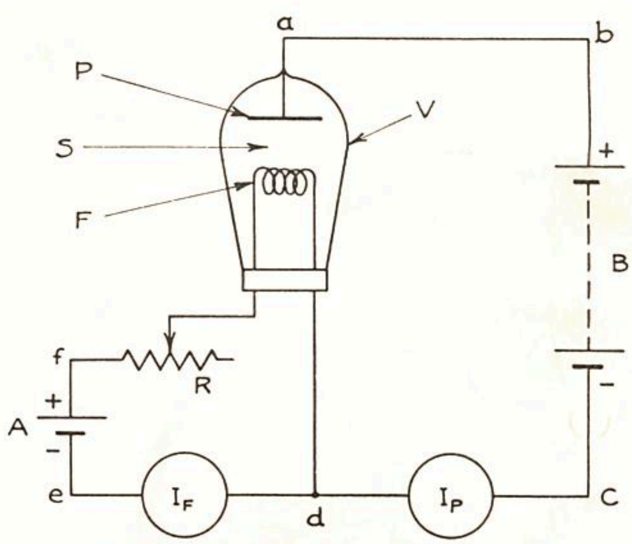

Fig. 1. The thermionic effect; two-electrode tube.

When the positive terminal of the B battery is connected to the plate P and the negative terminal to the filament F, the space S becomes a part of the circuit a b c d a which can carry a current only when electrons are caused to pass from F to P. The passage of the electrons from the filament to the plate through the intervening space is variously called the *space current, plate current*, or *thermionic current.* In Fig. 1 the plate current I_p is indicated by the milliammeter in the plate circuit. The filament current I_f is controlled by the rheostat R and

*The thermionic effect is not to be confused with the *thermoelectric effect* which is an entirely different phenomenon.

No. 71990—693
(formerly E93b)

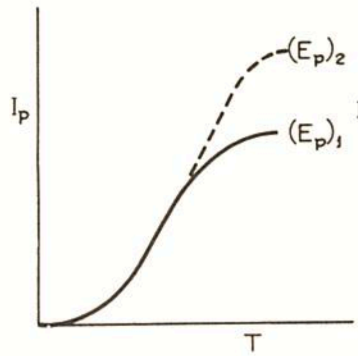

Fig. 2. Plate current vs. filament temperature (plate voltage constant).

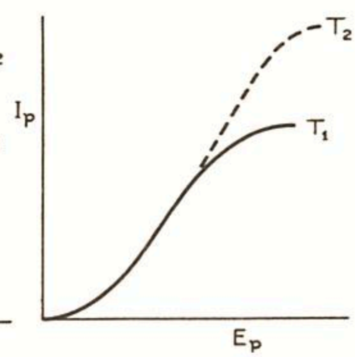

Fig. 3. Plate current vs. plate voltage (filament temperature constant).

indicated by the ammeter in the filament circuit. A tube, such as that represented by Fig. 1, which contains only a filament and a plate, is called a two-electrode tube, or a *diode.*

As the filament temperature is raised, the plate current (for a given plate voltage E_p) increases, slowly at first, and then very rapidly. However, the plate current does not increase indefinitely with filament temperature, but reaches a saturation value as shown in Fig. 2. The explanation of this behavior lies in the fact that the *space charge,* i.e., the accumulation of electrons in the space S, increases to the point where the mutual repulsion between the space charge and the electrons at the surface of the filament is so great as to prevent a further increase in the rate of emission of electrons. In other words, the space charge has the effect of reducing the electrostatic field. It thus acts like a "blanket" enshrouding the filament and suppressing the thermionic emission. When this state is reached, the current remains constant as the temperature is increased. The effect of the space charge may be reduced by raising the plate potential; this increases the attraction between the electrons and the plate and has the effect of sweeping the space charge from the region. The net result is to produce a higher value of the saturation current as is shown by the dotted portion of the curve in Fig. 2.

For a given filament temperature, the plate current depends upon the plate voltage as shown in Fig. 3. The fact that a saturation value is reached is explained by the fact that when the plate voltage becomes sufficient to attract to the plate all of the electrons that are emitted by the hot filament, no increase in current can be produced unless the supply of electrons is increased. If the emission is increased by raising the filament temperature, a higher saturation voltage is required to collect all of the electrons that are emitted at the higher temperature.

The principal use of the diode is as a *rectifier* of alternating current. From what has been said, it is obvious that the potential of the plate must be positive with respect to the filament in order for the electrons to traverse the space S; when a negative potential is applied to the plate, it serves to repel the electrons and thus prevent the flow of the current. If, therefore, the B battery is replaced by an alternating current generator, the meter I_p indicates a current in the plate circuit only during one half of the cycle. The tube thus acts as a "valve" which permits the flow of current in one direction only. A typical rectifier circuit is shown in Fig. 4(a). Since only one half the cycle is utilized, this process is called *half-wave* rectification; it is possible by using two such tubes, or with a tube containing two plates, to obtain *full-wave* rectification (Fig. 4b).

A notable contribution to the development of the thermionic tube was made by Lee DeForest who modified the two-electrode tube by inserting between the filament and the plate a third electrode in the form of a net, or *grid,* through which the electrons may pass. DeForest discovered that the introduction of the third electrode made possible a delicate control of the plate current by making slight changes in the potential of the grid. The amount of control depends upon the construction of the grid and upon its distance from the filament. The performance of a *triode* is most readily specified by means of graphs called *static characteristics,* showing either (1) the relationship between the plate current and the plate voltage, the grid voltage being held constant, or (2) the relationship between the plate current and the grid voltage, the plate voltage being held constant. The effect of changing the value of the fixed voltage is to shift the entire curve to the right or the left. These curves also exhibit saturation, but in most present day vacuum tubes the cathode is capable of emitting many more electrons than are required for the rated tube current, so that temperature saturation does not occur in operation. The curves thus continue to rise even beyond the maximum rated current for the tube.

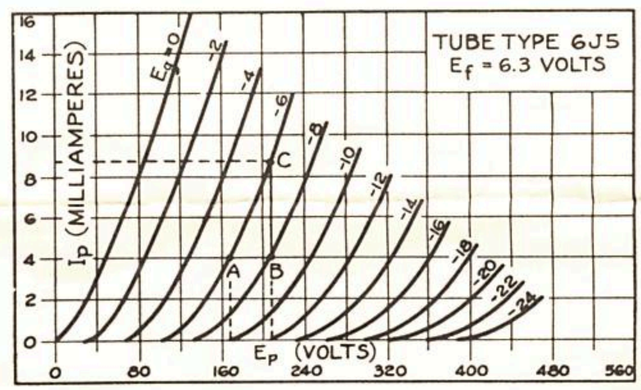

Fig. 5. Typical family of static characteristics of a triode.

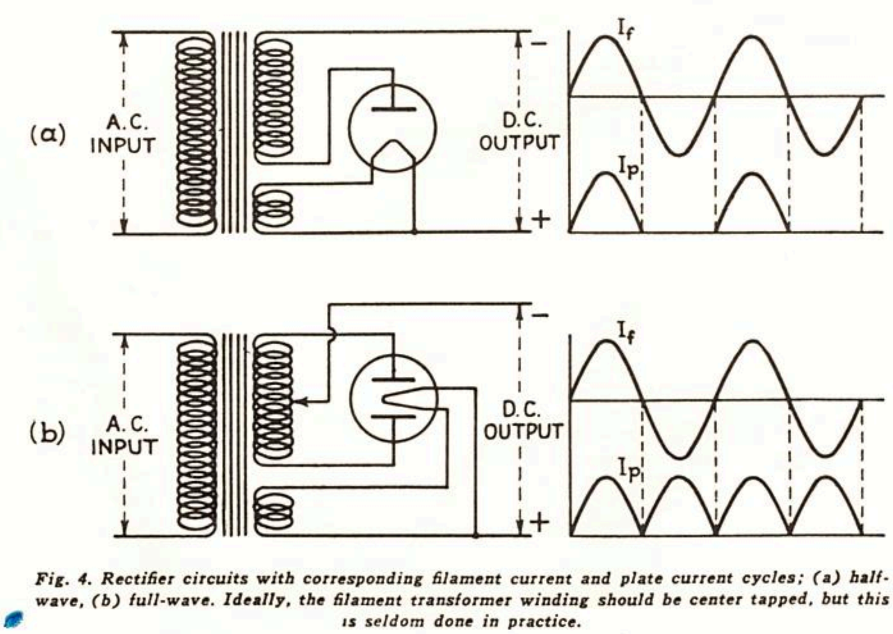

Fig. 4. Rectifier circuits with corresponding filament current and plate current cycles; (a) half-wave, (b) full-wave. Ideally, the filament transformer winding should be center tapped, but this is seldom done in practice.

Figure 5 is a typical family of static characteristics of a given triode tube in which the plate current I_p and the plate voltage E_p are the variables and the grid voltage E_g plays the role of an arbitrary constant which determines a particular one of a family of curves.

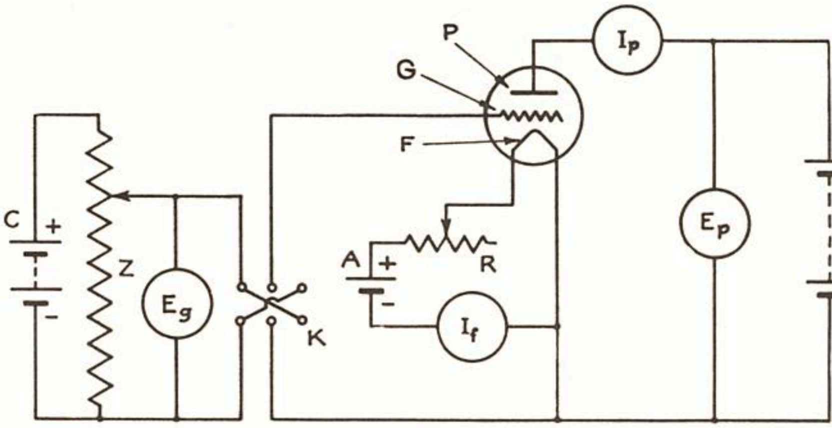

Fig. 6. Circuit for obtaining the static characteristics of a filament emitter type triode.

Tube Parameters, or Characteristics: The performance of a vacuum tube is usually specified in terms of three *parameters,* or characteristic values. The *voltage amplification factor* μ is defined as the ratio of the plate voltage change ΔE_p required to produce a given increment ΔI_p in plate current to the grid voltage change ΔE_g necessary to yield the same change in plate current. Thus

$$\mu = \frac{\Delta E_p}{\Delta E_g} (\Delta I_p = \text{constant}) \qquad (1)$$

This factor, which is practically constant for a given tube, indicates the relative effectiveness of the grid over the plate in controlling the flow of the plate current. The value of μ for triodes ranges from 1 to 100 with the majority in the range from 10 to 40.

The *mutual conductance* g_m is the ratio of the increment in plate current to the corresponding increment in grid voltage when the plate voltage is held constant. Thus

$$g_m = \frac{\Delta I_p}{\Delta E_g} (E_p = \text{constant}) \qquad (2)$$

The value of g_m is expressed in *micromhos.* (Since conductance is the reciprocal of resistance, one *mho* is the conductance of a circuit having a resistance of 1 *ohm.*)

The *plate resistance* R_p of a tube is the ratio of the plate voltage change to the plate current change, the grid voltage being kept constant, Thus

$$R_p = \frac{\Delta E_p}{\Delta I_p} (E_g = \text{constant}) \qquad (3)$$

The plate resistance is expressed in ohms. These three parameters μ, g_m and R_p are related in the following simple manner:

$$\mu = g_m \cdot R_p \qquad (4)$$

Hence, if any two of these values are known, the third can be calculated.

The values of μ, g_m and R_p can be determined graphically from the static characteristic curves for the tube. From a consideration of Fig. 5,

$$\mu = \frac{AB}{\Delta E_g} = \frac{210 - 170}{8 - 6} = \frac{40}{2} = 20. \qquad (5)$$

$$g_m = \frac{BC}{\Delta E_g} = \frac{.0085 - .004}{2} = \frac{.0045}{2} = .00225 \qquad (6)$$

$$R_p = \frac{AB}{BC} = \frac{210 - 170}{.0085 - .004} = \frac{40}{.0045} = 8880 \text{ ohms} \qquad (7)$$

The triode is used to perform three important functions in the field of electronics. In reception of radio waves it is used as a *rectifier* of the alternating current induced in the receiving antenna. In all phases of radio, as well as in countless other applications, the simple triode is used as an *amplifier,* i.e., as a device for obtaining an increased response from an originally weak stimulus. In radio transmission, the triode serves as an *oscillator* for the generation of waves of any desired frequency. Since the invention of the 3-electrode tube, there have been numerous modifications in which four, five (and more) electrodes have been used; but the triode is still the basic thermionic tube of today.

This experiment consists of an experimental study of the principles described above and of a determination of the static characteristics of a typical triode.

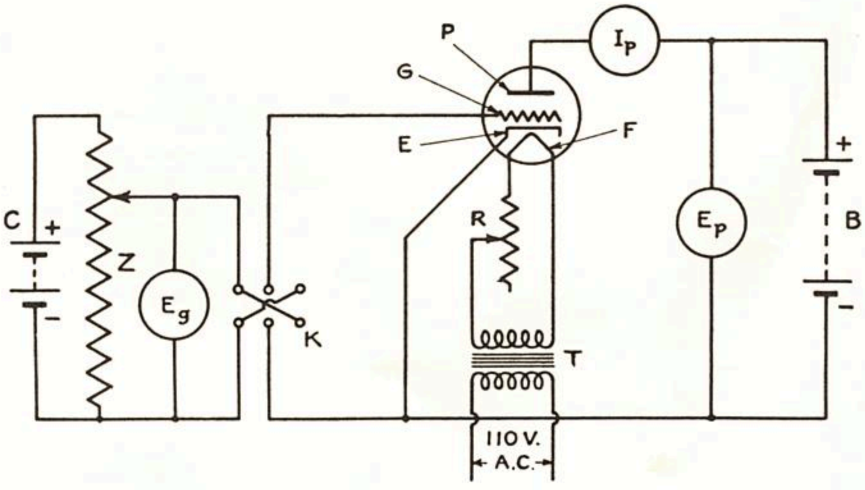

Fig. 7. Circuit for obtaining the static characteristics of a radiant emitter type triode using a.c. filament supply.

APPARATUS: The circuit for determining the static characteristic of a filament emitter triode is shown in Fig. 6. The corresponding circuit for the radiant emitter type is shown in Fig. 7. The battery which supplies the grid voltage is labelled C. The grid voltage E_g is varied by means of the slide wire rheostat Z. When used in this way, the rheostat is called a *potential divider.* A reversing switch K enables the grid potential to be made either positive or negative.

The experiment employs a test panel, the wiring diagram of which is shown in Fig. 8. The tube to be tested is a radiant emitter triode of the type known as 6J5.* Acces-

*Adapters are available which will permit the use of a 4-prong tube in this apparatus.

sory apparatus required for the respective measurements consists of the following:

E_g—d.c. voltmeter, range 0—10 volts
E_p—d.c. voltmeter, range 0—150 volts
I_p—d.c. milliameter, range 0—25 milliamp.
I_f—a.c. or d.c. meter, range 0—0.5 amp.

The filament supply may consist of an 8-volt A battery or a step-down transformer. For the plate potential, a B battery consisting of three 45-volt dry-cell batteries each tapped at 22.5 volts, is convenient. The C battery should consist of a 6-volt battery of dry cells or storage cells. It is frequently convenient to replace these batteries by power supply units when they are available.

PROCEDURE:

Experimental: Make a careful comparison of Figs. 6, 7, and 8. Connect the power supplies and the meters as shown by the wiring diagram of the test panel. The C battery is to be omitted from the circuit for the first observations. *Caution:* **Make certain that the polarities are correct.** Insert the tube in the socket and make the following tests.

1. Effect of emitter temperature upon plate current: With the radiant emitter type of tube, this relationship can only be shown indirectly since the cathode temperature cannot readily be determined. However, the cathode temperature is directly related to the filament temperature which, in turn, depends upon the filament current. For the purposes of this experiment, it is most convenient to determine the plate current as a function of the filament current.

Connect the grid to the cathode by joining the terminals E_g+ and E_g- with a piece of wire. This makes the grid potential the same as the cathode potential and causes the tube to act like a two-electrode tube. Adjust the plate potential E_p at 135 volts. Adjust the filament rheostat for minimum filament current and observe the plate current. Make a series of such observations, increasing the filament current in steps of .02 amp up to a maximum of 0.3 ampere. Repeat the series of observations with plate voltages of 90 volts and 45 volts.

2. Effect of plate voltage upon plate current: With the grid still connected to the filament, adjust the filament current to about 0.3 ampere. The filament current is to be kept constant during these observations.*

Make the plate voltage 22.5 volts and observe the plate current. Increase the plate voltage in steps of 22.5 volts to a total of 135 volts, recording the corresponding values of the plate current.

3. Effect of plate voltage upon plate current, grid voltage remaining constant: Connect a 6-volt battery at E_g and adjust the grid potentiometer to give a grid voltage of 5 volts. Set the grid switch to the minus position, thereby applying a negative potential to the grid. With a constant filament current and a grid voltage of −5 volts, vary the plate voltage in 22.5-volt steps between 22.5 and 135 volts, observing corresponding plate currents.

Repeat these observations with grid voltages of −3, −2 and 0 volts.

4. Effect of grid voltage upon plate current, plate voltage remaining constant: Connect a 6-volt battery at E_g and adjust the grid potentiometer to give a grid voltage of 5 volts. Set the grid switch to the "minus" position, thereby applying a negative potential to the grid. With a constant filament current and a plate voltage of 22.5 volts, take a series of readings of the plate current as the grid voltage is increased from −5 to +5 volts in 1-volt steps.

Repeat these observations with plate voltages of 45, 67.5 and 90 volts.

5. Voltage amplification factor: With 45 volts on the plate and a grid voltage of −2.0 volts, adjust the filament current to 0.3 ampere. Read the plate current. Increase the plate voltage to 90 volts and note the increase in plate current. Restore the plate potential to 45 volts and produce the same increase in plate current by increasing the grid voltage by means of the grid potentiometer. Note the change in grid voltage required to produce the same change in plate current as that produced by a change of 45 volts in plate voltage. Compute the voltage amplification factor by Eq. (1). Repeat the determination starting with zero grid voltage.

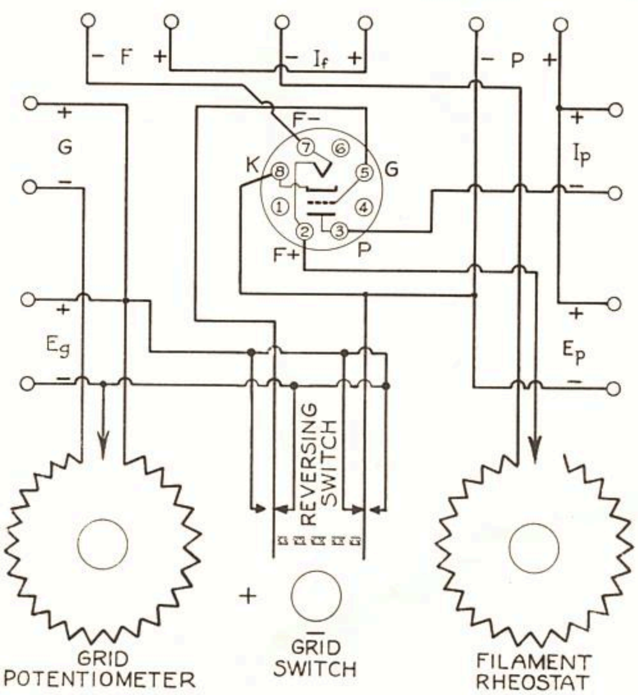

Fig. 8. Wiring diagram of test panel.

Analysis of Data: 1. Plot a curve of the data of paragraph 1 above, with plate current as the ordinate and filament current as the abscissa.

2. From the data of paragraph 2, plot the plate current I_p as the ordinate and the plate voltage E_p as the abscissa.

3. From data of paragraph 3, plot four static characteristics on the same sheet (plate current I_p as ordinates and plate voltage E_p as abscissas).

4. From the data of paragraph 4, plot three static characteristics on the same sheet (plate current I_p as ordinate and grid voltage E_g as abscissa).

Optional: Graphical determination of μ, g_m and R_p: Select two of the static characteristic curves and determine the tube parameters by the method outlined above.

QUESTIONS: 1. Explain the shape of curve 1.

2. What is the cause of saturation in curve 2?

3. Explain the action of the grid; to increase its effect should it be moved nearer to the plate or to the filament? Why?

4. When used as an amplifier the triode is operated so that all values lie on the linear portion AB of the characteristic curve (Fig. 5). There are two reasons for this; state them.

5. When used as a rectifier the triode is operated on the "toe" of the curve, i.e., so that zero grid voltage is at the bend (near A). Explain.

*For all experiments except that outlined in paragraph 1, the simplest way of fixing the filament current is to apply a constant potential of 6 volts d.c. or 6.3 volts a.c.

PRINTED IN U. S. A.